ASSESSMENT OF THE PROGRESSION OF COAL MINE SUBSIDENCE IN COLORADO, USING INSAR

by

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ABSTRACT

Coal mine subsidence is the deformation of the Earth’s surface caused by the collapse of rock and unconsolidated deposits into underground mine voids or entries, induced by the extraction of coal. This deformation can cause damage to roads, buildings, utility lines, or pipelines. Colorado’s history of coal mining dates back to the beginning of the 20th century and continues to this date. Inactive mines in Colorado pose a potential risk for 25,000 people along the front range urban corridor. An important step towards mitigating this problem, is to assess the applicability of remote sensing techniques for characterizing the vertical displacement, lateral extent, and formation sequence of subsidence features, in relation to the extent and timing of mining activities. This project evaluates the applicability of Interferometric Synthetic Aperture Radar (InSAR) for quantifying and delineating the progression of subsidence from active coal mines in Colorado.

The data used for this analysis is limited to SAR images collected by the Advanced Land Observation Satellite (ALOS), the Environmental Satellite (ENVISAT) and the European Remote Sensing (ERS) satellites I and II. Three study areas were selected to assess the method’s applicability under different conditions (density of vegetation, topography, activity status, and mining method). The study areas are the Deserado Mine, the King Coal II Mine, and the historical mining complex in Colorado Springs. The pertaining imagery was archived in a database, organized by the relative orbit and frame of provenance. SAR images were processed with General Mapping Tools SAR (GMT5SAR) and the Generic InSAR Analysis Toolbox (GIAnT) to produce a time series of quantified deformation. The results were ultimately compared with the extent of mine workings and subsidence models to assess the accuracy of the results. Clear subsidence signatures were found over the Deserado Mine and the King Coal II mine. Deformation above the longwall mine (Deserado) was detected with all the utilized data sets, proving that InSAR can be used to delineate the extent of subsidence over such type of mines. Deformation above the active room and pillar mine (King Coal II) was only detected using ALOS data. No clear signs of deformation were found within the historical mining complex in Colorado Springs. The low density of coherent pixels limits the use of InSAR for delineating troughs above such mine type.
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CHAPTER 1
INTRODUCTION

Subsidence is a major hazard throughout the United States (US). Approximately 20% of the area that has undergone subsidence in the country was undermined, mostly targeting coal (Baum, et al., 2008). “Subsidence attributed to underground coal mining, generally classified as pit subsidence or sag/trough subsidence, had affected about one quarter of the area undermined or 2 million acres in the United States by the 1970s …” (Baum, et al., 2008). In the future, it is expected that the undermined area, dedicated to coal mines, will be five times larger than what it currently is (Baum, et al., 2008). Assuming the ratio of subsided to mined land remains constant - which could be an underestimation given that longwall mining has become the preferred method - the US could expect the subsided area to reach 10 million acres.

Most of the mining and associated subsidence has occurred east of the Mississippi. The states that stand out for their historical and current coal production are Pennsylvania, West Virginia, and Illinois. Nevertheless, coal mining is also intrinsic to Colorado’s history. The gold rush that the region experienced back in the 19th century caused a significant population influx, resulting in a corresponding increase in energy demand. This energy demand fueled coal exploration, which revealed the existence of large deposits west and east of the Colorado’s Front Range (Colorado History n.d.; Matheson, 1985).

Presently, the US is the second largest coal producer in the world, and Colorado is amongst the states that mine the highest volumes of Coal in the US (EIA, n.d.). As of 2014, approximately 23 million tons of coal were produced in Colorado, and only approximately 8.5 million tons were sold inside the state. The remainder was sold out of state or outside of the US (Colorado Mining Association, nd). These facts evidence that coal mining is not only a historical aspect of the state’s economy, but a current and significant contributor to Colorado’s growth.

When mine workings collapse, the overburden readjusts, causing deformation at the surface and potential damages to structures. The Colorado Geological Survey (CGS) estimates that subsidence, as a result of historical mining, is a hazard for 25,000 people along the Front Range alone (Amundson, et al., 2009). This figure does not include the risk of subsidence from historical mining west of the Front Range, nor the risk of subsidence as a result of active mining. The number of affected people and the damage to structures will only increase with time.

There are still underground openings in Colorado from historical mines. Many of these openings underlay densely populated residential areas in cities like Boulder and Colorado Springs. The condition of the pillars, mine roofs, and mine floors, preventing the collapse of such openings is degrading with time due to many factors such as fluctuations in groundwater.
levels and exposure of openings to surface conditions. These openings will collapse and the failure could propagate to the surface. Therefore, techniques should be implemented in areas with history of underground mining to detect ground deformation in its early stages, and to prioritize mitigation measures.

A crucial step in assessing the risk that any hazard poses on people or structures is to characterize the hazard. The accuracy of risk assessments is fully dependent on the accuracy of the hazard characterization. Thus, the more comprehensive the characterization of deformation is, the more information is available for evaluating current and future risks.

Only a small percentage of Colorado’s coal reserves have been mined so far. Coal generates approximately 50% of the United States’ electricity, and the energy demand is continuously growing (Bauer, 2008). There have been efforts to reduce the reliance on coal as an energy source, through the implementation of renewable energy systems. However, this energy source will not be fully replaced in the near future. Thus, coal will continue to be mined over the next decades. Most active mines are in remote areas. Despite their remoteness, subsidence from active coal mines can induce damage to utility and transportation corridors, and pipelines. The growth of the coal mining industry will result in a proportional increase in ground subsidence. Thus, detecting and monitoring ground deformation above active mines is also paramount.

Deformation of the surface can be evaluated by data obtained from monitoring instruments installed onsite. However, it can be very costly and labor intensive to install and monitor an instrumentation network large enough to encompass historical mining sites in Colorado. Additionally, data obtained via instrumentation represents the conditions at discrete locations, posing the need of interpolation methods for extrapolating ground deformation in adjacent areas. The aforementioned limitations can be resolved by implementing remote sensing techniques, such as Interferometric Synthetic Aperture Radar (InSAR), that provide good spatial coverage and sensitivity to changes in ground surface elevation. InSAR has been used over the last two decades to quantitatively monitor ground deformation. The most common applications have been evaluating post-seismic or inter-seismic deformation, ground subsidence due to the extraction of oil or water, glacier movement, and volcanically induced strain.

1.1 Purpose

The purpose of this project is to evaluate the applicability of InSAR for monitoring coal mine subsidence, a different agent of deformation than those mentioned above. This thesis project will evaluate the effectiveness of InSAR at detecting ground subsidence in three different locations, where different mining methods (e.g. longwall or room and pillar) have been used,
different statuses of the mines (active or inactive) exist, and where there is different land cover (e.g. vegetation or non-vegetation) and relief. Two locations encompass active mines. The Deserado Mine is operated via longwall mining, and the King Coal II Mine is being developed using a room and pillar layout. The third location, the historical mining complex in Colorado Springs, has many abandoned room and pillar underground coal mines that ceased operations before 1960 (Matheson, 1985).

1.2 Scope of Work

The scope of this project is to assess the applicability of InSAR for monitoring subsidence in active and inactive mines around Colorado. This was done through the creation of deformation time series from 1992 to 2011. The results were compared with the reported extent of mine workings, subsidence predictions, and mining sequence information if available. The final deliverables will include deformation time-series and georeferenced maps showing the mining extent of the selected study sites. A flowchart describing the project’s general workflow is shown in Figure 1-2. The completion of this project will be limited to the following tasks:

1. Acquisition and review of characterization reports and mine layout maps for each mining location
2. Georeferencing and digitization of mine layout maps
3. Acquisition of ALOS, ENVISAT and ERS imagery
4. Creation of all the viable interferograms
5. Filtering of results and creation of deformation time series using the Small Baseline Subset (SBAS) Algorithm
6. Analysis of subsidence extents to quantify trough dimensions and draw angles.
7. Creation of shapefile to identify points where subsidence has occurred above room and pillar mines

The deliverables of this project are listed below:

1. A database of the available SAR imagery for the selected study sites, organized based on the study site name, the satellite of provenance, and the relative orbit and frame.
2. A digital library of materials related to the selected study sites. This library will include mine layout maps and characterization reports.
3. A digital library of relevant sources related to application of InSAR for monitoring ground deformation.
4. A directory containing interferograms for each study, based on imagery collected by three different satellites.
5. A directory within the database of time series analyses conducted through two different software packages, containing results in jpg, grd, and hdf5 formats.

6. A directory containing MATLAB, c-shell and python scripts used to complete a batch renaming of files, batch creation of working folders, and selection of viable interferograms.

The organization of the deliverables into separate folders or directories will facilitate the review and further processing of results. Subsidence develops over time, even in longwall and extraction mining scenarios. Thus, the produced interferograms may be utilized in future analyses as additional SAR imagery and processing techniques become available.

Figure 1-1 Flow chart portraying the project’s workflow (Part 1).
Figure 1-2 Flow chart portraying the project’s workflow (Part 2).
CHAPTER 2
BACKGROUND INFORMATION AND PREVIOUS STUDIES

The following sections include background information on the history of mining in Colorado, the current techniques used for assessing mine subsidence, the availability of SAR imagery, the InSAR principles, and the use of InSAR in the last two decades.

2.1 Colorado's Mining History

Colorado’s coal is deposited in eight basins and has been mined from over twelve coal fields. (Turney, 1985; Kirschbaum and Bascur, 1997). Figure 2-1 shows the location of historically mined areas and the extent of coal fields. The Colorado Geological Survey and the U.S. Geological Survey estimate that Colorado’s coal reserve base is approximately 16.4 billion tons. This figure accounts the areas where coal mining is not viable (Colorado Geological Survey, n.d.).

Figure 2-1 Locations of historic coal mining in Colorado in red. The grey polygons represent the extent of Colorado's coal fields (Turney, et al., 1985).
“Mining was far and away the most significant industry in nineteenth and early twentieth century Colorado and has remained important since that time. The pike’s Peak Gold Rush brought unprecedented number of people into the region and that in turn led to powerful social, economic, and political changes that brought about the creation of (the) Colorado Territory in 1861” (ColoradoHistory.org, n.d.)

Turney et al. (1985) indicates that Colorado’s coal mining history can be traced specifically to the 1860’s. Coal mines were concentrated along the Front Range, which was undergoing a population and economic boom at the time. The demand for coal was fueled by the energy demands of the gold mining industry in towns like Cripple Creek, and by local city needs. There were over 100 active coal mines in the Boulder-Weld area in the past (Colorado Geological Survey, n.d.). Between the 1940’s and 1950’s, the demand for coal declined leading to the closure of many mines throughout the state (Matheson, 1985). “In Colorado, there are 1724 abandoned coal mines, including 405 mines recorded for the Denver Basin coal region” (Greenman & Sherman, 2003). This equates to approximately 50,000 acres and does not include the sporadic “mom and pop” mining operations that accompanied growing settlements.

Prior to 1977, mining companies were not required to account for subsidence in the planning and development of mines. The potential of subsidence and its effects were not fully considered when development began in historically mined areas. What is worrisome is that many of these areas are now encompassed by some of the largest cities in Colorado, like Boulder and Colorado Springs, posing a significant risk to its inhabitants. The concentration of abandoned mines along the Front Range, within the Denver Basin is concerning. “A detailed evaluation of Boulder County using year 2000 census figures shows that about 13,500 people now live over abandoned mines” (Greenman & Sherman, 2003). Furthermore, the Colorado Geological Survey estimates that coal mine subsidence is a hazard for approximately 7,500 houses and 25,000 people in the urban corridor along the Front Range (Colorado Geological Survey, n.d.).

Following the enactment of the Colorado Mined Land Reclamation Act (1977) and the Colorado Land Reclamation Act for the Extraction of Construction Materials (1977), the CDRMS has the responsibility of enforcing the restoration of mine lands (Colorado Geological Survey, n.d.). Based on archived reports from the CDRMS, mining companies are required to provide subsidence control and prediction data prior to and during the extraction of the target material. The author reviewed initial characterization reports presented in the permitting stage of the Deserado and King Coal II mines. The review of subsidence documents included 4 quarterly subsidence monitoring reports for each site. None of the reviewed material mentioned the use
of remote sensing data as part of the subsidence monitoring process. The existing approaches rely on modeling and field observations which is consistent with traditional methods. Field monitoring has been the most common approach for assessing the magnitude and rate of mine subsidence. There are currently seven active underground coal mines, and all are located west of Colorado’s Front Range (Colorado Division of Reclamation Mining and Safety, 2012).

2.2 Current Techniques for Assessing Mine Subsidence

Subsidence began to be a concern in the US and elsewhere in the 1960s and 1970s. Subsidence monitoring was conducted using levelling lines of survey pegs, which were driven until bedrock was encountered. Surveys using this system solely provided a way of quantifying vertical deformation between adjacent pegs, assuming the pegs were fixed and deformation took place in between them (Department of the Environment, Australian Government, 2015). “Laser theodolites and three-dimensional location techniques in the 1980’s revolutionized subsidence monitoring. Horizontal movements were detectable to an accuracy of a few millimeters […]” (Department of the Environment, Australian Government, 2015).

Ground survey techniques, including survey lines, are valid methods for assessing ground deformation to this day. Nevertheless, the arrangement of the peg network has evolved since the early implementations. Survey techniques are normally combined with geophysical methods to interpret subsurface conditions and identify the location of voids causing subsidence. Hence, survey lines are normally completed along geophysical section lines. The current ground survey technique most commonly used is precise levelling, providing accuracies of 1 mm over 1 km. Control traversing, a different ground surveying technique, provides the vertical and lateral position of permanent survey locations. The applied survey technique is referred to as traversing. Control traversing yields accuracies in the range of 5 to 10 mm over 1 km (Department of the Environment, Australian Government, 2015).

In some instances, mining companies install extensometers to assess deformation in the subsurface. This information is valuable to predict the extent and timing of the collapse effects at the surface. This method is seldom used due elevated installation and monitoring costs of extensometers. “Other instruments sometimes installed in subsidence monitoring boreholes include tiltmeters, which record changes from vertical in the borehole, and seismic sensors (geophones), which can be used to determine where the caving is occurring” (Department of the Environment, Australian Government, 2015).

Global Navigation Satellite Systems (GNSS) is an additional surveying technique with an absolute accuracy that ranges between 5 and 10 mm. The position of a permanent surveying location is provided by GNSS receivers, which depending on the satellite could be GPS
receivers. The receivers, as in the creation of interferograms, record the difference in phase between waves emitted by different GNSS satellites.

There are three remote sensing techniques that have been applied recently to assess subsidence. Light Detection and Ranging (LiDAR) is one of them. LiDAR employs near infrared, ultraviolet, or visible electromagnetic light pulses to image or detect the distance between a target and the source. A narrow beam is emitted and different forms of backscattered signal are recorded and analyzed for ranging purposes. If the location of the emitter/receiver is geocoded, the position of the scattering body can be inferred using the backscattering information. Data from two acquisitions can ultimately be compared to assess changes in ground elevation (Froese & Mei, 2008). The vertical accuracy of this method ranges between 100 to 150 mm as reported by the Australian Department of the Environment (2015). Vertical accuracies have improved significantly over the last decade with improvements in the equipment. LiDAR was used by Froese and Mei (2008) to assess the locations of subsidence pits and mine workings in Turtle Mountain in southwestern Alberta (Froese & Mei, 2008).

