AER/AGS Open File Report 2018-07

Turtle Mountain Field Laboratory, Alberta (NTS 82G): 2016 Data and Activity Summary

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Contents

Tables

Figures

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Abstract

This report provides a summary of both the lessons learned from the Turtle Mountain monitoring system (TMMS), and from studies undertaken by the Alberta Geological Survey (AGS), Alberta Energy Regulator (AER) and collaborators between January 1 and December 31, 2016. The TMMS is a near-real-time remote monitoring system that provides data from a network of sensors and monitoring campaigns on Turtle Mountain, located in the Crowsnest Pass of southwestern Alberta.

As of April 1, 2005, the AGS took ownership of this system, and the responsibility for long-term monitoring, interpretation of data, and notification of the Alberta Emergency Management Agency should significant movements occur. Since that time, Turtle Mountain has been the site of ongoing monitoring and research focused on understanding the structure and kinematics of movements of the unstable eastern slopes. As this site provides a rich dataset and optimal conditions for the application of new and evolving warning characterization technologies, the site has been termed the 'Turtle Mountain Field Laboratory'.

As part of its long-term monitoring responsibility, the AGS performs an annual detailed review of the data stream. To help in the interpretation of the data, the AGS initiated specific studies to understand better the structure of the mountain and its relationship to the style and rate of movement seen in recent and historical deformations of South Peak. These studies also better define the unstable volumes of rock from the South, North, and Third Peak areas.

This report comprises four main sections.

The first section contains information about the major changes to the TMMS's network during the 2016 field season. This includes a review of the main repair and maintenance activities, synopsis of abandoned stations, and a summary of system performance and reliability.

The second section provides data analysis and interpretation for the primary and secondary monitoring equipment. These interpretations include slope conditions and displacement behaviour from instrumentation results.

The third section reviews supporting studies and research conducted during 2016: a photogrammetry field campaign, LiDAR campaign, and RADARSAT-2 analysis.

The last section contains information on the continued transition of, and future plans for, the Turtle Mountain Monitoring Program.

1 Introduction

In 2005, the Alberta Geological Survey (AGS), a branch of the Alberta Energy Regulator (AER), assumed responsibility for the long-term monitoring of Turtle Mountain, the site of the 1903 Frank Slide (Figure 1). In July 2016, the Turtle Mountain Monitoring Program (TMMP) transitioned from a near-real-time early warning monitoring system to a near-real-time remote monitoring system. This transition encompasses monitoring advancements due to improved displacement detection technologies and a review of over a decade of monitoring data and techniques. For more information, the reader may refer to Section 5, in this report.

The first priority of the TMMP is to provide monitoring on Turtle Mountain, which includes ongoing site characterization, hazard assessment, review of monitoring practices, and making recommendations for the future of the monitoring program. The secondary priority is to provide an opportunity for the research community to test and develop instrumentation and monitoring technologies to understand the mechanics of slowly moving rock masses better. This ongoing research will aid in understanding the movements on Turtle Mountain.

This annual report provides the public and researchers with a synthesized update on data trends, research on the mountain, and changes to the monitoring program.