Photogrammetry is also used for the remote assessment of ground conditions. Terrain models derived from two photogrammetry results can ultimately be compared to evaluate changes in ground elevation, that could result from subsidence. In photogrammetry, the three-dimensional position of an object is evaluated by capturing overlapping images from multiple view angles, using similar lighting conditions. Specific locations within the study site can be georeferenced to geocode the resulting cloud. Studies conducted over mines, to assess subsidence, were only able to detect vertical movements exceeding 200 mm, revealing a clear sensitivity limitation with respect to the aforementioned ground survey and remote sensing methods (Department of the Environment, Australian Government, 2015).

InSAR is also reported by the Australian Department of the Environment as one of the remote sensing techniques that can be used to evaluate subsidence. It is regarded as the better option, due to high accuracies even in areas of dense vegetation. Areas with such vegetation cover can seldom be analyzed via structure for motion (SfM) or LiDAR. However, the applicability is limited in areas with steep gradients (Department of the Environment, Australian Government, 2015). Ge et al. (2007) conducted subsidence analyses using D-InSAR techniques, in mines southwest of Sydney. The derived accuracy from the platforms used was in the sub-centimeter scale (Ge, et al., 2007). Racoules et al. (2007) reported a LOS sensitivity at the mm scale looking at persistent scatterers, and using a greater number of SAR images.

It was not possible to find any literature regarding the utilization of InSAR to quantify ground deformation in any of the active coal mines in Colorado. Eneva with Imageair, Inc.
published an article in which a wrapped interferogram shows deformation above the Twentymile mine, currently named Foidel Creek Mine. The report only highlights the existence of subsidence in the area (Eneva, 2010). Landsat and AVIRIS imagery has been used in the past to assess the composition of mine wastes, and aerial photography has been used to delineate the presence of subsidence features (Peters et al., 1996; Matheson, 1985). However, the nature of these remote sensing techniques differs significantly from InSAR and cannot be used to quantify subsidence. InSAR and LiDAR are the methods with the greatest coverage. Surveying techniques continue to be more utilized due to differences in data acquisition and data processing costs.

2.3 InSAR

“Synthetic aperture radar interferometry is an imaging technique for measuring the topography of a surface, its changes over time, and other changes in the detailed characteristics of the surface” (Rosen, et al., 2000). InSAR exploits the change in phase between two acquisitions, instead of the pulse travel time, to evaluate the change in the distance between the sensor and the earth surface, along the instrument’s line of sight (LOS). The negligible opacity of the atmosphere to radio waves, allows the emitted pulses to reach the surface without being scattered in the process. The analysis of phase changes in coherent pixels has allowed this remote sensing technique to evolve from an interpretative science to a tool of high precision, of detecting and quantifying surface deformation (Rosen, et al., 2000). Conventional SAR could only be used to assess the position of a point of interest (POI) in two dimensions, along and across the satellite’s track. SAR interferometry has enabled a third dimension, in the LOS direction. This allows the evaluation of changes in the POI’s position in all three dimensions, with sensitivities along the LOS vector in the centimeter to millimeter range (Rosen et al., 2000).

With SAR interferometry, a radar pulse is emitted from an antenna and the signal that is scattered from the earth surface is recorded in two antennas, a conventional antenna and a SAR antenna. “[...] InSAR systems were developed to record the complex amplitude and phase information digitally for each antenna. In this way, the relative phase of each image point could be reconstructed directly” (Rosen, et al., 2000). The recorded echoes are combined coherently, and compared with echoes obtained from a different pass. This comparison results in an interferogram, in which the fringing pattern represents the phase changes between the two acquisitions. The components that contribute to phase changes between acquisitions include those listed below. The modelling or removal of some or all of those components from an interferogram, allow the utilization of InSAR as a tool for detecting deformation:

1. Topography
2. Earth’s curvature
3. Orbital error
4. Ionospheric delay
5. Tropospheric delay
6. Noise
7. Surface deformation (Sandwell, et al., 2011)

Interferometry principles applied for the processing of SAR images can be used to evaluate the surface’s topography, surface changes, or both. The latter is achieved by the application of repeat track interferometry (RTI). This method is only viable if one or more satellites are set to approximately retrace their orbital tracks over regions of interest. If there is a slight separation between the satellite tracks, the interferogram will evidence changes in the LOS length that result from the terrain’s topography. If targeting deformation, phase changes resulting from track discrepancies, can be deduced based on orbital information. In the event the flight track is repeated with exactitude, the interferogram will not contain phase changes mostly caused by topography, improving the ability to detect radial deformation caused by other parameters. However, the flight path of satellites is seldom repeated without discrepancies, forcing the need of removing the topographic signature from interferograms, if intending to isolate phase changes caused by deformation. “The approach for reducing […] data into velocity or surface displacement by removing topography is generally referred to as “differential interferometric SAR” (Rosen, et al., 2000). Such method is one of the basis for this research project.

An interferometer can be ground-based, it can be installed in unmanned aerial vehicles, in airplanes or in satellites, as previously inferred. The tradeoffs between the use of the different platforms lies on the resolution and coverage of the imagery. “The spaceborne platforms have the advantage of global and rapid coverage and accessibility […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” (Rosen, et al., 2000). The coverage combined with the temporal separation of collections defines the circumstances in which this method can be applied. Spaceborne platforms have variable repeat periods ranging from hours to weeks. The life of the platforms extends to several years. This method is advantageous when deformation occurs over such time scale and when a very high spatial resolution is not required. Airborne and ground-based platforms are preferred for shorter repeat periods, for projects that require a shorter duration of data collection, needing a higher spatial resolution. The latter method also avoids refraction or delay effects induced in the scattered pulses, caused in the troposphere and
ionosphere. Advances in modelling have allowed this phenomenon to be accounted when processing spaceborne SAR imagery (Rosen, et al., 2000).

The separation between flight tracks is termed baseline separation. The component of the separation vector, that is perpendicular to the LOS direction has a maximum value (critical baseline) that is partially dependent and proportional to the distance between the sensor and the surface. If exceeded, the phase change per range resolution will equal or exceed $2\pi$, causing the decorrelation of the interferometric signal, and an offset beyond the reach motion compensation techniques. Consequently, track repeatability is crucial for the viability of InSAR as a remote sensing technique. The critical baseline for airborne platforms is substantially lower than the critical baseline for spaceborne InSAR. “[… A] radar operating at C-band at 40-MHz range band-width, looking at 35° from an airborne altitude of 10 km has a critical baseline of 65 m […] The same radar configuration at an 800 km” (Rosen, et al., 2000). This can be a problem for airborne systems given the high cost of track control systems and the susceptibility to weather conditions that may challenge the repeatability of flight paths.

The satellites emit a microwave pulse away from the nadir, in the across-track direction. Thus, in the presence of a perfectly smooth surface, none of the emitted signal would be scattered back to the satellite. The area illuminated by single pulse depends on several parameters, which include the incidence angle of the pulse, the topography, the distance between the instrument and the surface, and the pulse’s wavelength. The smallest separation between distinguishable points, which effectively is the resolution, is different between the along-track and across-track direction. As shown in Figure 2-2 Figure 2-3 the across track resolution is a function of the duration of the pulse ($\tau_p$) and the incidence angle ($\eta$), while the along track resolution is conditioned by the wavelength ($\lambda$), the line of sigh distance ($R_m$), and the length of the antenna ($L_a$). The antenna is synthesized to a greater length by accounting for consecutive returns along the satellite’s track.

2.4 SAR Imagery

The wavelength of the electromagnetic signal emitted by SAR instruments can be grouped into different bands. The most common wavelengths are X-band (2.5 - 3.75 cm), C-band (3.75 - 7.5 cm), and L-band (15 - 30 cm). S-band (~10 cm), although viable for InSAR, has been implemented in few missions. The band selection for satellite designs is based on the type of targeted terrain and type of deformation. The emitted signal interacts most strongly with objects that have a diameter equal or greater than its wavelength. Thus, X and C bands are scattered by smaller objects than S or L bands. In the presence of vegetation, band selection is crucial, for interferograms based on images from satellites with shorter bands tend to lose
coherence between passes more noticeably than in interferograms created with longer band images. Nevertheless, height error and resolution are smaller in systems with shorter bands than in systems with longer bands (Rosen, et al., 2000).

\[
\Delta R_y = \frac{\Delta R_s}{\sin \eta} = \frac{c \tau_p}{2 \sin \eta}
\]

Figure 2-2 InSAR resolution in the across-track direction (Curlander and McDonough 1991).

SAR imagery is and has been collected by multiple platforms over the last four decades. The first attempt at using spaceborn SAR imagery dates to 1978, when SeaSat was first launched to conduct an experimental earth observation mission. Although the satellite was only operational for 106 days, it provided a wealth of data that was used to study phenomena such as sea-surface winds, rainfall, ocean circulation, sea ice, etc. Since then, over 20 satellites have been launched, carrying SAR instruments. Some of the missions are listed below. Figure 2-4 shows the launching and operation timeline for most scientific SAR missions after 1992.

- The ERS and ENVISAT constellation - Three C-band satellites launched and managed by the European Space Agency (ESA)
- The ALOS missions, consisting of satellites ALOS and ALOS-2 - Two L-band satellites launched and managed by the Japanese Aerospace Exploration Agency (JAXA)
- The Sentinel constellation, consisting of satellites Sentinel-1a and Sentinel-1b - Two C-band satellites launched and managed by ESA. Additional Sentinel satellites will be launched in the future
- The RADARSAT missions, consisting of RADARSAT-1 and RADARSAT-2 - Two C-band satellites managed by the Canadian Space Agency (CSA)
- The COSMO-SkyMed constellation - Four X-band satellites managed by the Italian Space Agency (ASI)
- The TerraSAR-X and TanDEM-X constellation - Two X-band satellites managed by the German Aerospace Center (DLR)

\[ L_g \approx R_m \theta_H \approx \frac{R_m \lambda}{L_a} \]

Figure 2-3 InSAR resolution in the along-track direction (Curlander and McDonough 1991).
Figure 2-4 Chart displaying the band type and timeline of scientific SAR missions completed between 1992 and 2024 (UNAVCO, 2015).
2.5 Past InSAR Applications

According to Rosen et al. (2000), the first application of radar interferometry was done by Rogers and Ingalls, for removing north-south ambiguity of Venus maps made from antennas based on Earth. A similar methodology was used shortly after by Zisk, to measure the Moon’s topography (Zisk 1972). The first publicly reported application of InSAR for evaluating the Earth’s surface, was authored by Graham in 1974, and was conducted to map the Earth’s surface topography (Graham 1974). Since then, SAR systems have been upgraded to record the complex amplitude and phase of the signal return, digitally. Currently, there are over twenty SAR satellites orbiting the earth, and two additional ones will be launched in the next five years (UNAVCO, 2015). The increasing presence of these satellites has been driven by the commercialization of InSAR-derived digital elevation models, the quality of results obtained from research, and an increase in governments’ operational needs (Rosen, et al., 2000).

InSAR has proved to be an effective remote sensing technique for assessing interseismic and coseismic deformation. The first interferogram showing coseismic deformation was published by Massonnet and Rabaute, using ERS-1 imagery collected before and after the Landers earthquake in California (Zhou, Chang and Li 2009). One of the interferograms made it to the cover page of Nature, published in July 8, 1993 (European Space Agency 2006). The cover is shown in Figure 2-5. In 2013 Kaneko et al. (2013) presented high resolution measurements of creeping along a specific section of the North Anatolian Fault (NAF), using ALOS and ENVISAT imagery. This InSAR analysis of the NAF revealed “[...] discontinuities of up to ~5 mm/yr across the Ismetpasa segment of the NAF, implying surface creep at a rate of ~9mm/yr” (Kaneko, et al. 2013).

InSAR has also been an effective tool for volcanology studies. “Volcanic processes such as magma accumulation in subsurface reservoirs, magma transport, and emplacement beneath volcanic structures [results] in surface deformation” (Zhou, et al., 2009). The study of volcanoes in the western United States and Alaska using InSAR has revealed that many volcanoes that were thought to be dormant are deforming at the surface, implying volcanic activity. One of the studies was conducted on an area encompassing the Three Sisters, a cluster of volcanoes in central Oregon. The interferograms were produced using ERS, ENVISAT, and ALOS imagery. The results showed signs of uplift in an area where the last eruption had taken place 1,500 years before (Riddick, 2011). The detected deformation was later confirmed by seismometers that were installed following the discovery of deformation. InSAR was also used to estimate the depth of the volcanic intrusion, which was approximately 6 to 7 km (Heltz, nd). An interferogram showing the uplift near the Three Sisters is shown in Figure 2-6.
Figure 2-5 "Image of an earthquake", the cover title given to the interferogram representing the deformation caused by the Landers earthquake in California (European Space Agency, 2006).
Figure 2-6 Interferogram showing the uplift southwest of the Three Sisters, between 1997 and 2001 (Heltz, nd).
Regarding subsidence, there are several articles that report the use of InSAR for quantifying ground deformation as a result of groundwater pumping and extraction of oil and gas. Carbognina et al (2004) used ERS-1 and ERS-2 imagery to demonstrate that the city of Venice was affected by subsidence, caused by consolidation following local groundwater pumping between 1950 and 1970. The displacement rates determined via InSAR were between +1 and -2 mm/year (Carbognina, et al., 2004). Furthermore, Massonnet et al. (1998) identified 90 mm of subsidence over two years, in southern California, near the East Mesa geothermal plant. The analysis was completed utilizing two ERS-1 images. The results were ultimately used to estimate the volume loss, and the estimated value was found to be consistent with the reported pumped volumes. Zhou et al, (2006) quantified subsidence above an oil field in northern Alaska using ERS-1 and ERS-2 imagery.

InSAR has also been used in landslide investigations. Depending on the direction of movement relative to the location of the satellite, the terrain may appear to be moving towards the satellite, if there is a significant lateral component in the movement vector. Schlogel et al. (2015) used geomorphologically-guided D-InSAR method to evaluate landsliding rates and movement types (translational, rotational, or complex sliding) of two active landslides in southeast France. However, analysis of landslides via InSAR can have ambiguity and decorrelation problems caused by the steep and rugged topography of landslide-prone areas. Such problems can be mitigated by the utilization of persistent scatterers or the implementation of ground-SAR interferometer systems (Zhou, et al., 2009).

The movement of glaciers and ice sheets is also detectable through InSAR analysis. Kwok and Fahnestock (1996) used radar interferometry to assess glacier topography. Gray (2011) to estimate the dynamics of glacier movement in northern Ellesmere Island, Canada, in three dimensions. InSAR has also been used in Hydrology to monitor soil moisture, water level changes, and forestry applications (Zhou et al., 2009).

### 2.6 InSAR Applications in Mine Subsidence

The first application of InSAR for monitoring mine subsidence, found through literature review, was published in 1998 (Perski, 1998). In this publication, the author reported the viability of utilizing ERS-1 and ERS-2 imagery for monitoring subsidence in Poland. Since then many articles have been published on the utilization of InSAR for monitoring mine subsidence around the world. The variations between these articles lie on the type of imagery used, the algorithms used for processing such imagery, and the complementary data that is integrated with the final InSAR results to evaluate the InSAR results’ accuracy. Gueguen et al. (2009) analyzed the residual subsidence of the Nord/Pas-de-Calais coal basin in northern France, applying
differential InSAR and Persistent Scatterer Interferometry (PSI) principles to ERS and Envisat images. The results were ultimately compared with precise leveling data (Gueguen, et al., 2009). As shown in Figure 2-7, the InSAR analysis revealed the presence of several locations, within mining concessions, undergoing subsidence rates of up to 1.25 cm per year. The project presented in this report includes the use of L band data, which has not been used for coal mine subsidence projects per the reviewed literature. This project also applies a modification of the Small Baseline Subset algorithm, NSBAS, to create a time series of deformation. This algorithm has not been used to assess the progression of coal mine subsidence in previous studies.
Figure 2-7 Subsidence rate obtained via the analysis of persistent scatterers. Positive and negative values indicate uplift and subsidence, respectively (Gueguen et al, 2009).
CHAPTER 3
STUDY AREAS

Three study sites are selected for this project. These sites include two active coal-mining locations in western Colorado. One of them is a longwall mine suggested by the CDRMS personnel during an informational meeting. The other active mine was selected by the author to test the applicability of InSAR in densely vegetated terrain with high relief, under a room and pillar design. The third study is a historical mining complex along the Front Range, specifically north of Colorado Springs, where subsidence problems have been reported over the four decades. The selected mines are listed in Table 3-1. The location of each mine is shown in Figure 3-1.

Table 3-1 Selected study sites for InSAR analysis

<table>
<thead>
<tr>
<th>Mine</th>
<th>Address</th>
<th>Mining Method</th>
<th>Center Coordinates</th>
<th>Permit #</th>
<th>Mining Company</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deserado Mine</td>
<td>3607 Co Rd 65, Rangely, CO 81648</td>
<td>Long Wall</td>
<td>40.20 -108.73</td>
<td>C-1981-018</td>
<td>Blue Mountain Energy, Inc. (BMEI)</td>
</tr>
<tr>
<td>King Coal II Mine</td>
<td>6473 Co Rd 120, Hesperus, CO 81326</td>
<td>Room and Pillar</td>
<td>37.24 -108.10</td>
<td>C-1981-035</td>
<td>GCC Energy, LLC</td>
</tr>
<tr>
<td>Colorado Springs Mining Complex</td>
<td>Northern Colorado Springs, CO</td>
<td>Room and Pillar</td>
<td>38.8 -104.8</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

3.1 The Deserado Mine

“The Deserado Mine is an underground operation utilizing both continuous and longwall mining equipment” (Blue Mountain Energy, Inc., 2008). The mine is located in the Rio Blanco County, approximately 7 miles northeast of Rangely, Colorado. It has operated since 1981 and it produces approximately 1.5 to 2.1 million tons of coal per year. The mine targets two Cretaceous seams within the Mesaverde group, referred to as B and D seams (Lepro, 2003). The top of the sandstone hosting the B seam – the lower of the two - is the contact between the lower Williams Fork Formation and the Iles formation.
Figure 3-1 Map showing the locations of the study areas.
The Mesaverde group becomes finer at shallower depths, towards the D seam. The rock overlaying the B sandstone consists predominantly of mudstones, siltstones, and carbonaceous shales, with laterally discontinuous, coarse, channel deposits (Lepro, 2003).

“The Deserado Mine area lies on the southwest flank of the Red Wash Syncline, an asymmetrical flexure on the northeast flank of the Rangely Anticline. The axis of the syncline trends northwest-southeast and plunges to the southeast into the much larger synclinal structure of the Piceance Basin. Dips in the mine permit area average about seven degrees to the northeast, whereas the dip increases to about 70 de degrees on the northeast flank of the syncline." (Lepro, 2003)

The D seam, within the permit area, has overburden thicknesses that range from 120 m to 210 m. The average thickness of the seam is approximately 2.6 m, exceeding that of the B seam. The B seam consists of “[...] a complex assembly of thinner coal seams that merge in the Deserado lease to form a mineable thickness of composite seams” (Lepro, 2003). The D seam was mined between 1992 and 1999, along the eastern half of the permit area. Mining of the first longwall panel in the B seam began in 2000. The operations targeting the B seam are ongoing, and are predicted to continue for another 20 years (Lepro, 2003).

The thickness of the overburden, overlaying the targeted section of the B seam, ranges from approximately 90 m to 210 m. (Blue Mountain Energy, Inc., 2008). The variability of overburden thickness results from the structural conditions of the seam and the local relief. The lowest and highest elevations within the permit area are approximately 1625 m and 1830 m, respectively. The higher elevations are encountered along the southwestern edge of the permit area, while the lower elevations are predominantly along the northeastern edge. Thus, the terrain is predominantly sloped to the northeast, with localized slope breaks around hogbacks and drainage channels. A profile of ground elevation is shown in the bottom panel of Figure 3-2.

The Deserado Mine is in a semi-arid region, with partial vegetation cover, consisting of mostly brush. The type of ground cover can be observed in the top panel of Figure 3-2. The coal is extracted from longwall panels with the exceptions of areas in between panels where the mine has a room and pillar layout. The panels have variable widths and lengths, in the order of several hundred and thousand feet, respectively. The panels trend to the east southeast. The Deserado Mine layout maps included as supplemental electronic files show the mining sequence for both seams by labelling each panel with the year in which mining occurred or will occur.

There is a county road, 6 building structures, and a power line corridor, within the permit area that could be impacted by subsidence associated with mining. As required by the CDRMS,
BMEI submitted subsidence prediction parameters for both longwall and room and pillar areas. Greater subsidence is expected in areas where the regolith is the thinnest. “Predictions [were] based on results of subsidence studies made by the U.S. Bureau of Mines and on the model produced by the British National Coal Board” (Blue Mountain Energy, Inc., 2008). The modelled maximum vertical subsidence for panels in the D seam ranges from 1.28 m to 2.35 m. Furthermore, the modelled maximum vertical subsidence above panels in the B seam ranges from 1.89 to 2.13 m. Subsidence above room and pillar sections was predicted to be significantly lower than the reported subsidence values pertaining to longwall mining (Blue Mountain Energy, Inc., 2008). No ground surveying data, including precise leveling or GPS surveying, was found in archives maintained by the CDRMS. The reviewed subsidence reports evidence that BMEI is solely required to inspect “Differential Settling” or “Cracks or Slides” based on visual inspections (Dubbert, 2003). As it is to expect with longwall mining, tension cracks were found above mined panels. Figure 3-3 and Figure 3-4 include examples of such tension cracks.

3.2 The King Coal II Mine

The King Coal II Mine is an underground, room and pillar mine, located approximately 13 miles west of Durango, in La Plata County. “Operations at the mine first began in the late 1930’s, and the site was formally permitted by National King Coal, Inc. in 1982… For several decades, mining activities and the permit area were confined to lands located south of Hay Gulch and La Plata County Road 120, at the site now referred to as the “King I” Mine. In 2006, a revision to the permit was approved creating the “King II” Mine portion of the operation on 730 acres located north of CR 120 and west of King II” (Talvitie, 2015). The permitted area constitutes 2,658 acres out of which 1,296 and 640 are federally and privately owned, respectively. The State of Colorado has jurisdiction over the remaining 722 acres, and can only enforce reclamation measures in such location. A composite mine layout map of King Coal I and King Coal II is included as a supplemental electronic file.

Structurally, the King Coal II Mine is located around the northeastern corner of the Four Corners Platform, and to northwest of the San Juan Basin. The bedrock exposed throughout the area is of Cretaceous origin and is part of the Mesaverde Group. This stratigraphic group overlays the Mancos Shale, and is composed of the Point Lookout Sandstone, the Menefee Formation, and the Cliffhouse Sandstone, in ascending order. The targeted coal seams in the mine are within the Menefee Formation. Locally, the dip of the aforementioned formations ranges from 2 to 11 degrees, to the south. The terrain overlaying the mine workings is gently sloped to the south, with pronounced drainage valleys that drain surface water predominantly to
Figure 3-2 Multipanel figure of the Deserado Mine location. The top panel shows aerial imagery of the mine. The middle panel includes a hillshaded representation of the terrain. The bottom panel is an exaggerated terrain profile along the A-A' section shown in the middle panel.
Figure 3-3 Photograph of subsidence feature encountered during inspections around the Deserado Mine (Dubbert, 2003).

Figure 3-4 Close-up of subsidence feature found at the Deserado Mine (Dubbert, 2003).
the southwest (Talvitie, 2015). The local topography is shown in Figure 3-5. “Quaternary sediments, both alluvial and colluvial, are present in the valley bottoms, and minor landslides have been mapped on the valley slopes” (Talvitie, 2015).

"Of the two mineable seams exposed in the permit area, only the upper seam (Peacock, or "A") of the Menefee formation […]” (Talvitie, 2015) is currently being mined. The lower seam, named seam “B” was mined at an adjacent mine during the 1940’s. The thickness of overburden overlaying the A seam ranges from approximately 30 m to 120 m. throughout most of the permitted area (Talvitie, 2015). The B seam “[…] lies approximately 80 feet [-24 m] below the upper seam, with interbedded sandstone and shale between the two seams” (Talvitie, 2015). No information was found regarding the timing of coal extraction or mining sequence. However, this is not as important for room and pillar mines, for subsidence does not tend to occur immediately after extraction as it occurs in longwall mines.

The climate around the King Coal II Mine is semi-arid, with hot and dry summers. The regional precipitation occurs mostly in the form of snow, with water equivalent values ranging from 38 to 48 centimeters. “The dominant vegetation in the King I and King II Mine area is a mountain shrub community. Gambel Oak is the most prominent shrub along the side slope, forming dense stands of grasses interspersed… A piñon juniper woodland community is also located in the King II Mine, extending from the edge of the flat colluvial bottoms up the side slopes of the dissected drainage basins” (Talvitie, 2015). Aerial imagery and hillshade representation surface conditions are shown in Figure 3-5.

The CDRMS requires the submission of semiannual subsidence reports. The reports indicate that subsidence monitoring is conducted by evaluating (visually) the orientation of monuments and structures. The observations are ultimately compared with subsidence predictions submitted during the permitting stages. Survey monuments were only installed around a residence that reported tension cracks on 2001. The monuments were surveyed between October of 2001 and April of 2003. The subsidence event that was found in the reviewed reports were formation of tension cracks in the residence mentioned above. However, the exact location of such features was not reported (Kaldenbach, 2010).
Figure 3-5 Multi panel figure of the King Coal II Mine location. The top panel includes regional aerial imagery. The middle panel includes a hillshaded representation of the terrain. The bottom panel is an exaggerated terrain profile along the A-A’ section shown in the middle panel.
3.3 The Historical Mining Complex in Colorado Springs

Colorado Springs is the second largest city in the state of Colorado and one of the fastest growing cities in the Front Range. The city is on the piedmont of the Rockies Front Range. The terrain is steeper to the west, and slopes face east predominantly. Changes in slope orientation are found in drainage channels and along the edges of pediments. Colorado Springs is located on the southern edge of the Denver Basin. Coal seams within the Laramie formation are 30 m from the surface, on average (Roberts 2007; Sherman et al. 2003). Due to the proximity of this resource to the surface, the northern portion of the city started to be mined for coal in the 1850’s. Such mining activity was fueled by the energy demands of the gold mining industry in Cripple Creek and by the city’s local needs (Matheson Vol. 2, 1985).

Between the 1940’s and the 1950’s such demand declined substantially and this induced the eventual closure of the mines in the city. The presence of these mines did not pose a threat to Colorado Springs until its population, unaware of the risk, started to settle on areas underlain by mined bedrock. The areas that were heavily mined and currently host large developments are the Rockrimmon, Country Club, Rustic Hills and Palmer Park areas. Their location are shown in Figure 3-7. The development of these areas started in the 1860’s, in reaction to the population boom that Colorado experienced at the time (Matheson, 1985).

The historical mines in Colorado Springs were completed using a room and pillar system. The arrangement and dimensions of pillars was irregular. Pillar extraction was conducted in some mines to maximize productivity. In such cases, surface deformation was induced over a shorter period. Approximately 30 subsidence events were reported in the Country Club area alone, between 1960 and 1984 (Matheson, 1985). Since then, two large scale investigations have been conducted, to characterize the extent of the subsidence hazard and the potential of occurrence.

In 1984, the CDRMS requested Dames & Moore to investigate all four areas to delineate sections with very low, low, medium, and high subsidence potential. Areas with high subsidence potential were delineated along the southern edges of the mining fields, where the targeted coal fields are closest to the surface, and where shafts or sloped entries were completed (Matheson, 1985). Several intact openings were found during the investigation, in which the pillars and the floor appear to have degraded, following the abandonment of the mine. There were also rubble horizons proximate to the surface with bulk density factors too low to prevent the upward propagation of failure. The map showing the extent of historical mine workings presented by Dames & Moore is included as a supplemental electronic file.
The second investigation was conducted by Zapata Inc. in 2009, in a residential area, known as the Country Club Circle, that had been previously classified by the Dames and Moore investigation to have a high subsidence potential. The investigation revealed the presence of a large haulage way with signs of imminent roof failure. The conditions of the haulage way are shown in Figure 3-6. The opening was mitigated by backfilling it with sand. Both investigations revealed that subsidence will continue to occur in Colorado Springs until the abandoned mines are properly reclaimed. No remote sensing has been conducted to evaluate changes in the terrain in northern Colorado Springs, however reclamation projects have been funded by the US Department of the Interior, Office of Surface Mining Reclamation and Enforcement. The location of reclamation projects is shown in Figure 3-8. Most of the reclamation projects were completed before or after the period covered by SAR imagery. Nevertheless, there are locations that could be assessed via InSAR. The areas where subsidence could occur are developed and inherently possess numerous corner reflectors, that prevent the loss of coherence between satellite passes.

Figure 3-6 Haulage way discovered during the investigation conducted by Zapata Inc. (Zapata Inc. - Blackhawk Division, 2009).
Figure 3-7 Multi panel figure of the historical mining complex in Colorado Springs. The top panel includes regional aerial imagery. The middle panel includes a hillshade representation of the terrain. The bottom panel is an exaggerated terrain profile along the A-A' section shown in the middle panel.
Figure 3-8 Map showing the location of reclamation projects within the historical mining fields in Colorado Springs. Each location is labelled with the year in which the reclamation project was drafted (US Department of Interior, Office of Surface Mining Reclamation and Enforcement, 2016).
CHAPTER 4
DATA ACQUISITION AND CREATION OF DATABASE

The following sections describe the type of data used for the completion of this project, the steps taken to obtain such data, and the structure of the database where both the original and processed data sets were stored.

4.1 Geotechnical Information

The geotechnical reports and mine layout maps for the Deserado and King Coal II mines were obtained via the Laserfiche Weblink database, managed and maintained by the CDRMS. The database includes scanned copies of reports, correspondence, and maps for all the permitted mines since the division’s instauratio. The downloaded data were queried using a mine’s permit number. The downloaded data include midterm and characterization reports containing geotechnical information, borehole logs, site characterization reports, subsidence reports, subsidence modelling results, and mine layout maps.

Information pertaining to the historical mining fields in Colorado Springs were obtained from the Colorado Geological Survey. The information was summarized in two reports, one produced by Dames and Moore in 1985 (Matheson, 1985) and a second report produced by Zapata Inc. in 2009 (Zapata Inc. - Blackhawk Division, 2009). These reports include a composite map of mine workings in all four areas, bore hole logs, strength parameters, location of subsidence features prior 1984, based on stereographic analysis and localized geotechnical studies, and the extent of areas with high subsidence potential. More recent subsidence information, corresponding to the years of collection of utilized SAR imagery, was obtained from a database maintained by the U.S. Department of Interior, Office of Surface Mining Reclamation and Enforcement.