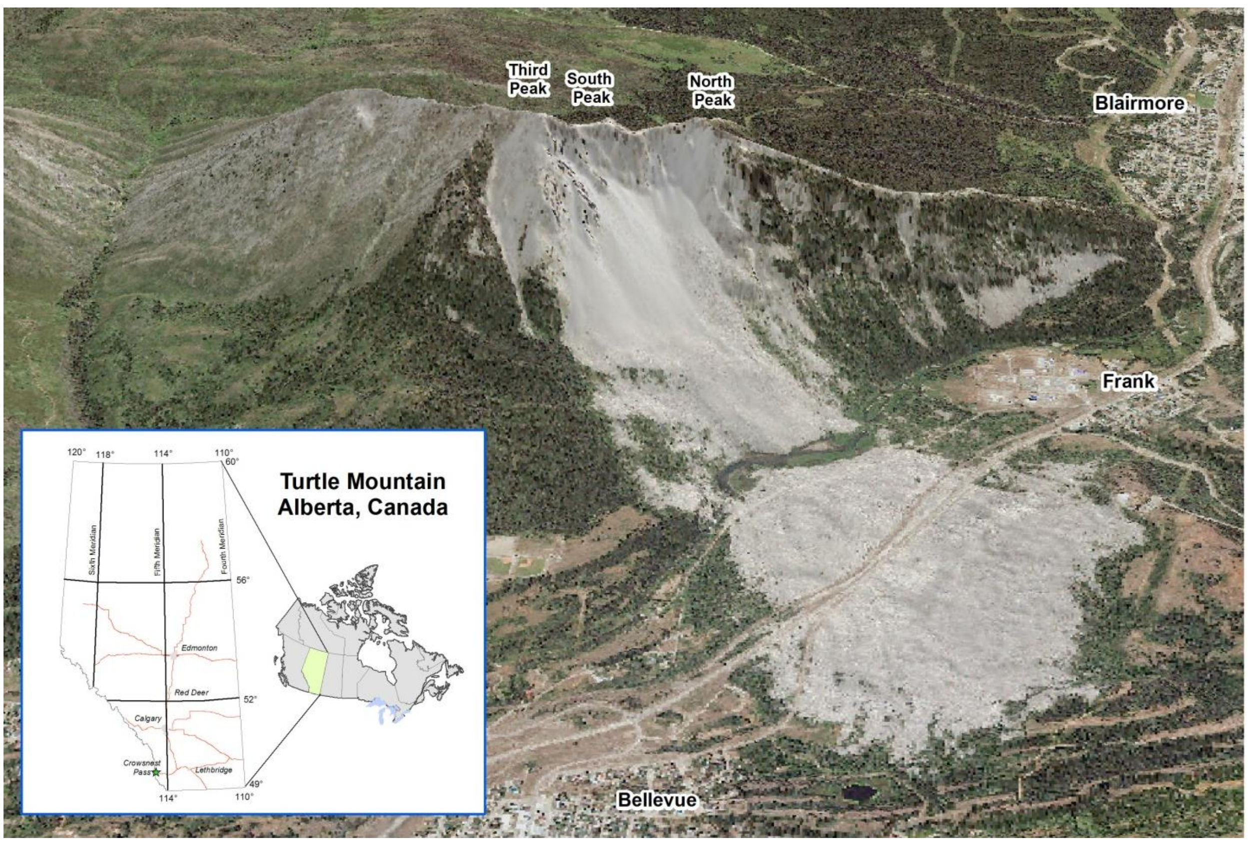

Figure 1. Location of Turtle Mountain in southwestern Alberta and full-extent aerial view of the Frank Slide.

2 Sensor Network Activity

This section provides an overview of the major upgrades, repair, maintenance activities, and performance of the sensor network of the monitoring system during 2016.

The main activities undertaken with respect to the sensor network during 2016 included

- inventory of extensometers, crackmeters, and tiltmeters for future decommissioning;
- cataloguing photogrammetry targets for restoration or replacement; and
- annual LiSAmobile ground-based interferometric synthetic aperture radar (GB-InSAR) equipment maintenance.

The AGS leases a GB-InSAR monitoring system known as LiSAmobile from Ellegi. LiSAmobile was installed in June 2014 and has been in continuous operation. In 2016, LiSAmobile transitioned to the new primary monitoring system, and the dGPS stations were discontinued. In addition, AGS also uses secondary monitoring campaigns. These secondary monitoring campaigns, such as aerial light detection and ranging (LiDAR) scanning, photogrammetry, terrestrial laser scanning (TLS), etc. are selected by the AGS based on monitoring frequency. In 2016, monitoring campaigns selected included photogrammetry, LiDAR, and RADARSAT-2 for supporting studies and research (Section 4).

The AGS receives and reviews monitoring reports on a quarterly basis from Ellegi. Ellegi also provides *Quick Reports* if an area has displacement values outside of the defined thresholds. The AGS's lease with Ellegi includes customer service and technical support in case of emergency or equipment changes. During this period, LiSAmobile and Ellegi have proven to be optimal for monitoring surface displacements and will continue to be the primary sensor into 2017.

The AGS has a radio licence from Industry Canada that allows us to operate the TMMS network link without interference from other frequencies in the surrounding Crowsnest Pass area.

2.1 Repairs and Maintenance

2.1.1 dGPS Annual Maintenance

The AGS has decided to discontinue the dGPS stations because of the availability of newer technologies better suited to remote monitoring of Turtle Mountain and aging batteries and equipment. In 2016, no annual maintenance campaign was scheduled for the dGPS stations.

2.1.2 LiSAmobile Annual Maintenance

In 2016, an annual maintenance campaign was conducted in mid-June which included a team from Ellegi and the AGS. The field maintenance objectives included

- inspection of the radome for any structural or waterproofing issues,
- examination of all power and communication cables,
- replacement of the chain cable,
- mechanical maintenance on the radar head with lubrication of moving parts,
- replacement of the ball bearings and microwave components and cables,
- internal radome cover and gasket checks,
- power box inspection,
- dust and lubrication of drive belt and instrument components,
- replacement of various filters,
- radio frequency evaluation, and
- mechanical shut-down and restart testing.

During the site maintenance, the radome was inspected for signs of physical damage, structural deterioration, and water leak exposure. The radome protects LiSAmobile from significant fluctuations in precipitation and temperatures that are typical throughout the year in the Crowsnest Pass, Alberta. These exposures include high and low temperatures during summer and winter, respectively, extreme wind gusts, and heavy precipitation events. The inspection revealed the radome had continued to withstand all the environmental factors and protected the LiSAmobile system effectively as designed. The radome test pilot was successful and is now integrated into Ellegi's LiSAmobile stations worldwide. The AGS is confident in the radome's ability to protect LiSAmobile. AGS will continue to evaluate the radome throughout 2017.