4.2 SAR Imagery Download

Images from four different satellites, one L-band and three C-band, were used to assess changes in the surface at all three mining locations. The utilized L-band imagery was collected by the ALOS. The C-band imagery was collected by the ERS I, ERS II, and ENVISAT. The evaluation of metadata and data download was completed using the seamless synthetic aperture radar archive (SSARA).

SSARA provides seamless distributed access to the different agencies’ SAR archives (Baker, 2016). The search of pertaining imagery was completed using both the SSARA’s graphical user interface (GUI) and SSARA’s terminal executable. An ROI was plotted for each mine location. The initial search based on the plotted ROI’s provided a list and graphical display of all the SAR imagery encompassing the mines. This initial search helped evaluate which
relative orbit, and frame were the most appropriate for the project. In some instances, more than
one frame or relative orbit were found to be useful. Once the aforementioned parameters were
established, the author proceeded to use the terminal executable to do a batch download of all
the imagery, by specifying the platform or satellite, the relative orbit, the frame, the processing
level, and the beam swath number. The same command line was used to query a command for
downloading a 30-m DEM, encompassing all the SAR images registered in the search. All the
DEM’s were downloaded from Open Topography and converted to a compatible format via
GDAL.

The parameters used for data download and the resulting imagery are shown below. Table 4-1 and Error! Reference source not found. show the metadata and coverage of the
images encompassing the Deserado Mine. Error! Reference source not found. and Figure
4-2 show the metadata and coverage of the images encompassing the King Coal II Mine. Table
4-3 and Figure 4-3 show the metadata and coverage of the images encompassing the historical
mining fields in Colorado Springs. Except for ERS-2 data, collected after January 2000, all the
freely available images from the aforementioned satellites were used for this project. ERS-2
images collected after January 1, 2000 were not included due to quality problems caused by
gyroscopic failures in the satellite (European Space Agency, nd). As shown in the tables below,
an average of 15 SAR images was downloaded per satellite, for each study site

Table 4-1 Metadata for download of SAR imagery encompassing the Deserado Mine.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>ALOS</th>
<th>ERS-1</th>
<th>ERS-2</th>
<th>ENVISAT</th>
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<tr>
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<td>456</td>
<td>456</td>
<td>320</td>
</tr>
<tr>
<td>Frame</td>
<td>790</td>
<td>2799</td>
<td>2799</td>
<td>801</td>
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<td>Swath Number</td>
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<td>STD</td>
<td>STD</td>
<td>S2</td>
</tr>
<tr>
<td>Collection Name</td>
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<td>WInSAR ESA</td>
<td>WInSAR ESA</td>
<td>WInSAR ESA</td>
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<td>Descending</td>
<td>Ascending</td>
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<tr>
<td>Look Direction</td>
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<td>Right</td>
<td>Right</td>
<td>Right</td>
</tr>
<tr>
<td>End Date</td>
<td>Dec, 2010</td>
<td>May, 1995</td>
<td>Dec, 1999</td>
<td>Dec, 2009</td>
</tr>
<tr>
<td># Images</td>
<td>16</td>
<td>13</td>
<td>16</td>
<td>14</td>
</tr>
</tbody>
</table>
Table 4-2 Metadata for download of SAR imagery encompassing the King Coal II Mine.

<table>
<thead>
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<th>PARAMETER</th>
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<th>ERS-1</th>
<th>ERS-2</th>
<th>ENVISAT</th>
</tr>
</thead>
<tbody>
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<td>Descending</td>
<td>Ascending</td>
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<tr>
<td>Look Direction</td>
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<td>R</td>
<td>R</td>
<td>R</td>
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<td># Images</td>
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<td>16</td>
<td>10</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 4-3 Metadata for download of SAR imagery encompassing the historical mining fields in Colorado Springs.

<table>
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<th>ERS-1</th>
<th>ERS-2</th>
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<td>STD</td>
<td>S2</td>
</tr>
<tr>
<td>Collection Name</td>
<td>ASF</td>
<td>WInSAR ESA</td>
<td>WInSAR ESA</td>
<td>WInSAR ESA</td>
</tr>
<tr>
<td>Flight Direction</td>
<td>Ascending</td>
<td>Descending</td>
<td>Descending</td>
<td>Descending</td>
</tr>
<tr>
<td>Look Direction</td>
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<td>Right</td>
<td>Right</td>
<td>Right</td>
</tr>
<tr>
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<td>Jul, 2004</td>
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<tr>
<td># Images</td>
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<td>15</td>
<td>20</td>
<td>28</td>
</tr>
</tbody>
</table>
Figure 4-1 Map showing the coverage of SAR images utilized for analyzing surface deformation above the Deserado Mine.
Figure 4-2 Map showing the coverage of SAR images utilized for analyzing surface deformation above the King Coal II Mine.
Figure 4-3 Map showing the coverage of SAR images utilized for analyzing surface deformation above the historical mining fields in Colorado Springs.
CHAPTER 5
SOFTWARE SELECTION

The following sections describe the software packages used for the completion of this project, and the criteria for the selection of such software packages. The software were run from Linux and Windows platforms.

5.1 InSAR Software

InSAR software consists of computer programs that compile and execute algorithms, used to process SAR images. Generically, the software initially registers and converts images initially provided in a native raw or pre-processed software and converts the SAR information into a generic format. Then, a processor is used to align pairs or stacks of images into single look complex images to later compare the phase information derived from the images. The coregistered SLC images can be further processed to reduce noise levels, reduce speckle effects, and mitigate additional artifacts (Sandwell, et al., 2011). The topographic phase can then be removed using a DEM, to isolate phase changes caused by a phenomenon of interest. The processing proceeds with flattening and unwrapping of the phase to quantify changes in the terrain (Zhou, et al., 2009).

The aforementioned steps are normally completed in radar coordinates, which specify the location of a pixel or signal return with respect to the satellite position, orienting the primary axes of the coordinate system parallel and perpendicular to the satellites flight direction. For the results to be useful, to locate any anomalies identified via InSAR, the interferograms are ultimately geocoded. The geocoding process projects the results into commonly used coordinate systems. The geocoding steps are normally conducted by additional software, depending on the interoperability of the InSAR program (Zhou, et al., 2009).

There are software programs that can be used to analyze and further process InSAR results. These software programs include algorithms for modelling atmospheric delays, removing residual topographic artifacts, creating time series of deformation, based on a stack of unwrapped interferograms, conduct analyses of persistent scatterers, and calibrate results using GPS survey data. These processing steps can be applied individually or collectively. There is a variety of methods and algorithms that can be used to execute each of the steps (Agram, et al., 2012).

SAR imagery and its respective metadata may be provided by different spatial agencies, depending on the satellites used for the analyses. Each agency has a unique (native) format of providing such data. For example, ENVISAT imagery does not include a leader file indicating geospatial parameters as is the case of ALOS imagery. For ENVISAT and ERS data, orbital
information must be downloaded separately, while the ALOS imagery includes orbital information in the raw files. Given the increasing number of satellites collecting SAR data, and the validity of images collected by satellites that are no longer active, it is necessary to account for a variety of data types and formats to conduct comprehensive InSAR analyses. Commercial and open source InSAR software are continuously evolving to accommodate for changes in the way SAR data are reported. Software are also continuously implementing improvements in the existing algorithms and including new processing techniques.

5.1.1 GMT5SAR

All the interferograms produced for this project were completed using GMT5SAR. GMT5SAR is an open source (GNU General Public License) InSAR processing system made by University of California San Diego and the University of Hawaii. The software is built on a Generic Mapping Tools (GMT) foundation. Thus, the format and structure of the commands used to process SAR imagery is similar to the commands used in GMT.

GMT5SAR completes three main steps. First, it preprocesses the information in native format from each satellite into a generic format. Second, the system’s InSAR processor focuses a stack of images, aligns the images and models topography into phase, and ultimately constructs interferograms. In the third step, the system filters the interferograms and produces standard interferometric products in raster format. These include coherence maps, phase change maps, amplitude maps, and maps showing displacement along the line-of-sight vector. The third step is mostly completed with GMT executables and the resulting information is provided in radar and polar coordinates (Sandwell, et al., 2011).

The software is compiled and runs on C-shell scripts. NETCDF and GMT are the open source platforms used for geocoding and displaying all the final products of SAR processing. GMTSAR relies on accurate orbital information. The processing algorithms are significantly simpler than those in other InSAR software, due to the orbital accuracy assumption. This limits the SAR imagery that can be processed via GMTSAR. The orbital information of satellites like RADARSAT-1 and JERS-1 is not accurate to 10 m, making their imagery unviable for GMTSAR.

This software was selected due to the author’s familiarity with c-shell scripting and the GMT command structure, and the software’s capability of processing a stack of images. Furthermore, GMT5SAR’s data format is recognized by the Generic InSAR Analysis Toolbox, which was utilized for completing time-series analyses of deformation at three study sites. Ultimately, the gridded data format that GMT5SAR outputs is easily manageable, and can be converted or be processed in software like MATLAB and ArcGIS. GRD files can also be processed and easily displayed using GMT.
5.1.2 GIAnT

"[GIAnT] is a suite of commonly used time-series interferometry algorithms in a common Python framework" (Agram, et al., 2012). These algorithms improve the signal to noise ratio by accounting for a stack of interferograms. The improvement helps detect subtle deformations, induced by events like mine subsidence, creeping faults, and interseismic accumulation, which are less likely to be detected using conventional InSAR processing techniques. The available time-series techniques include Small Baseline Subset (SBAS) (Berardino, et al., 2002), N-SBAS (Lopez-Quiroz, et al., 2009).

GIAnT provides an interface to weather model databases. The software has the capability of downloading historical weather information, based on the location of a study site, and executing phase-screening corrections. This provides a way of filtering false positives that could have resulted from phase changes produced by atmospheric delays (Agram, et al., 2012).

GIAnT includes tools for estimated orbital errors, and induced ramps, which may have a significant impact on the accuracy of results. The estimation of orbital errors can ultimately be used to correct interferograms. There are tools for conducting either network de-ramping or GPS de-ramping. Network de-ramping is completed by estimating orbital errors on individual interferograms, based on a least square approach. This step is followed by the re-estimation of orbital parameters for each SAR acquisition, via inversion, and the combination of the re-estimated parameters into correction maps (Agram, et al., 2012).

Regarding GPS de-ramping, GPS information is projected to radar coordinates, and the recorded displacements are projected along the LOS direction. The orbital parameters can then be estimated by accounting for the GPS displacement information, the phase values of the pixels where the GPS data are collected, the location of the GPS stations, and the original orbital parameters. Only GPS information overlapping coherent pixels is utilized in the de-ramping process (Agram, et al., 2012).

This software was selected for this project because it is the most comprehensive suite of open source tools currently available. GIAnT includes utilities that read grd files, facilitating the post-processing of GMT5SAR products. The source code is made available upon installation, which allowed the personalization of routing executables, to recognize the archiving structure that resulted from GMT5SAR processing. The software’s module structure allows the user to combine different modeling techniques.

GIAnT includes a series of visualization scripts that were practical for the initial recognition of subsidence features. The available georeferencing tools allow the creation of kml files, and the display of subsidence information in GIS software. Post-processing of time-series
can easily be done for processing results that are stored in Hierarchical Data Format 5 (HDF5), recognized by MATLAB and python libraries.

5.2 GIS and Scripting Software.

Geographic information systems (GIS) are programs designed to “[…] store, retrieve, manage, display, and analyze all types of geographic and spatial data. GIS software [lets the user] produce maps and other graphic displays of geographic information for analysis and presentation” (Caliper Corporation, n.d.). Data types that can be displayed in GIS programs can be classified as vector or raster data types.

Vector data types are those that consist of discrete features. They are represented with geometric primitives like lines or points. Examples of elements best represented with vector data types include rivers, sampling locations, and specific to this project: mine layout maps or permit area outlines. Raster data types are designed to represent continuous features, through the spatial arrangement of information into grids. Each pixel in the grid has an individual value. Thus, the spatial detail or resolution of a raster data set is enhanced with smaller pixel sizes. Properties like elevation, slope, air quality are best represented in raster forms. In the case of coal mine subsidence, rasters are also the most appropriate data type for analyzing surface deformation.

Scripting is used to create algorithms, in this specific case, for processing data, relocating files, or executing pre-programed commands iteratively. Scripts increased the efficiency of data management and processing, and reduced the risk of human induced errors. This project entailed the processing of large number of data sets per study site. Each data set requires numerous data handling and processing steps for the creation of interferograms. Once interferograms are produced, additional data handling and processing is required for populating all the required inputs for executing GIAnT tools. Many of the data handling steps were optimized via algorithms. The algorithms were compiled and executed in MATLAB and C-shell.

5.2.1 ArcGIS

ArcGIS is GIS platform designed by ESRI. ArcGIS is the most widely-used, commercial, GIS software in the market. Over the last decade, it has become an industry standard in the management, analysis, and display of geospatial information. ArcGIS was used for digitizing the mine layout maps, creating subsurface models to visualize the depth and extent of coal seams, and for displaying the extent of subsidence along with the extent of mine workings. This software was selected due to its versatility in the digitization of vector data types, the processing or raster data types, and the overlay and display of geospatial data.
5.2.2 Google Earth

Google Earth is also a GIS program. It is mostly used for visualizing current and historical aerial imagery, and features such as streets, stored in a virtual database. Google is the most popular GIS software in the market, and owes its popularity to the simplicity with which different data types and data sets can be displayed and overlaid. This software was selected because it is the quickest platform for displaying time-series information. One of the tools offered by Google Earth is a slider bar, that allows the user to pan through historical imagery. This same slider bar can also be used to visualize a series of raster files resulting from time-series analyses. The data formats used in Google Earth (KML or KMZ) can be shared easily, facilitating the peer review of InSAR results.

5.2.3 GMT

“GMT is an open source collection of about 80 command-line tools for manipulating geographic and Cartesian data sets and producing PostScript illustrations” (Lang, 2013). The set of tools allow users to complete processes, like filtering, resampling of raster data, projecting, and gridding. GMT recognizes and outputs gridded files in NetCDF format. This is the format used by GMT5SAR and such is the reason why GMT5SAR’s backend operations are handled with GMT executables. This software was selected for handling GMT5SAR results, because it recognizes GRD NetCDF files.

5.2.4 Geospatial Data Abstraction Library (GDAL)

GDAL is a library of conversion scripts compatible with numerous geospatial data formats. It was used for converting raster files containing InSAR processing results between grd and geotiff formats. Geotiff files were created to upload InSAR results to ArcGIS. This software was selected because it is open source and compatible with the data formats used by ArcGIS and GMT5SAR. Furthermore, GDAL libraries are included in the installation of GMT5SAR and GIAnT.