The belt and motor that drives LiSAmobile were cleaned, lubricated, and inspected for signs of deterioration as it has been in continuous motion since 2014. Inspection of the belt system showed little sign of wear, and the motor was in good operating condition. The ball bearings were replaced within the belt system for preventative maintenance (Figure 2). The annual field maintenance for LiSAmobile found no problems with the system and only preventative maintenance was completed.

Figure 2. LiSAmobile annual maintenance.

2.2 Non-operational Instruments

After review of the instrument data in 2015, we decided that the use of specific instruments would be discontinued in the 2016 field season due to different underlying issues (Wood et al., 2016 and 2017a). The term 'non-operational instrument' refers to an instrument that has been abandoned due to poor quality or inadequate data.

During a reconnaissance trip in June 2016, AGS inventoried all non-operational instrumentation and equipment located on South Peak. These instruments were assessed and catalogued in detail to plan for their future decommission in 2017.

2.2.1 Weather Station

The weather station became inoperable in March 2014, and it was verified in June 2015 that the weather station's electronic components were either missing or considerably damaged, beyond repair. The missing instruments are assumed to have been lost during extensive wind, snow storms or due to vandalism.

The weather station was catalogued and its status was listed as non-operational in 2016. AGS will decommission this station during the 2017 field season, as it is no longer viewed as a critical data source.

2.3 Performance

Continuous slope monitoring is challenging in the harsh and highly variable weather conditions on Turtle Mountain. However, the effects of these adverse conditions on the normal operation of the monitoring system are minimized with a series of preventive measures, including frequent inspections, replacement of aging equipment, and system modifications and upgrades. This section provides detailed information on sensor performance in 2016.

The TMMS has been operational for over a decade. This has enabled us to understand not only the challenges of maintaining a reliable and continuously running system but also to identify the factors that affect the normal operation of the monitoring network.

2.3.1 Continuous-Reading dGPS Monitoring Network

The dGPS stations have been the primary (2014–2015) and secondary (2005–2013) monitoring systems for the TMMS to provide up-to-the-minute status reports via email and the desktop application GeoExplorer. In July 2013, the AGS convened an independent international expert panel to provide a review of the current management of the slope hazards on Turtle Mountain. A report by the panel was submitted to AGS in October 2014 (Wood et al., 2016, appendix 3). This report examined the current practices and future recommendations of the TMMP.

Based on the report's recommendation, the AGS decided that the dGPS stations will be decommissioned in 2017. In April 2016, the stations were discontinued due to the aging stations and changing technologies better suited to monitor Turtle Mountain. Data collected from the dGPS stations from January to March 2016 were not analyzed due to limited data collection.

2.3.2 LiSAmobile Ground-based InSAR

The LiSAmobile system was leased to the AGS and installed in June 2014 (Figure 3a). Additional documentation on the feasibility study, service contract, fabrication of supporting materials, LiSAmobile installation, and initial system calibration is included in Wood et al., (2016).

LiSAmobile continued to provide high-quality data throughout 2016 with little to no interruption. The innovative radome structure (Figure 3b) continued to perform as expected and protected the equipment from harsh environmental factors. The internet service provider lost the connection between LiSAmobile and its network communication once in January and twice in March. Data collected during these disruptions was temporarily stored on a local disk and transmitted once the internet connection was re-established; therefore, no displacement data was lost.

Ellegi provided a premium level of technical support, innovative shelter technology, and timely detailed reporting. AGS will continue to utilize LiSAmobile as a primary monitoring system.

a)

b)

Figure 3. a) LiSAmobile system without radome and temperature regulation unit; b) LiSAmobile system assembled with the radome.

3 Data Analysis

3.1 Deformation Monitoring Data

3.1.1 Continuous-Reading dGPS Monitoring Network

Over the past decade, eight dGPS stations were operating on Turtle Mountain with two base stations. During a site visit in July 2016, AGS staff cataloged the dGPS and base station equipment on Third and South Peak. This inventory will allow staff to prepare for the decommission fieldwork in 2017.

3.1.2 LiSAmobile Ground-based InSAR

LiSAmobile was installed at the Bellevue pump house (Figure 4) in June 2014 to monitor small displacements on the eastern face of Turtle Mountain. The LiSAmobile GB-InSAR uses the interferometric synthetic aperture radar technique to measure small displacements at each point on the surface of the mountain.

Figure 4. LiSAmobile system at the Bellevue pump house station.

LiSAmobile consists of two main parts: the radar head and mechanical components. The radar head is an active radar sensor that transmits microwave pulses towards an object and receives in return a backscattered signal (Figure 5). The radar head, which consists of two antennas (transmit and receive), is attached to a linear positioner (cradle) mounted on a horizontal track. The travel distance of the radar head along the track can be adjusted to allow for optimal scanning coverage of the mountain face. The radar head travels back and forth along the 2.5 metre track once every ~8.5 minutes.

The LiSAmobile system is connected via the Internet through a WiFi connection that allows VPN access. The data are processed onsite, and the results are transferred to Ellegi via VPN to be assessed.