5.2.5 MATLAB

MATLAB stands for matrix laboratory and is a computing software with statistical and numerical processing tools. MATLAB is a powerful platform for matrix manipulations and it also has the capability of completing string operations. MATLAB scrips were created for assessing viable interferometric combinations and creating input tables needed for GMT5SAR and GIAnT processing tools. This software was selected due to the author’s familiarity with the program’s scripting language.
5.2.6 C-shell

C-shell is a UNIX platform where commands can be executed. This program was used to execute data handling scripts written by the author, and to copy, resize, and rename files iteratively. Both GMT5SAR and GIAnT were installed in a UNIX workstation. C-shell was selected for scripting and executing programs for it was readily available in the workstation.
CHAPTER 6
PROCESSING METHODS

Data processing was conducted in four stages. First, mining information was compiled for each of the study sites, georeferenced, and digitized. Then, InSAR processing was conducted to create the largest number of viable interferograms from which deformation data could be possibly obtained. The standard InSAR results were analyzed with GIAnT. This analysis entailed creating time series and modeling atmospheric delays. The last step was overlaying the InSAR and GIAnT analysis results over digitized mine information to assess the presence and possible progression of subsidence. The individual processing steps are described in the sections to follow.

6.1 Digitization of Mine Layout Maps and Mining Field Outlines

The mine layout maps and permit area outlines were digitized using ArcGIS. In the case of the Colorado Springs’ mining complex and the King Coal II mine, solely the outline of the mined areas was digitized. Individual rooms and adits were not digitized for the Colorado Springs historical mining complex due to the lack of accurate historical records. Regarding the King Coal II Mine, digitizing the internal configuration of the mine served no purpose in the prediction of subsidence features. In room and pillar mines, troughs can be formed above pillars, for failure can propagate at an angle with respect to the vertical. The maps obtained from the CDRMS and the CGS were georeferenced using a minimum of five control points.

The available mine layout maps did not contain reference points with coordinates. The control points were placed on recognizable geomorphic features and in the corners of United States Public Land Survey System (USPLSS) sections. The control points in USPLSS section corner locations were positioned using a publicly available georeferenced USPLSS layer. The control points placed in prominent geomorphic features were positioned using publicly available aerial imagery and topographic maps. The georeferencing was completed using geographic coordinate system WGS 1984, used by Google Earth, which is the software where the results are displayed. This measure prevents the need of transformation that could affect the accuracy of the georeferenced maps.

The mine outlines and internal layouts were digitized by creating polygon features and tracing the extent of rooms or longwall panels in the georeferenced maps. The shape files were created maintaining consistency with the coordinate system used during the georeferencing stage. In the case of shape files containing long wall panels, mining sequence information was tabulated in the attributes table to assess the progression of subsidence above panels. This information was ultimately used to label the digitized longwall panels.
6.2 InSAR Processing

InSAR processing and post-processing was completed using GMT5SAR (Sandwell, et al. 2011) and GIAnT (Agram, Jolivet and Simons 2012). Please refer to the respective manuals for a detailed explanation of the steps completed. “Image alignment is problematic if the perpendicular baseline between the master image and one of the slave images is greater than about \( \frac{3}{4} \) of the critical baseline” (Sandwell, et al., 2011). Exceeding such separation causes baseline decorrelation. Decorrelation can also occur if the scattering properties of a pixel changes between two acquisitions, due to natural processes. This phenomenon is termed temporal decorrelation.

Both the temporal and spatial separations between the collection of images were accounted when defining suitable master and slave images. In most cases, all images in a data set were aligned to a single master. However, in the presence of images with large temporal and perpendicular baselines with respect to the master image, alignment was completed using the multi-step alignment approach. This approach allows the usage of a previously aligned slave image as a surrogate master. Figure 6-1 shows the alignments used for the ALOS dataset encompassing the Deserado Mine.

All the suitable interferometric pairs were scripted in a text file using two methods. In the case of ALOS imagery, the author assessed viable combinations visually, staying within a half of the critical baseline, which is approximately 9 km based on reported acquisition parameters. In the case of ERS and ENVISAT imagery, a MATLAB script was created to output all interferometric pairs using two inputs: a maximum perpendicular baseline, and maximum temporal baseline. The MATLAB script is shown in Appendix A. In most cases, ERS and ENVISAT interferograms were formed with perpendicular and temporal baselines shorter than 500 m and 1000 days, respectively. Figure 6-2 illustrates the interferometric pairs selected for the data set shown in Figure 6-1. Table 6-1 summarizes the total number of interferograms.

The quality of an interferogram is conditioned by the presence of noise. Noise is produced by thermal and geomorphic conditions (Abdallah & Abdelfattah, 2013). Noise in interferograms can be dampened through the application of filters. The author tested Gaussian filters of different wavelengths to assess which one yielded better results. In most cases, filtering wavelengths of 200 m and 100 m were found to be optimal. The specific filters used for individual imagery sets are saved in the “batch.config” files of each study site, in the database. By default, GMT5SAR also applies a fixed decimation factor of 4 in the azimuth direction, and user-defined decimation factor in the range direction. All interferograms were produced with a decimation factor of 1 in the range direction to optimize their resolution.
Figure 6-1 Baseline plot of ALOS imagery encompassing the Deserado Mine. The gray lines denote the pairs used for alignment.

Satellite: ALOS
- Super Master
- Primary match
- Secondary match

2007 2008 2009 2010 2011
Baseline (m)
Figure 6-2 Baseline plot of ALOS imagery encompassing the Deserado Mine. The gray lines represent the interferometric pairs selected for the analysis.
Table 6-1 Number of interferograms produced per data set.

<table>
<thead>
<tr>
<th>Study Site</th>
<th>ALOS</th>
<th>ERS-1 and ERS-2</th>
<th>ENVISAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deserado Mine</td>
<td>58</td>
<td>83</td>
<td>76</td>
</tr>
<tr>
<td>King Coal II Mine</td>
<td>46</td>
<td>85</td>
<td>56</td>
</tr>
<tr>
<td>Colorado Springs</td>
<td>38</td>
<td>131</td>
<td>50</td>
</tr>
<tr>
<td>Mining Complex</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Unwrapping was conducted using the statistical-cost, net-work-flow phase-unwrapping algorithm (SNAPHU) (Chen & Zebker, 2000). This algorithm, like other unwrapping algorithms, “[…] estimates unambiguous phase values from observed phase data known only [in] modulo 2π radians.” (Chen & Zebker, 2000). SNAPHU was selected over the alternative phase gradient approach (Sandwell & Price, 1998) due to implementation of a superior computing methodology. The SNAPHU approach partitions interferograms into “[…] tiles that are unwrapped individually and then divided further into independent, irregularly shaped reliable regions. These regions are subsequently assembled in a full unwrapped solution, with the phase offsets between regions computed in a secondary optimization problem […]” (Chen & Zebker, 2000). This method allows the unwrapping of large interferograms, that could not be unwrapped in commercial workstations, using the alternate unwrapping tool.

An unwrapping threshold equal or smaller than 0.1 was used in all cases, to minimize areas of masked data in the resulting unwrapped interferograms. The exact unwrapping thresholds are in the “batch.config” files included in the database provided. Unwrapping was the most computationally intensive step in the processing workflow. To minimize the processing time and memory usage, the unwrapping extent was limited to the areas immediately around the study sites. An example of the selected unwrapping extent, relative to the extent of the wrapped interferograms, is shown in Figure 6-3.

Once all the interferograms were produced, a c-shell script was written to select viable interferograms for time-series analysis. Viability was defined in terms of the average coherence within the unwrapped extent. The viable interferograms were uploaded to Google Earth for visualizing the quality of data and the percentage of masked pixels within the areas of interest. Unwrapped interferograms with inconsistent fringing patterns and substantial masked areas were removed from the viability list. Table 6-2 shows the number of viable interferograms from each data set. SBAS and NSBAS processing requires unwrapped interferograms and
coherence images to have the same size. Resizing of coherence values was also completed using a c-shell script, taking as input the list of viable interferograms. Amongst the requirements were metadata tables with specific formats. These tables were compiled using MATLAB and python scripts. These scripts are included in Appendix A.

Figure 6-3 Unwrapped interferogram overlaying a wrapped interferogram encompassing the Deserado Mine. The larger black polygon denotes the unwrapping extent. The smaller black polygon indicates the mine’s outline.
Table 6-2 Number of selected interferograms per data set, for time-series analysis. The King Coal Mine's ENVISAT cell contains two values, one for the ascending track, and one for the descending track.

<table>
<thead>
<tr>
<th>Study Site</th>
<th>ALOS</th>
<th>ERS-1 and ERS-2</th>
<th>ENVISAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deserado Mine</td>
<td>25</td>
<td>33</td>
<td>22</td>
</tr>
<tr>
<td>King Coal II Mine</td>
<td>15</td>
<td>12</td>
<td>8</td>
</tr>
<tr>
<td>Colorado Springs Mining Complex</td>
<td>27</td>
<td>36</td>
<td>38</td>
</tr>
</tbody>
</table>

6.2.1 SBAS processing

SBAS processing was conducted using the SBAS modules in GMT5SAR and GIAnT. The SBAS approach facilitated the production of mean deformation velocity maps. The principles of this post-processing technique are described by Lanari et al. (2007). Individual time series analyses were completed for each satellite data set. For SBAS processing using GIAnT, the author defined radar coordinates to establish an area of no deformation. This information was different for each satellite data set. Additional inputs are listed and described below:

- Unwrapped interferogram dimensions: This information consists of the pixel count along the x and y axes. The values were obtained via “grdinfo”.
- Average incidence angle: This information was provided both as grid file and as constant, and was calculated processing DEM and LOS information using the tools “grdsample”, “grd2xyz”, and “SAT_look”. The values were also different for each satellite.
- Coherence Threshold: This parameter sets a threshold for SBAS and NSBAS pixel selection. Due to the limited number of viable interferograms for all study sites, this parameter was set to 0.1 or 0.05.
- Minimum number of interferograms where a pixel needs to be coherent: This parameter sets a minimum number of images in which a pixel needs to have a coherence value above the coherence threshold, to be included in a time series analysis. This value was set to 2 in all cases to maximize the number of pixels, given the low number of viable interferograms.

Network deramping, DEM error estimation, and atmospheric corrections were applied in all the time series analyses. An empirical model for estimating atmospheric delays was also tested (Lin, et al., 2010). The model estimates stratified atmospheric phase contribution "[…]"
assuming a simple linear relationship with topography” (Agram, et al., 2012). GPS deramping was not tested due to the lack of freely available GPS survey data in all the study sites. The weather models tested for atmospheric delay corrections are listed below.

- European Center for Medium-Range Weather Forecasts’ (ECMWF) ERA-interim global atmospheric reanalysis program
- National Oceanic and Atmospheric Administration’s (NOAA) North American Regional Reanalysis (NARR)
- National Aeronautics and Space Administration’s (NASA) Modern – Era Retrospective Analysis for Research and Applications

The specific inputs for each of the time series analyses using GIAnT are recorded in the prepxml.py file within each study site folder. The SBAS analysis via GMT5SAR was completed without the need of any user-defined variables. The inputs for this software were a table with baseline information and acquisition dates, the number of unique SAR images, and the number of interferograms. No weather models were included in SBAS analyses completed with GMT5SAR.

6.2.2 NSBAS processing

NSBAS handles InSAR processing steps starting from raw data to time-series analysis. In this case, GIAnT solely executed the modules post unwrapping. This specific tool inverts the phase delay of each pixel and ultimately “[…] solve[s] for the total phase delay, of each date relative to the first date, whose delay is set to zero” (Doin, et al., 2011). Least squares is used to solve the system. The constrains include a prescribed function of perpendicular baseline and set parameters for the temporal evolution of surface strain (Doin, et al., 2011). The atmospheric delay and deramping models used for SBAS time-series analyses were also included in the creation of time-series via NSBAS. Similarly, user-defined variables like correlation threshold and the minimum number of interferograms where a pixel needs to be coherent were kept unchanged.

6.2.3 Stacking

Stacking is the simplest method for mitigating the effects of noise and phase delays caused by tropospheric or ionospheric conditions. This tool calculates the mean of each pixel from a stack of images, for pixels that are coherent in all the provided images. Stacking was only conducted in ALOS interferograms encompassing the Deserado Mine. Only, three unwrapped interferograms were selected due to the low density of coherent pixels within the mine permit area, in most interferograms. The interferograms included in the stacking process
were selected by visually inspecting the significance of masked pixels within the mine outline. The inspection was completed using Google Earth.

6.2.4 Geocoding

Both GMT5SAR and GIAnT have geocoding libraries that transform interferograms and time-series results from radar coordinates to polar coordinates. In the case of GMT5SAR, the transformation is completed using a trans.dat file, which contains azimuth, range, latitude, longitude, and elevation information. GIAnT uses latitude and longitude grid files, provided by the user, to project raster files in radar coordinates into polar coordinates. The transformations are executed via GDAL plugins.

All the interferograms, wrapped and unwrapped were geocoded automatically by GMT5SAR. SBAS results obtained from GMT5SAR were not geocoded if the raster files had a low density of coherent pixels near the mining location and if significant error was present. Erroneous results were identified through the presence of areas denoting significant uplift or where subsidence was unexpected. If stacking or SBAS results were deemed valuable, geocoding was completed using the tool proj_ra2ll.csh. Geocoding of GIAnT outputs were completed via geocode.py or make_kml.py. The general InSAR processing workflow is illustrated in Figure 6-4.

6.3 Storage / Creation of database

A database was created to store all the raw and processed InSAR data, and the reports obtained from the CDRMS and the CGS. The information was organized according to the site location, the data type, the satellite of provenance, and the stage of SAR processing. The database was saved in an external hard drive. The structure is illustrated below:

- InSAR Library
- InSAR processing
  - Colorado Springs Mining Complex
  - King Coal II Mine
  - Deserado Mine
    - Site Reports
    - Maps
      - Georeferenced
      - Shapes/Outlines
      - Rasters
      - Original
    - InSAR Data
- ALOS
- ENVISAT
- ERS
  - Original
  - Raw SAR imagery
  - DEM
  - Processed Data
    - GMTSAR
      - Configuration and Input Files
      - Preprocessed Images
      - Aligned Images
      - Interferograms
      - Stacking or Time Series
    - GIAnT
      - Input Files
      - Executables
      - Results
Figure 6-4 InSAR processing workflow. Modified from Sandwell et al. (2011)
CHAPTER 7
RESULTS

The following sections present selected interferograms and time-series results for each of the study areas. The complete set of interferograms and time-series are included in the database.

7.1 Deserado Mine

The sub-sections to follow include selected interferograms encompassing the Deserado Mine. The interferograms were created using ALOS, ENVISAT, and ERS imagery.

7.1.1 ALOS results

This subsection presents selected results for the Deserado Mine based on ALOS imagery. The results are based on conventional DInSAR, Stacking, SBAS, and NSBAS processing.

Figure 7-1 Interferogram encompassing the Deserado Mine. The mine's outline is delineated with a black polygon. The interferogram was created with ALOS images captured in 09/15/2007 and 05/08/2010. The different colors represent phase changes between acquisitions.
Figure 7-2 The unwrapped phase of the interferogram in Figure 22 is shown on the left. The mask for the unwrapped interferogram, based on a coherence threshold of 0.1, is shown on the right. The pixels in blue have a coherence lower than 0.1. Note the deformation near the center of the frame.