The LiSAmobile system obtains raw data measurements from the radar head. This data is processed by LiSAmobile and is evaluated for data quality by Ellegi and used to create displacement maps showing a pixelated image of ground displacements that range from positive to negative values. Positive values are depicted as blue colours indicating displacement away from the sensor, while red colours illustrate displacement towards the sensor.

3.2 Discussion and Interpretation of Monitoring Data

3.2.1 Continuous-Reading dGPS Monitoring Network

The dGPS stations were discontinued in April 2016 and moved to non-operational status. The trends in displacement at the dGPS stations collected from January to March 2016 were not analyzed due to limited data collection.

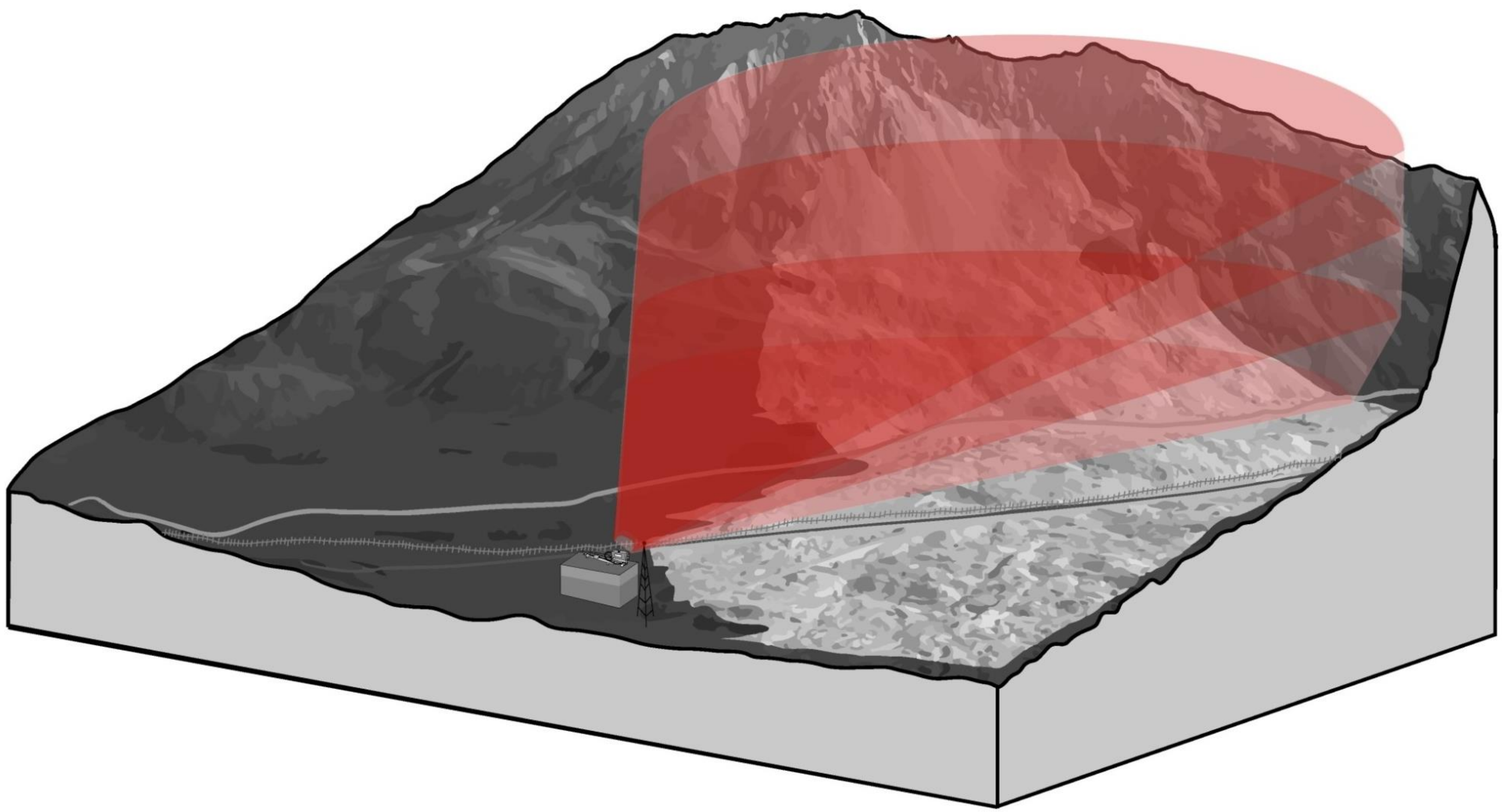

Figure 5. Overview, as of December 2016, of the TMMS. The drawing marks the location of the LiSAmobile system, and the red beam depicts the scanning of the mountain. The light gray area represents the extent of the original 1903 slide. The image is not drawn to scale, and its purpose is to highlight the area LiSAmobile scans.