Figure 7-3 Result obtained via stacking of unwrapped interferograms encompassing the Deserado Mine. Negative values represent ground movement away from the satellite.
Figure 7-4 Time-series of deformation above the Deserado Mine. The analysis was completed using GMT5SAR’s SBAS tool. Each frame portrays the modeled cumulative deformation at the time of acquisition. The yellow regions portray no deformation. The red pixels near the center of each frame coincide with panels mined during the acquisition period.
Figure 7-5 Time series of deformation above the Deserado Mine, obtained via SBAS, using GIAnT. The time stamp for each stage of deformation is shown at the top of each panel. Negative values represent ground movement away from the satellite. The shown extents are a close-up of the extent shown in Figure 7-2.
Figure 7-6 Time series of deformation above the Deserado Mine, based on ALOS imagery. The analysis was completed using NSBAS, via GIAnT. The time stamp for each stage of deformation is shown at the top of each panel. Negative values represent ground movement away from the satellite.
Figure 7-7 Deformation profiles of the Deserado Mine based on ALOS NSBAS results. Sections of the profile that overlap pixel with no information were estimated using a linear interpolation.
Figure 7-8 Deformation timeline for pixel 769, 763, located within the Deserado Mine’s outline. The subsidence progression is based on NSBAS results. The red data points represent the reconstructed, un-filtered deformation at each acquisition time. The blue points represent the reconstructed and filtered time series.
7.1.2 ERS Results

This subsection presents selected results for the Deserado Mine based on ERS imagery. The results are based on conventional DInSAR, SBAS, and NSBAS processing.

Figure 7-9 Interferogram encompassing the Deserado Mine. The mine's outline is delineated with a black polygon. The interferogram was created with ERS images captured in 11/09/1993 and 12/07/1995. The different colors represent phase changes between acquisitions.

Figure 7-10 The unwrapped phase of the interferogram in Figure 7-9 is shown on the left. The mask for the unwrapped interferogram, based on a coherence threshold of 0.1, is shown on the right. The pixels in blue have a coherence lower than 0.1. Note the deformation on the upper left quarter of the frame showing the unwrapped phase.
Figure 7-11 Time series of deformation above the Deserado Mine, based on ERS imagery. The analysis was completed using GIAnT's SBAS tool. The time stamp for each stage of deformation is shown at the top of each panel. Negative values represent ground movement away from the satellite. The shown extents are a close-up of the extent shown in Figure 7-10. Note the concentric deformation pattern around the center of each frame.
Figure 7-12 Time series of deformation above the Deserado Mine, based on ERS imagery. The analysis was completed using GIAnT’s NSBAS tool. The time stamp for each stage of deformation is shown at the top of each panel. Negative values represent ground movement away from the satellite. Note the deformation on the upper left quarter of both frames.
Figure 7-13 Deformation profiles of the Deserado Mine based on ERS NSBAS results. Sections of the profile that overlap pixel with no information were estimated using a linear interpolation.
Figure 7-14 Deformation timeline for pixel 401, 245, located within the Deserado Mine’s outline. The subsidence progression is based on NSBAS results. The red data points represent the reconstructed, un-filtered deformation at each acquisition time. The blue points represent the reconstructed and filtered time series.
7.1.3 ENVISAT Results

This subsection presents selected results for the Deserado Mine based on ENVISAT imagery. The results are based on conventional DInSAR, SBAS, and NSBAS processing.

![Figure 7-15 Interferogram encompassing the Deserado Mine. The mine’s outline is delineated with a black polygon. The interferogram was created with ENVISAT images captured in 03/21/2007 and 11/21/2007. The different colors represent phase changes between acquisitions.](image)

![Figure 7-16 The unwrapped phase of the interferogram in Figure 7-15 is shown on the left. The mask for the unwrapped interferogram, based on a coherence threshold of 0.1, is shown on the right. The pixels in blue have a coherence lower than 0.1. Note the deformation on the upper left quarter of the frame showing the unwrapped phase.](image)
Figure 7-17 Time series of deformation above the Deserado Mine, based on ENVISAT imagery. The analysis was completed using GIAnT’s SBAS tool. Negative values represent ground movement away from the satellite. The shown extents are close-ups of the extent shown in Figure 7-16. Note the concentric deformation pattern around the center of each frame.
Figure 7-18 Time series of deformation above the Deserado Mine, based on ENVISAT imagery. The analysis was completed using GIAnT’s NSBAS tool. The time stamp for each stage of deformation is shown at the top of each panel. Negative values represent ground movement away from the satellite.
Figure 7-19 Deformation profiles of the Deserado Mine based on ENVISAT NSBAS results. Sections of the profile that overlap pixel with no information were estimated using a linear interpolation.
Figure 7-20 Deformation timeline for pixel 828, 756, located within the Deserado Mine’s outline. The subsidence progression is based on NSBAS results.
7.2 King Coal II

The sub-sections to follow include selected interferograms encompassing the King Coal II Mine. The interferograms were created using ALOS and ERS imagery.

7.2.1 ALOS Results

This subsection presents selected results for the King Coal II Mine based on ALOS imagery. The results are based on conventional DInSAR, and SBAS processing.

Figure 7-21 Interferogram encompassing the King Coal II Mine. The mine’s outline is delineated with a black polygon. The interferogram was created with ALOS images captured in 09/15/2007 and 05/08/2010. The different colors represent phase changes between acquisitions.

Figure 7-22 The unwrapped phase of the interferogram in Figure 7-21 is shown on the left. The mask for the unwrapped interferogram, based on a coherence threshold of 0.1, is shown on the right.
Figure 7-23 Time series of deformation above the King Coal II Mine, based on ALOS imagery. The analysis was completed using GIAnT’s SBAS tool. The time stamp for each stage of deformation is shown at the top of each panel. Negative values represent ground movement away from the satellite. Note the two locations with blue pixels, denoting subsidence, and the presence of yellow along drainage valleys.
Figure 7-24 Deformation profiles of the King Coal Mines based on ALOS SBAS results. Sections of the profile that overlap pixel with no information were estimated using a linear interpolation.
Figure 7-25 Deformation timeline for pixel 786, 844, located within the King Coal II Mine’s outline, in an area of suspected subsidence. The subsidence progression is based on SBAS results. The red data points represent the reconstructed, un-filtered deformation at each acquisition time. The blue points represent the reconstructed and filtered time series.
7.2.2 ERS Results

This subsection presents selected results for the King Coal II Mine based on ERS imagery. The results are based on conventional DInSAR, and SBAS processing.

![Interferogram encompassing the King Coal II Mine](image1.png)

Figure 7-26 Interferogram encompassing the King Coal II Mine. The mine's outline is delineated with a black polygon. The interferogram was created with ERS images captured in 12/05/1995 and 05/28/1996.

![Unwrapped phase and mask](image2.png)

Figure 7-27 The unwrapped phase of the interferogram in Figure 7-26 is shown on the left. The mask for the unwrapped interferogram, based on a coherence threshold of 0.1, is shown on the right. The pixels in blue have a coherence lower than 0.1. Note the number and density of masked-out areas.
Figure 7-28 Time series of deformation above the King Coal Mine, based on ERS imagery. The analysis was completed using GIAnT’s SBAS tool. The time stamp for each stage of deformation is shown at the top of each panel. Negative values represent ground movement away from the satellite.
Figure 7-29 Deformation timeline for pixel 601, 755, located within the King Coal Mine’s outline. The subsidence progression is based on SBAS results. The red data points represent the reconstructed, un-filtered deformation at each acquisition time. The blue points represent the reconstructed and filtered time series.
7.3 Colorado Springs Mining Complex

The sub-sections to follow include selected interferograms encompassing the historical mining complex in Colorado Springs. The interferograms were created using ALOS, ENVISAT and ERS imagery.

7.3.1 ALOS results

This subsection presents selected results for the historical mining complex in Colorado Springs, based on ALOS imagery. The results are based on conventional DInSAR, and SBAS processing.

Figure 7-30 Interferogram encompassing the historical mining complex in Colorado Springs. The historical mining fields are delineated with black polygons. The interferogram was created with ALOS images captured in 07/04/2007 and 10/09/2009.

Figure 7-31 The unwrapped phase of the interferogram in Figure 7-30 is shown on the left. The mask for the unwrapped interferogram, based on a coherence threshold of 0.1, is shown on the right. The pixels in blue have a coherence lower than 0.1.
Figure 7-32 Time series of deformation encompassing the historical mining complex in Colorado Springs, based on ALOS imagery. The analysis was completed using GIAnT’s SBAS tool. The time stamp for each stage of deformation is shown at the top of each panel. Negative values represent ground movement away from the satellite.
7.3.2 ERS Results

This subsection presents selected results for the historical mining complex in Colorado Springs, based on ERS imagery. The results are based on conventional DInSAR, and SBAS processing.

Figure 7-33 Interferogram encompassing the historical mining complex in Colorado Springs. The historical mining fields are delineated with black polygons. The interferogram was created with ERS images captured in 11/15/1992 and 06/13/1993.

Figure 7-34 The unwrapped phase of the interferogram in Figure 7-33 is shown on the left. The mask for the unwrapped interferogram, based on a coherence threshold of 0.1, is shown on the right.
Figure 7-35 Time series of deformation encompassing the historical mining complex in Colorado Springs, based on ERS imagery. The analysis was completed using GIAnT’s SBAS tool. The time stamp for each stage of deformation is shown at the top of each panel. Negative values represent ground movement away from the satellite. Note the high number of areas undergoing apparent uplift.
Figure 7-36 Deformation timeline for pixel 700, 575, located within the analyzed quadrangle. The subsidence progression is based on SBAS results. The red data points represent the reconstructed, un-filtered deformation at each acquisition time. The blue points represent the reconstructed and filtered time series. Note the positive (upward) trend after 1996.
7.3.3 ENVISAT Results

This subsection presents selected results for the historical mining complex in Colorado Springs, based on ENVISAT imagery. The results are based on conventional DInSAR, and SBAS processing.

Figure 7-37 Interferogram encompassing the historical mining complex in Colorado Springs. The historical mining fields are delineated with black polygons. The interferogram was created with ENVISAT images captured in 09/07/2005 and 05/10/2006.

Figure 7-38 The unwrapped phase of the interferogram in Figure 7-38 is shown on the left. The mask for the unwrapped interferogram, based on a coherence threshold of 0.1, is shown on the right.
Figure 7-39 Time series of deformation encompassing the historical mining complex in Colorado Springs, based on ENVISAT imagery. The analysis was completed using GIAnt’s SBAS tool. The time stamp for each stage of deformation is shown at the top of each panel. Negative values represent ground movement away from the satellite. The location undergoing apparent subsidence is beyond the mined areas in Colorado Springs.
Table 8-1 summarizes the figure numbers pertaining to the results shown in the previous section. This table includes the time-series analyses completed for each study site and remarks on the magnitude and extent of detected deformation.

<table>
<thead>
<tr>
<th>Site</th>
<th>Data</th>
<th>Figures</th>
<th>Methods</th>
<th>Remarks</th>
</tr>
</thead>
</table>
| Deserado Mine         | ALOS | Figure 7-1 to Figure 7-8 | Stacking, SBAS, and NSBAS | • The extent of deformation is consistent with the mining timeline.  
• Subsidence was detected. The maximum LOS deformation is 28 cm. |
|                       | ERS  | Figure 7-9 to Figure 7-14| SBAS              | • The extent of deformation is consistent with the mining timeline.  
• Subsidence was detected. The maximum LOS deformation is 14 cm.     |
|                       | ENVISAT | Figure 7-15 to Figure 7-20 | SBAS              | • The extent of deformation is consistent with the mining timeline.  
• Subsidence was detected. The maximum LOS deformation is 14 cm.     |
| King Coal II Mine     | ALOS | Figure 7-21 to Figure 7-25| SBAS              | • The extent of deformation is within the extent of mine workings.  
• Subsidence was detected. The maximum LOS deformation is 7 cm.       |
|                       | ERS  | Figure 7-26 to Figure 7-29| SBAS              | • No clear subsidence signatures were detected                      |
| Colorado Springs      | ALOS | Figure 7-30 to Figure 7-32| SBAS              | • No clear subsidence signatures were detected                       |
| Mining Complex        | ERS  | Figure 7-33 to Figure 7-36| SBAS              | • No clear subsidence signatures were detected                       |
|                       | ENVISAT | Figure 7-37 to Figure 7-39 | SBAS              | • No clear subsidence signatures were detected                       |
8.1 Deserado Mine

Interferograms produced from all three data sets encompassing the Deserado Mine evidence the progression of subsidence within the mines’ outline. As shown in Figure 7-1 through Figure 7-18, troughs had formed close to the southwestern edge of the mine outline, in the period between 2004 to 2010. Additional subsidence features are revealed with ERS interferograms near the northeastern corner of the mine. Such features had been formed between 1993 to 1999. The troughs’ location and time of formation is mostly consistent with the mining timeline presented in layout maps included as supplemental electronic files. Figure 8-1 shows the composite deformation above the Deserado Mine, produced by mosaicking the last step of ALOS-based, ERS-based, and ENVISAT-based time-series results.

![Figure 8-1 Map of composite deformation above the Deserado Mine.](image)

The D seam, which is located along the eastern half of the permit area, was mined during 1992 to 1999. This time frame corresponds to the acquisition period of ERS imagery. The western half started to be mined in 2000 and will continue until approximately 2040.
Deformation caused by mining of the initial longwall panels could not be assessed via InSAR, for there is a gap in the downloaded SAR imagery between 1999 and 2004. The panels mined between 2004 and 2011 induced a deformation signature that is perceived via InSAR, and that corresponds closely with the panel’s extent. InSAR results obtained from imagery collected between 2004 and 2011, evidence the presence of additional troughs in locations that do not correspond to the mining sequence reported by the mine. ENVISAT and ALOS interferograms reveal the occurrence of subsidence above two panels that were reportedly mined in 1997 and 1988. These are locations where subsidence should have been perceived mostly by ERS interferograms. Figure 8-2 shows the extent of such troughs.

![Figure 8-2 Deformation above D-seam panels, captured via ALOS-based InSAR.](image.jpg)

In longwall mining, the bulk of subsidence occurs over a period of two days. However, deformation continues for additional years at very slow rates (Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Developments, 2014). Figure 8-3 shows that the extent of deformation perceived by ALOS and ENVISAT interferograms exceeds the
acquisition periods of both satellites. In both cases, the deformed area extends further south than the extent of the panels mined during the respective acquisition periods, to areas previously mined. The deformation signatures beyond the extent of the panels mined during the satellite’s acquisition period are probably caused by residual subsidence above previously mined panels. The subsidence shown in the Figure 8-2 could have also resulted from the slow progression of subsidence above panels mined prior 2004.

The distribution of deformation values in all data sets is unimodal, with mean values close to zero. There is a subtle tail towards negative values, representing subsidence, which is consistent with type and magnitude of deformation under analysis. The maximum detected deformation along the LOS vector is approximately 29 cm, over a period of 4 years, detected by ALOS-based interferometry. The Vertical deformation is greater than the reported values by a factor of 1.3 to 1.5, depending on the radio waves’ angle of incidence. Maximum subsidence would be approximately 40 cm. BMEI modeled that subsidence would reach a maximum of 128 cm to 235 cm, depending on the thickness of overburden. The model calibration from BMEI is not available in their report. Both values from BMEI’s modeling are greater than the maximum subsidence recorded via InSAR.

The discrepancy could be caused by the interpretation of inaccurate subsidence values, caused by the presence of low coherence pixels within the subsidence troughs. The error would have originated in the unwrapping step, during which unambiguous phase values are estimated from phase data in modulo $2\pi$ radians. High deformation rates, as those expected over longwall mines, can cause aliasing of the signal. This problem can induce the underestimation of deformation, given that phase changes exceeding $2\pi$ radians over proximate pixels can be unaccounted during the unwrapping process.

The high number of low coherence pixels within a trough above longwall panels, is most probably caused by the high degree of deformation that such location undergoes during mining. Substantial deformation ultimately induces a change in the dielectric and scattering properties of the surface. The lack of coherent pixels within this study area and reduced number of small baseline interferograms is evidenced in the SBAS analysis conducted for the Deserado Mine. The last frame of the SBAS result based on ALOS imagery is shown in Figure 8-4.

Figure 8-4 shows that the deformation above the mine is only perceivable around the edges of the longwall panels, where subsidence is expectedly less prominent. The bulk of the areas immediately above the mined panels are masked out due to the low coherence of pixels, despite setting a coherence threshold of 0.1 and an “nvalid” value of 2 - the number of images in which a pixel needs to have a coherence greater than the threshold to be included in the
analysis. Thus, the most reliable information to quantify deformation is around the edges of longwall panels.

Figure 8-3 Reclassified extent of deformation over the Deserado Mine. The areas that have deformed over 1 cm, based on ALOS data, are shown in red in the top panel. The areas that have deformed over 4 mm, based on ENVISAT imagery, are shown in red in the bottom panel.
Figure 8-4 SBAS analysis result based on ALOS imagery.

Despite the high number of areas with low coherence, the type of ground cover was ideal for the analysis of subsidence via InSAR. Deformation was detectable with C-band images, which is seldom the case when working on vegetated ground, lacking corner reflectors. Nevertheless, the edges of deformation were clearer in interferograms produced with L-band. This indicates that L-band imagery is more reliable for this type of analysis. Such statement is supported by lower subsidence values yielded by C-band data and by the low number of viable ENVISAT and ERS interferograms used for time-series analyses.

The subsidence values obtained via C-band interferograms ranged from 5 to 15 cm near the middle of the trough. These values are lower than the values obtained via L-band data, on average. Furthermore, C-band information yielded the lowest percentage of viable interferogram, with respect to the total number of interferograms created per data set. This evidences that coherence was lost more prominently in C-band interferograms. A raster analysis of the last frames for all SBAS reveals the following:
- 47% of pixels were masked out from ALOS-based SBAS results
- 78% and 88% of pixels were masked out from ERS-based and ENVISAT-based SBAS results

ENVISAT and ALOS results show that subsidence extends beyond the edges of the digitized panels to the west, north, and south. However, deformation does not extend beyond the eastern edge. This is anomalous, for subsidence propagates to the surface at an angle with respect to the vertical, causing deformation away from the mined area, in all directions. The anomaly may have resulted from georeferencing errors, that may have led to the digitization of panels west of their actual location. Subsidence extends approximately 120 m. north of the northernmost mined panel. Assuming a seam depth of 210 m., the draw angle is approximately 30 degrees, which is within the typical range of draw angles.

Many interferograms created with all three data sets contained phase delays that were more closely spaced in areas of high relief. This evidence that phase changes as a result of topography were not fully mitigated during the removal of the topographic phase. Stacking, SBAS, and NSBAS mitigated this problem as shown in Figure 7-3 through Figure 7-6. Similarly, some interferograms had phase delays forming a parallel fringing pattern across. Such artifact was most probably a ramp induced by error in alignment, caused in turn by orbital inaccuracies. As with topographic phase delays, this problem was also mitigated via stacking, SBAS, and NSBAS processing. An example of the effectiveness of deramping is shown in Figure 8-5.

Atmospheric corrections also contributed to the presence of false positives in the many of the interferograms. The phase delays induced by atmospheric conditions were modeled and removed mostly with ERA data. An example of the effectiveness of atmospheric modeling is shown in Figure 8-6. Topography influenced the density of coherent pixels. The location of areas without data in Figure 7-4, correspond to regions with steep terrain. This was more noticeable in interferograms with large temporal baselines. The predominant slope aspect was to the northeast. In the case of ALOS images, collected during ascending tracks, and looking to the right (east), the shadowing and foreshortening effects might have been more prominent. This could have had a direct effect on the accuracy of deformation values.

Stacking was the quickest method of mitigating the presence of undesired phase delays. Figure 7-3 shows a subsidence signature that is consistent with ones obtained via SBAS and NSBAS. The limitation of this method is that it cannot be used to quantify subsidence. This method will always underestimate the degree of deformation in locations of maximum subsidence.
The number of viable interferograms was low for all the data sets. This has a direct effect on the temporal resolution of the time series analyses. The time series based on ERS data had 22 time steps to cover 7 years of deformation. Similarly, the time series based on ALOS data had 11 time steps to cover 4 years of deformation. Such temporal resolution is not sufficient to assess how immediate is surface deformation to subsurface activities. The spatial resolution was not a problem given the type of mining conducted in the Deserado Mine. The extent of subsidence troughs can be easily delineated clearly with C-band and L-band data.

The error in the SBAS results ranged from less than a cm to approximately 2 cm. Error was solely calculated on SBAS results via bootstrapping. The error estimation function of NSBAS is still under construction, the error estimation for this study cannot be obtained at this time. Figure 8-7 includes a profile of subsidence progression that includes error bars for...
modeled data points. The best fit line was modeled using a second order polynomial. The size of error bars increase with time, as the terrain becomes more deformed in relation to initial conditions. This is consistent with the loss of coherence in areas within the trough that had undergone significant deformation. Figure 8-8 illustrates the distribution of error in relation to the extent of subsided areas.

Figure 8-7 Subsidence progression profile of pixel 787, 801. The information is based on SBAS processing of ALOS data encompassing the Deserado Mine.
Figure 8-8 Spatial distribution of subsidence error based on ALOS-SBAS results.
8.2 The King Coal II Mine

A few subsidence features were found within the King Coal II mine outline by processing ALOS imagery. The maximum change in elevation is approximately 6 cm. There are also subsidence features located southwest of the King Coal II permit. A review and digitization of nearby mining concessions, revealed that the troughs southwest of the King Coal II mine are encompassed by the extent of mine workings of the King Coal I Mine. The maximum change in elevation above the King Coal I mine is approximately 5.5 cm. Figure 8-9 shows the extent of the subsidence features in relation to the mine working for both mines.

![Figure 8-9 Deformation above the King Coal I and King Coal II Mines.](image)

There are pixels that denote deformation near the study area as well as in areas distant from the reported mining locations. The location of these pixels coincides with local drainage valleys. This indicates that the phase delays caused by the regional topography could not be fully removed, forming false positives along areas of high relief. In consistency with this problem, many interferograms showed fringing that corresponded with the regional topography. There was also fringing that seemed to be caused by atmospheric delays. This fringing was partially mitigated by the inclusion of atmospheric models. Final time series results based on ALOS imagery included patches of subtle deformation, where no deformation is expected, that were probably residuals of atmospheric delays. The presence of ramps was not as prominent as in the interferograms produced for the Deserado Mine.

No subsidence was detected using ERS imagery. Loss of coherence was the main limitation in this case. Table 6-1 and Table 6-2 reveal that only 14 percent of the produced
interferograms with ERS or ENVISAT data, were deemed viable, based on average coherence values within the unwrapping extent. Figure 7-26 illustrates this problem. There is noise covering a significant portion of the interferograms. The extent of areas covered with noise corresponds to densely vegetated areas. This limitation is to be expected for C band radar tends to be scattered from tree tops. Considering the poor time-series results obtained using ERS data, the author refrained from processing ENVISAT interferograms.

Although it was possible to detect the deformation using L-band imagery, the temporal resolution was rather low to evaluate with detail the progression of deformation. Unfortunately, the number of ALOS images was the lowest out of all the data sets. The lower the number of images, the lower the number of interferograms, and ultimately, the greater the temporal baseline between SAR collections. This has a direct effect on coherence. Fifteen interferograms created with a total of 7 SAR images pose less than optimal conditions to conduct time series analysis. Grzovic and Ghulam (2015) used over 35 interferograms for completing time series analyses to evaluate subsidence. With such a low number of viable interferograms the presence of error in one of them has significant effect over the entire series. Figure 8-10 shows the error associated with the last SBAS frame, based on ALOS imagery.

Some areas proximate or within the King Coal II Mine permit area showed signs of subsidence initially. However, the progression profile of pixels within such area indicate uplift towards the end of the series, invalidating the possibility of true subsidence. This type of error could be caused by noise, foreshortening, atmospheric delays, among other factors. A method for mitigating this problem is the inclusion of a higher number of interferograms in the analysis.

The reports downloaded from the CDRMS database mentioned a single subsidence event near a residence within the permit area for King Coal I Mine. The diameter of the trough is approximately 90 m. The area where the trough is located is masked out from the both ALOS and ERS SBAS results, due to the low coherence of the corresponding pixels. However, SBAS results based on ALOS interferograms indicate the occurrence of subsidence in the vicinity. This ratifies the viability of InSAR for detecting subsidence over active room and pillar mines. A greater density of coherent pixels is necessary for delineating the extent of troughs with precision. Subsidence over room and pillar mines is sporadic and less pronounced than subsidence over longwall mines. The trough features can be smaller than the pixel size of an interferogram. Given the resolution and noise level of the obtained interferograms, InSAR is not ideal for detecting small subsidence features.
Figure 8-10 Spatial distribution of subsidence error based on ALOS-SBAS results
8.3 Historical Mining Complex in Colorado Springs

No clear signs of subsidence were found in the Rockrimmon or Country Club areas in Colorado Springs, that could be easily distinguished from noise and false positives in surrounding areas. Figure 3-8 shows the location of subsidence reclamation events completed in historical mining fields in Colorado Springs. Most of such reclamation projects preceded the earliest SAR acquisition. There are three locations where subsidence problems were addressed during the period of acquisition of ERS imagery, and none of them show signs of deformation based on interferometry.

Coherence loss was also a conditioning factor despite the presence of corner reflectors throughout the areas of interest. The ALOS data set yielded the highest percentage of viable interferograms. Unviable interferograms were mostly those with large temporal baselines. A visual analysis of a random set of interferograms revealed that many pixels with low coherence corresponded to areas where new structures had been built in between acquisitions.

Atmospheric corrections based on ERA data exacerbated the presence of false positives. Figure 8-11 is an example of the problem that was encountered in a number of corrections models based on such data. The ERA-based models targeted with spatially accuracy areas where delays were more prominent. However, the corrections seem to overestimate the delays. In the example shown, the atmospheric delays were greater along the right edge and lower left corner of the image. The model also predicts that atmospheric delays will be most prominent in the same areas. However, the delay predictions are greater in the model than in the time-series obtained from the unwrapped information. NARR and empirical models were not found to be more accurate.

![Figure 8-11 Example of atmospheric correction applied to ERS interferograms, based on ERA-interim data.](image-url)
Mining activities in Colorado Springs stopped in 1956. Matheson (1985) established that the appearance of subsidence features peaked approximately 30 to 40 years after the completion of mining activities. Thus, it is to expect that the occurrence and dimensions of troughs will be minimal in both the Rockrimmon and Country Club areas. Thus, the identification of subsidence features via InSAR, considering the resolution and temporal baseline of the downloaded data, would be rather difficult.

The size of subsidence features identified by Matheson and in individual geotechnical reports (Matheson, 1985) have diameters that seldom exceed 15 m. Subsidence, under ideal conditions, would only be recorded in a couple of pixels. Such subsidence signatures would not be statistically significant, given the magnitude of noise present in time series results. There are a couple of features in the ALOS time series, within areas delineated to have a high risk of subsidence (Matheson, 1985), that could denote deformation. The noise levels in the area have direct effect on the confidence with which such features could be defined to be troughs. The employed data and methodology would be applicable in Colorado Springs, if subsidence would daylight in the form of broader troughs. Without a precise record of subsidence events, that could be used to calibrate the InSAR results, the application of InSAR in this context is unviable, considering the temporal and spatial resolution of the used data.
CHAPTER 9
CONCLUSIONS

The deformation signature obtained from the interferograms encompassing the Deserado Mine is consistent with the mining timeline reported by BMEI. The years during which longwall panels were mined corresponds to the years of deformation revealed via InSAR. The results were consistent independent of the type of used SAR imagery. Nevertheless, loss of coherence was less significant in interferograms created with ALOS images. ALOS-based subsidence values were also the highest and most similar to the subsidence estimated via modelling. The used methodology was also effective for detecting residual subsidence above panels that were mined prior a satellite’s acquisition period.

The subsided area above the Deserado Mine, detected via InSAR goes beyond the outline of the mined panels, only in three directions. This anomaly could have resulted from inaccuracies associated with the georeferencing of the mine layout map. The extent of subsidence to the north of the northernmost panel was used to estimate a draw angle of approximately 30 degrees, which is consistent with the range of draw angles reported in the literature. Unfortunately, the uncertainty associated with such value is large, given the evident presence of georeferencing errors. Precise GPS surveying data would be required to delineate the mined extents with accuracy, to subsequently compare such information with subsidence extents deduced via InSAR, to ultimately estimate accurate draw angles.

The error associated with InSAR results increases towards the middle of troughs, especially in longwall mining. This is to expect given that coherence values tend to be lower in such location, due to substantial deformation. The error bars ranged from approximately 0.5 cm to 2 cm in areas of maximum deformation. Unfortunately, it is not possible to assess the accuracy of deformation solely based on modelling data completed in 1992. Thus, in the case of longwall mining, it cannot be established if InSAR is an effective method for quantifying subsidence. Regarding the extent of subsidence, the deformation signature was clearly portrayed by InSAR results. The area of subsidence aligns closely with the mined longwall panels. Thus, it can be established that InSAR based on C and L band data are effective for delineating subsidence above longwall mines.

Subsidence features were found above the King Coal I and King Coal II mines using ALOS imagery. The troughs identified above the King Coal I mine are near a trough that was monitored by GCC Energy, LLC between 2001 and 2003. The high relief in the area induced topographic phase delays that could not be removed through the processing methods used.
No subsidence features were found in the historical mining complex in Colorado Springs. The reclamation projects reported by the United States’ Department of Interior did not correspond to areas of deformation portrayed in ERS interferograms. Although there were pixels denoting subsidence in the Rockrimmon and Country Club areas in Colorado Springs, the signal to noise ratio is rather low to establish that subsidence occurred. Furthermore, Matheson (1985) indicated that the peak period for the formation of subsidence features following mining is 30 to 40 years. Since more than 60 years have gone by since the closure of the last coal mine in Colorado Springs, it may be possible that no subsidence occurred during the period of acquisition of SAR imagery. Hence the absence of clear deformation in the interferograms.

The size of troughs above room and pillar mines can be similar or smaller than the size of InSAR pixels. Thus, subsidence, under ideal conditions, would only be recorded in a couple of pixels. Such subsidence signatures would not be statistically significant, given the magnitude of noise present in time series results. The signal to noise ratio would increase by increasing the number of interferograms, for which a higher number of images is required.