3.2.2 LiSAmobile Ground-based InSAR

The displacement maps displayed in Figures 6 and 9 depict how the slopes on the east face of the mountain are affected by slow and small movements, measured in the millimetre range. Displacement maps are created through a collection of data from the LiSAmobile system over a 91-day period (per quarter), with approximately 15-day increments. The displacement maps were produced from data collected from the start of LiSAmobile operation in June 2014 to the end of December 2016 and provided by Ellegi to the AGS in quarterly reports (Q7 to Q10 for 2016). Each report contains the cumulative data starting from June 20, 2014, to the end of the respective quarterly reporting period.

The data are divided into seven regions (A–G, Figure 6), which are further subdivided into twelve points of interest (POIs, labelled P_1 through P_12, in Figure 7). Additional documentation of the LiSAmobile parameters can be found in Wood et al. (2016).

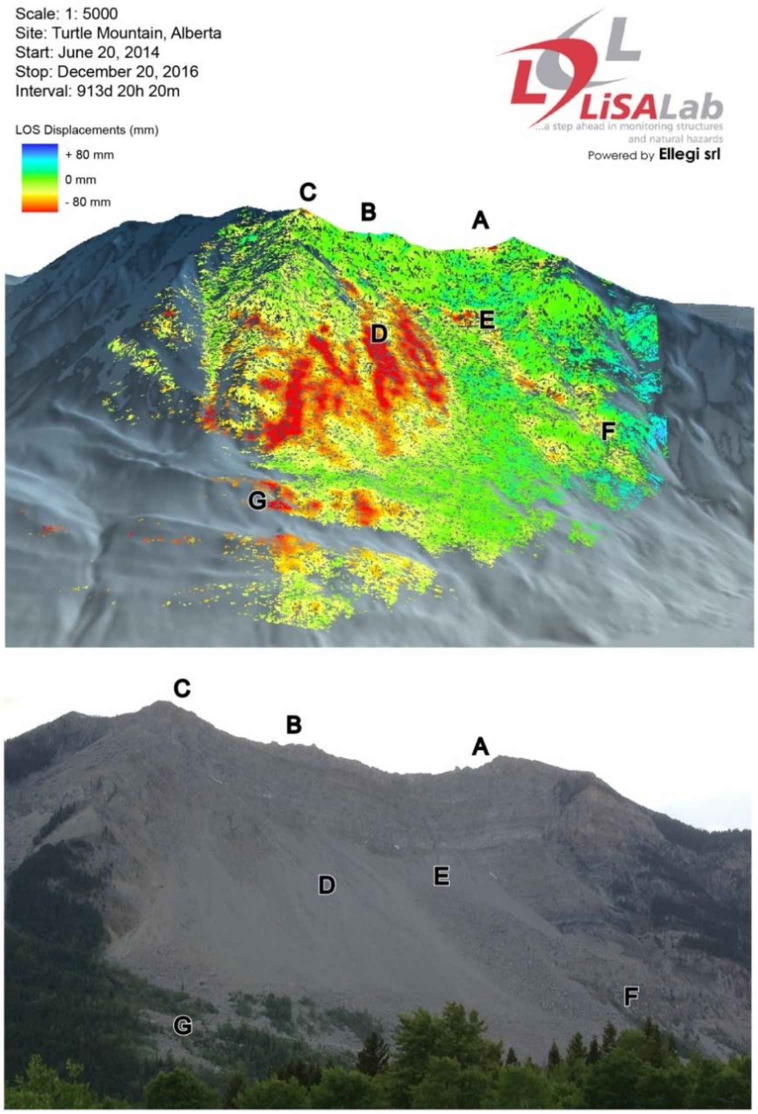

Figure 6. 3D displacement map (top) measured from June 20, 2014, to December 20, 2016, and view of the eastern face of Turtle Mountain (bottom). Letters A to G denote the location of regions described in Tables 1 to 8.

The high displacement rates detected in the vegetation zone (region F, Figures 6 and 9) are considered to be measurement errors introduced by atmospheric moisture within the line of sight.

The results from reports Q7 to Q10 provided to the AGS by Ellegi are shown in Tables 1 to 8.

LiSAmobile data shows no large displacements of larger coherent blocks of material (generalized movement) have been identified near North and South peaks throughout 2016. Generalized displacement in the regions of interest for the period from June 20, 2014, to the end of the respective quarterly reporting period (i.e., Q7, Q8, Q9, Q10) is shown in Tables 1, 3, 5, and 7, respectively. Measured displacements at points of interest (POI) for the same time periods are presented in Tables 2, 4, 6, and 8.

On the displacement maps (Figures 6 and 9) both positive and negative displacement values are depicted using colours. Blue colours indicate displacement away from a sensor (positive value), for example, rocks calving off and exposing new rock surfaces from behind. Red colours indicate displacement towards the sensor (negative value), such as rocks falling and accumulating in the debris zones (region D, E, and G). Green colours depict a neutral range of displacement with minimal movements towards or away from the sensor.

For simplicity, AGS has removed the negative sign from the reported displacement tables (Tables 1 to 8) and is reporting the cumulative movements towards the sensor (i.e., only the red colours).

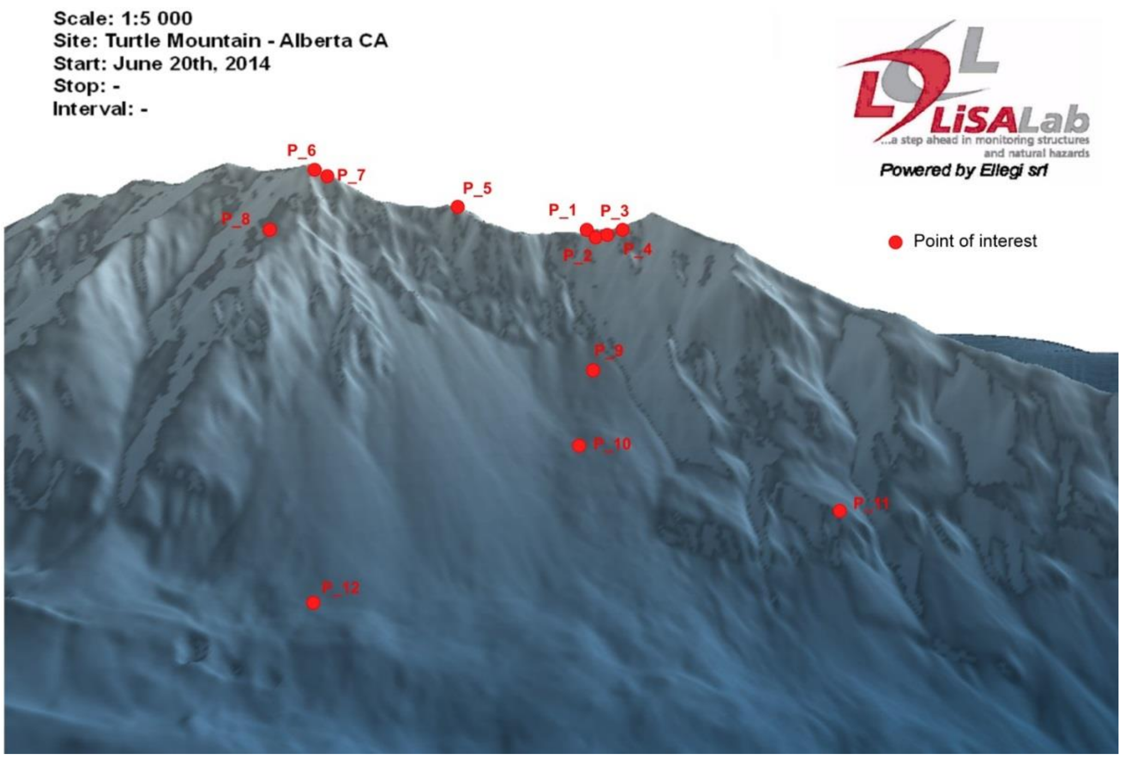

Figure 7. Turtle Mountain points of interest in regions A to G (Figure 6).

Table 1. LiSAmobile generalized displacement in regions of interest for the period from June 20, 2014, to March 20, 2016 (638 days).

Region	Location Description	Displacement (mm)	Approximate Region Area (m^2)
A	Close to North Peak	7.6 to 80.0	4600
B	Between North and South Peak	≤26.0	600
C	Close to South Peak	≤38.0	1200
D	Debris area toe of South Peak rock wall	>20.0	-
E	Debris area toe of North Peak rock wall	>30.0	-
F	Mid to lower vegetative rock wall	-	-
G	Debris zone run out area	6.6 to 17.6	-

Table 2. LiSAmobile measured displacement at points of interest (POI) for the period from June 20, 2014, to March 20, 2016 (638 days) with observations specific to quarter Q7.

Region	Point of Interest (POI)	Displacement (mm)	Displacement Descriptions Specific to Q7
A	P_1	7.6 to 80.0	Continuous movement.
	P_2		
	P_3		
	P_4		Continued decelerated movement and fluctuating trend. Errors introduced by snow cover.
B	P_5	≤26.0	Acceleration of movement, subject to errors due to snow cover.
C	P_6	≤38.0	Small acceleration throughout Q7, subject to errors due to snow cover.
	P_7		
D	P_8	-	Data is omitted due to errors introduced by snow cover.
E	P_9	≤32.4	Slight acceleration throughout Q7.
	P_10	-	Rate of displacement unchanged displaying stable behaviour until the end of Q7. Errors introduced by snow cover.
F	P_11	-	Data is omitted due to error introduced by snow cover.
G	P_12	-	A fast acceleration of movement is reported from the end of December 2015 until March; likely due to errors introduced by snow cover.

Generalized displacement in Q7 for all seven regions was relatively unchanged compared to Q6. Measured displacements at some POIs were subject to errors due to snow cover and atmospheric moisture (e.g., fog, snowfall, rain).