Overall, InSAR was an effective tool for detecting deformation over active room and pillar, and longwall mines. In the case of longwall mines, InSAR can be used to delineate the extent of deformation. With regards to room and pillar mines, InSAR could also be used for delineating deformation given a high density of coherent pixels. L band imagery yielded the most consistent results out of the two types of used imagery.
CHAPTER 10
RECOMMENDATIONS

The millimeter accuracy of subsidence by InSAR could not be obtained anywhere at any time. This project’s main limitation is the signal to noise ratio encountered in the study areas where room and pillar mining was conducted. This problem would be mitigated through the use of larger data sets, with shorter temporal baselines. Shorter temporal baselines lower the probability of encountering temporal decorrelation, and ultimately compromising the accuracy of interferometric results. Newer data sets collected by satellite constellations such as Cosmo Sky Med satellites, and TerraSAR X and Tandem X, have a higher repeat frequency than ERS, ENVISAT and ALOS satellites. Data sets from these satellites would solve the temporal baseline problem. Modern SAR systems also provide more accurate orbital information. This improvement would decrease the presence of ramps in interferograms and the need of deramping. GIAnT includes a GPS deramping tool that could be used if precise GPS surveying data were present within the extents of the used SAR images. This is an alternative to the network deramping tool also available in GIAnT.

The subsidence above the Deserado Mine, calculated via InSAR, differs significantly from the modeled subsidence values reported by Blu Mountain Energy, Inc. Due to the lack of precise leveling information, it was not possible to assess which of the two sets is more accurate. Levelling information would be very useful to evaluate the effectiveness of the used methodology, not only for delineating subsidence, but also quantifying it.

The use of persistent scatterers (PS) could solve the decorrelation problem encountered in this project. Interferometry, through the use of persistent scatterers, exploits “[...] stable natural reflectors or permanent scatterers (PSs) starting from long temporal series of interferometric SAR images. When, as it often happens, the dimension of the persistent scatterer is smaller than the resolution cell, the coherence is good even for interferograms with baselines larger than the decorrelation one” (Ferreti, et al., 2001). This would allow the creation of a much larger number of interferograms, which is ideal for PS interferometry. This method would also prevent the need of discarding interferograms due to presence of low coherence values in the areas of interest, as it was done in this project. This method would be mostly applicable in longwall mining areas where there may be one or more natural reflectors within a panel. In historical room and pillar mining scenarios, subsidence features are sporadic and don’t encompass large areas as in longwall mining, unless subsurface instability induces regional deformation.
REFERENCES


http://mining.state.co.us/SiteCollectionDocuments/Coal%20Mine%20Summaries%202012%20(1).pdf.


Department of the Environment, Australian Government. 2015. Monitoring and Management of Subsidence Induced by Longwall Coal Mining Activity. Canberra: Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development.


MATLAB script used for creating a text file with all the viable interferometric pairs, based on user-defined perpendicular baseline and temporal baseline parameters. This script was used for large SAR data sets, most commonly ERS data sets.

```matlab
function viable_combinations(tab, temp, perp)
%function scene_intf(int, table, corr, unw)
%tab = baseline_table.dat obtained during pre-processing step
%This tool prepares the list of viable interferogram combinations based on limiting temporal baseline and limiting perpendicular baseline
%Steps needed for creating mat variables and saving the data into arrays
%filename='int'
baseline_table=single(load(tab));
%Steps needed to create the two text files needed for executing the sbas algorithm
intf_tab=nchoosek(baseline_table(:,1),2);
final_list=[1 1];
%Steps taken to populate intf_tab array
for n=1:length(intf_tab);
    master=intf_tab(n,1);
    slave=intf_tab(n,2);
    ind_master=find(baseline_table(:,1)==master);
    ind_slave=find(baseline_table(:,1)==slave);
    temp_baseline=abs(baseline_table(ind_master,2)-baseline_table(ind_slave,2));
    perp_baseline=abs(baseline_table(ind_master,5)-baseline_table(ind_slave,5));
    if temp_baseline > temp && perp_baseline > perp
        final_list=[final_list; intf_tab(n,:)];
    else
        final_list=final_list;
    end
T=table(num2str(final_list(:,1)), num2str(final_list(:,2)));
writetable(T,'final','Delimiter',' ','WriteVariableNames',false);
```
C-shell script used for selecting viable interferogram for post-processing using GIAnT. The script executes GMT commands that help determine whether an interferogram is viable or not based on the average coherence of the coherence grd file, within the unwrapped extent. Such value is ultimately compared with a user-defined threshold.

```
#!/bin/bash
#This tool selects the interferograms that can be used to run sbas
#The tool needs to be executed from within a directory at the same level as directory "intf"
#./viable.sh corr_threshold

rm viab.txt
rm unviab.txt
touch viab.txt
touch unviab.txt
echo "please enter the threshold"
read T
echo "the threshold is $T"

for directory in ../intf/*; do
    b=$(basename $directory)
echo "working on $b"
    n=`grdinfo $directory/corr.grd -L2 -C -R$directory/unwrap.grd | awk '{print $12}'`
echo "threshold is $n"
    if [ "$n" > "$T" ]; then
        echo "$b" >> viab.txt
echo "threshold is exceeded"
    else
        echo "$b" >> unviab.txt
echo "threshold not exceeded"
    fi
done
```
C-shell script used for resizing coherence files used for SBAS processing. The script executes grdcut using the pertaining unwrapped raster as resizing mask, and names the output file “corr_but.grd”

```bash
#!/bin/bash
#This tool helps cut the correlation files to right size to be used by giant
#usage ./cut2.sh list_of_viable_interferograms_in_julian

for directory in `cat $1`; do
cd $directory
grdcut corr.grd -Runwrap.grd -Gcorr_cut.grd
cd..
done
```
Python Script used for creating the input table for SBAS and NSBAS processing using GIAnT. The executable reads the “intf.in” file which contains the list of viable interferograms, and fetches the perpendicular baseline and the date in which the SAR images were collected. (modified from Lindsey, 2016)

```
#!/opt/local/bin/python

"""convert GMTSAR-formatted intf.in to ifg.list for GIANT
(implemented currently for ALOS and ENVISAT)
For ALOS:
intf.in format:
IMG-HH-ALPSRP154997060-H1.0__A:IMG-HH-ALPSRP161707060-H1.0__A
ifg.list output format:
yyyyymmdd yyyyymmdd baseline(m) ALOS
For ENVISAT
intf.in format:
ENV1_2_356_0000_09428:ENV1_2_356_0000_21953
ifg.list output format:
yyyyymmdd yyyyymmdd baseline(m) ENVI
Assumes the file 'intf.in' exists, and contains a list of all your interferograms.
also assumes the existence of a baseline table located at 'raw/baseline_table.dat'
"

import sys
import os.path

def get_orbit(filestem,SAT):
    if SAT == 'ALOS':
        #orbit IDs used by GMTSAR are in the ALOS filename
        return filestem[13:18]
    elif SAT == 'ENVI':
        #orbit IDs used by GMTSAR should be in the ENVI filename
        return filestem[16:21]
```
# baseline table identifier is in filename

    elif SAT == 'ERS':
        return filestem[0:7]

def get_baseline(orbitID, baseline_table):
    # GMTSAR records baseline info in file raw/baseline_table.dat, column 5
    with open(baseline_table, 'r') as f:
        for line in f:
            entries = line.rstrip().split()
            if entries[0] == orbitID:
                return float(entries[4])

def get_date(prmfile, SAT):
    with open(prmfile, 'r') as f:
        for line in f:
            if SAT == 'ALOS':
                if 'date' in line:
                    entries = line.rstrip().split()
                    return '20%s' % entries[2]
            elif SAT == 'ENVI':
                if 'SC_clock_start' in line:
                    entries = line.rstrip().split()
                    datestr = entries[2]
                    return jdate_to_date(datestr[0:7])
            elif SAT == 'ERS':
                if 'SC_clock_start' in line:
                    entries = line.rstrip().split()
                    datestr = entries[2]
                    return jdate_to_date(datestr[0:7])
def jdate_to_date(jdate):
    import datetime
    fmt='%Y%j'
    dt=datetime.datetime.strptime(jdate,fmt)
    return '%04d%02d%02d'%(dt.year,dt.month,dt.day)

def date_to_jdate(date):
    import datetime
    fmt='%Y%m%d'
    dt=datetime.datetime.strptime(date,fmt)
    tt = dt.timetuple()
    return '%4d%03d'%(dt.year,tt.tm_yday)

def write_ifg_list(SAT,intf_in,baseline_table):
    with open(intf_in,'r') as f:
        outdata=[]
        for line in f:
            images = line.rstrip().split(':')
            orbit0=get_orbit(images[0], SAT)
            orbit1=get_orbit(images[1], SAT)

            date0 = get_date('raw/%s.PRM' %images[0], SAT)
            date1 = get_date('raw/%s.PRM' %images[1], SAT)

            #compute baseline for a pair using the file raw/baseline_table.dat
# currently, guessing that the sign
convention is later date - earlier date.

base0=get_baseline(orbit0,baseline_table)

base1=get_baseline(orbit1,baseline_table)
    baseline = base0 - base1
#test that unwrap_ll.grd exists
before writing to array

inf_dir='%s_%s'%(date_to_jdate(date0),date_to_jdate(date1))

if
os.path.isfile('intf/%s/unwrap_ll.grd'%inf_dir):
    #build array for output

outdata.append([date0,date1,baseline,SAT])

with open('ifg.list', 'w') as f:
    counter=0
    for entry in outdata:
        string='\s %s %s
\s
\s\n\s\n\n\n\n
f.write(string)
    counter=counter+1
    print("wrote ifg.list with %d
completed interferograms."%counter)

if __name__ == '__main__':
    if len(sys.argv) < 2:
        print("\nUsage: %s SAT [inf.in]
[raw/baseline_table.dat], where SAT is either ALOS or ENVI\n"%sys.argv[0])
        print("inf.in and
baselinetable.dat are taken as defaults, but may be specified")
        exit()
#defaults

intf_file='intf.in'
baseline_file='raw/baseline_table.dat'

if len(sys.argv) > 2:
    intf_file = sys.argv[2]

if len(sys.argv) > 3:
    baseline_file = sys.argv[3]

write_ifg_list(sys.argv[1],intf_file,baseline_file)
MATLAB script for creating the input table for SBAS and NSBAS processing using GIAnT. The script reads a list of selected interferograms and the “baseline_table.dat” file, which contains perpendicular and temporal baseline information. The output is the “ifg.list” file required for post-processing with GIAnT.

```matlab
function te=giant_ifg_list_prd(int,tab)
% %
%function scene_intf(int, tab)
%int = list of selected interferogram
%tab = baseline_table.dat obtained during pre-processing step
%sat= name of satellite in between quotation marks
%This tool prepares the ifg.list table that is necessary to run GIAnts sbas tool

%Steps needed for creating mat variables and saving the data into arrays
%filename='int'
intf=dlmread(int,'_');
baseline_table=dlmread(tab);
baseline_tab(:,2)=fix(baseline_table(:,2));
% t4=baseline_tab(:,2);

%Steps needed to create the two text files needed for executing the sbas
%algorithm
scene_tab=ones(numel(unique(intf)), 2);
scene_tab(:,1)=unique(intf);
master=ones(size(intf,1),1);
slave=ones(size(intf,1),1);
% B_perp=single(ones(size(intf,1),1));
B_perp=ones(length(intf),1);
% trial_slave=ones(length(intf),);
% trial_master=ones(length(intf));

%Steps taken to populate scene_tab array
%julian to gregorian calendar
years  = floor(scene_tab(:,1)/1000);
days = scene_tab(:,1)-years*1000;
months = ['Jan';'Feb';'Mar';'Apr';'May';'Jun';'Jul';'Aug';'Sep';'Oct';...
   'Nov';'Dec'];

% work out dates:
normalDate = cell(length(days),1);
yr1=0;
j=1;
for i=1:length(years)
    diff=years(i)-yr1;
    if diff>0
        yrEnd(j)=i-1;  %first element will be the end of non-exsitant year
        yr1=yr1+diff;
        yrs(j)=yr1;
        j=j+1;
    end
end
yrEnd(j)=i;  %last element will be the end of last year in data
for jj=1:length(yrs)
    ly = any(yrs(jj)==leap_years);  %check if the year is a leap year (yes:1, no:0)
    if ly == 0
        dMonths = [31;28;31;30;31;30;31;31;30;31;30;31];  %days of months
        % in normal years
    else
        dMonths = [31;29;31;30;31;30;31;31;30;31;30;31];  %days of months
        % in leap-years
    end
    for j = (yrEnd(jj)+1):yrEnd(jj+1)  %start from beg of the yr go to end
        % of that yr
        i = 1;
        while days(j) > dMonths(i)
            days(j) = days(j)-dMonths(i);
            i = i+1;
        end
end
mnth = months(i,1:end); %this is the month of the
% original Julian day
dy = num2str(days(j)); %actual day after subtracting
% cumulative days of earlier months
normalDate{j}= strcat(dy,'-',mnth,'-',num2str(yrs(jj))); %write
% string dates in cell-array
end
end
normalDate = datestr(datenum(normalDate),'yyymmdd');
scene_tab(:,2)=floor(str2num(normalDate));
% t5=scene_tab;

%Steps taken to populate ifg_list array
for m=1:size(intf,1);
    ind=find(scene_tab(:,1)==intf(m,1));
    master(m)=scene_tab(ind,2);
    dni=find(scene_tab(:,1)==intf(m,2));
    slave(m)=scene_tab(dni,2);
    in=find(baseline_tab(:,2)==intf(m,1));
    dn=find(baseline_tab(:,2)==intf(m,2));
    B_perp(m)=baseline_table(dn,5)-baseline_table(in,5);
end

te=[master slave B_perp];
% te=[master slave trial_slave trial_master];
dlmwrite('testt3.txt',te,'delimiter','\','precision',8);
%T=table(master, slave, B_perp, satellite);
%writetable(T,'ifg_list','Delimiter',' ','WriteVariableNames',false)
The supplemental electronic files consist of geographic data files. These files include mine layout maps for each of the active mines investigated in this report and a map showing the extent of mine workings in the historical mining complex in Colorado Springs. All of these maps were georeferenced and digitized to assess the extent of deformation in relation to the extent and timing of mining activities. The file descriptions are organized based on the statuses of the mines and the year in which the maps were produced.

<table>
<thead>
<tr>
<th>Geographic Data Files</th>
<th>Files containing geographic information related to the mines investigated for this project. These files consist of maps. All the files are provided in PDF format.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deserado Mine Layout Map, 2006.pdf</td>
<td>Layout map of the Deserado Mine drafted by SCW from Blue Mountain Energy on 2006, at a scale of 1”=2000’. The map contains the extent of the panels for both sections of the mine (B-Seam and D-Seam). The panels on the western half of the mine are labeled with year in which mining was or will be completed.</td>
</tr>
<tr>
<td>Deserado Mine Layout Map, 1989.pdf</td>
<td>Mine layout map of the Deserado Mine drafted by Western Fuels on 1989, at a scale of 1”=1000’. The map only includes the location and extent of the panels mined between 1988 and 1999. Such panels solely targeted the D seam. The panels are labeled with the year in which they were mined.</td>
</tr>
<tr>
<td>King Coal Mines Layout Map, 2016.pdf</td>
<td>Mine layout map of the King Coal I and King Coal II mines, drafted by Tom Bird on 2016. The map was drafted at a scale of 1”=2100’ and it portrays the permit boundaries and the extent of mine workings for both mines.</td>
</tr>
<tr>
<td>Colorado Springs Mining Complex Map, 1985.pdf</td>
<td>Map of the extent of historical mine workings in Colorado Springs. The map was drafted by KLR on 1985, at a scale of approximately 1”=5000’. It was included in the reported completed by Dames and Moore in 1985, regarding coal mine subsidence in Colorado Springs.</td>
</tr>
</tbody>
</table>