The Q7 summary report from Ellegi noted that the system was operational from the installation date in June 2014, with minimal interruptions. Three transmission disruptions occurred during Q7 due to internet service provider outages throughout the Crowsnest Pass. During these disruptions in service, no data was lost due to on-site data collection.

Table 3. LiSAmobile generalized displacement in regions of interest for the period from June 20, 2014, to June 20, 2016 (730 days).

Region	Location Description	Displacement (mm)	Approximate Region Area (m^2)
A	Close to North Peak	6.2 to 102.0	4600
B	Between North and South Peak	≤30.7	600
C	Close to South Peak	≤44.5	1200
D	Debris area toe of South Peak rock wall	-	-
E	Debris area toe of North Peak rock wall	>32.4	-
F	Mid to lower vegetative rock wall	-	-
G	Debris zone run out area	17.6 to 22.3	-

Table 4. LiSAmobile measured displacement at points of interest (POI) for the period from June 20, 2014, to June 20, 2016 (730 days) with observations specific to Q8.

Region	Point of Interest (POI)	Displacement (mm)	Displacement Descriptions Specific to Q8
A	P_1	6.2 to 102.0	Continuous movement, rate of displacement unchanged.
	P_2		
	P_3		
	P_4		Continued decelerated rate of movement until May 2016, followed by a quick acceleration, then deceleration at the end of Q8.
B	P_5	≤30.7	Continued trend of movement from Q7 until the end of May 2016, followed by a deceleration until the end of Q8. Measurements in area are subject to errors due to snow cover in late spring.
C	P_6	≤44.5	Small acceleration from early March 2016 until the end of April, followed by trend stabilization. Measurements in area are subject to errors due to snow cover in late spring.
	P_7		
D	P_8	-	Debris zone exhibited a stabilized trend with small fluctuations until the end of Q8. Measurements in area are subject to errors due to snow cover.
E	P_9	≥32.4	Exhibited a stabilized trend with small fluctuations until the end of Q8.
	P_10	-	Rate of displacement unchanged displaying stable behaviour until the end of Q8.
F	P_11	-	Data is omitted due to errors introduced by snow cover.
G	P_12	-	Rate of displacement stabilized from Q7.

Generalized displacement in Q8 for all seven regions was slightly larger than that measured in Q7, which is expected during the spring. Measured displacements at some POIs were subject to errors due to snow cover and atmospheric moisture, such as heavy rainfall or fog. The Q8 report marks the end of two years since installation in 2014.

The Q8 summary report from Ellegi noted that the system was operational from the installation date in June 2014, with minimal interruptions.

Table 5. LiSAmobile generalized displacement in regions of interest for the period from June 20, 2014, to September 20, 2016 (822 days).

Region	Location Description	Displacement (mm)	Approximate Region Area (m^2)
A	Close to North Peak	2.0 to 122.0	4600
B	Between North and South Peak	≤31.4	600
C	Close to South Peak	≤49.5	1200
D	Debris area toe of South Peak rock wall	-	-
E	Debris area toe of North Peak rock wall	>35.0	-
F	Mid to lower vegetative rock wall	-	-
G	Debris zone run out area	22.3 to 24.4	-

Table 6. LiSAmobile measured displacement at points of interest (POI) for the period from June 20, 2014, to September 20, 2016 (822 days) with observations specific to Q9.

Region	Point of Interest (POI)	Displacement (mm)	Displacement Descriptions Specific to Q9
A	P_1	2.0 to 122.0	Continuous movement, rate of displacement unchanged.
	P_2		
	P_3		
	P_4		Increased acceleration observed throughout Q9, similar to August 2014 and May 2015. At the end of Q9, a significant acceleration in this region is noted.
B	P_5	≤31.8	No significant movement in Q9.
C	P_6	≤49.5	Continuous movement from June until the end of Q9, with a small acceleration, noted in early July in region C.
	P_7		
D	P_8	-	Debris zone exhibited a stabilized trend with small fluctuations until the end of Q9, similar to Q8.
E	P_9	-	Small fluctuations are noted in Q9, similar to Q8 in region E. Small positive displacements are observed at the end of August in region E.
	P_10		
F	P_11	-	Data is omitted due to errors introduced by vegetation in the LOS.
G	P_12	-	Movement trend is stabilized and maintained in Q9, similar to Q8.

Generalized displacement in Q9 for all seven regions accelerated minimally, similar to Q8 and otherwise generally showed stable (unchanged) rates of displacement during summer 2016. The exception to this statement is P_4 which observed rapid acceleration from the end of Q8 to early June; followed by continuous acceleration until the end of Q9. The Q9 summary report from Ellegi noted that the system was operational from the installation date in June 2014, with minimal interruptions.

An analysis from Q1 to Q5 identified an area with a very slow rate of displacement near region C, between South and Third Peak. Ellegi was able to evaluate the displacement rates within the region, identifying small-scale movements over a larger area. In 2015, Ellegi measured this area to have a surface area of 45 000 m² and measured a displacement value of 2.4 mm over 457 days.

A similar study was conducted in 2016, with a total period of 365 days from September 20, 2015, to September 20, 2016. In comparison with the analysis in 2015, it appears the area observed in 2015 has divided into two separate moving blocks. Each block displayed displacements of about 4 mm over the entire period (Figure 8). Ellegi states results are influenced by the size of the area chosen (large vs. small) and whether pixel values are precisely measured or averaged; and therefore are extremely subjective.

This study confirms our belief that overall large block movements are extremely small. This provides assurance that the LiSAmobile system has the capability to identify and record data points for both large block movement and smaller natural rockfalls. Ellegi will complete another investigative study on this area after collecting and compiling data for another year. This data will be compared to that of the previous year to monitor and investigate large block movements.

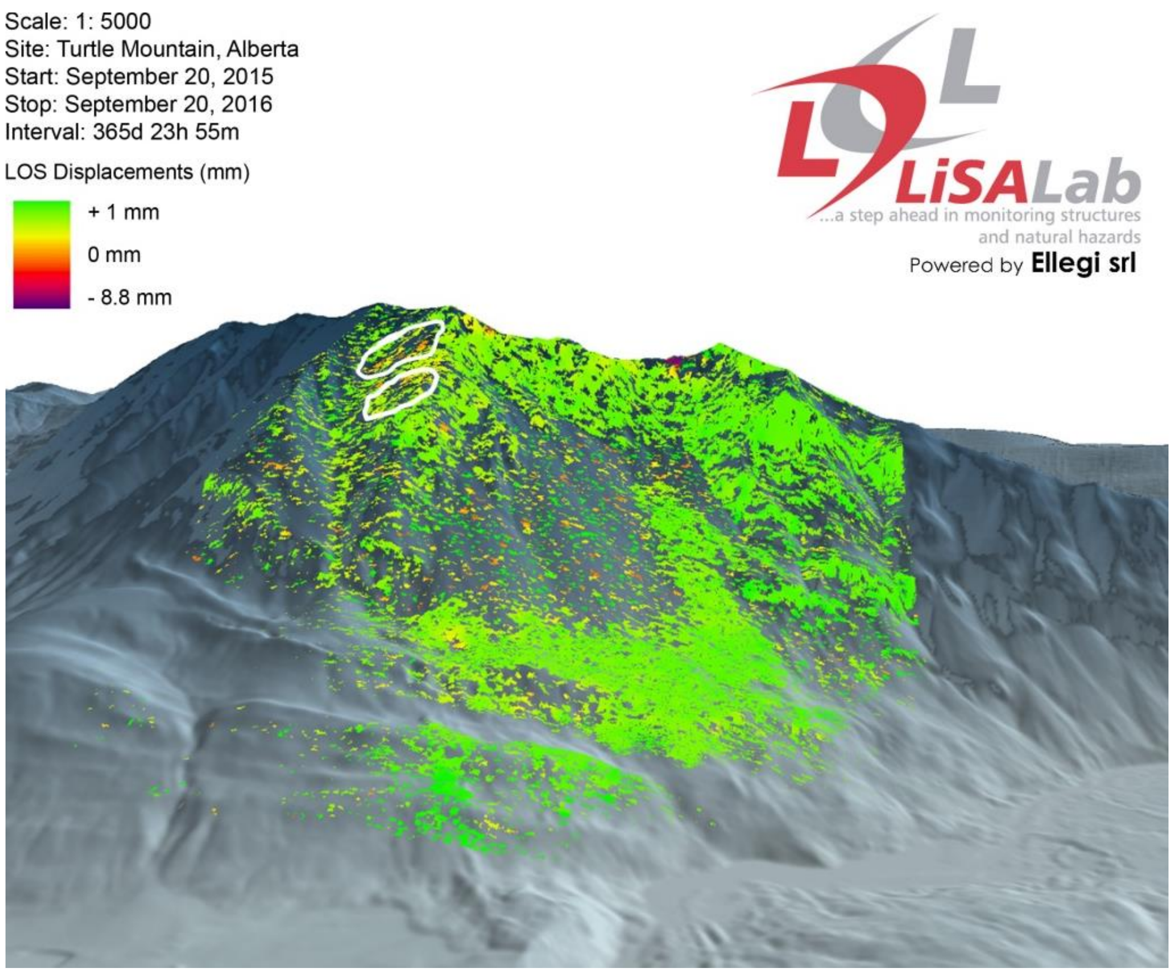

Figure 8. Annual analysis of large block movements near region C, from September 20, 2015, to September 20, 2016 (365 days).

Table 7. LiSAmobile generalized displacement in regions of interest for the period from June 20, 2014, to December 20, 2016 (913 days).

Region	Location Description	Displacement (mm)	Approximate Region Area (m^2)
A	Close to North Peak	4.0 to 160.0	4600
B	Between North and South Peak	≤21.4	600
C	Close to South Peak	≤46.6	1200
D	Debris area toe of South Peak rock wall	-	-
E	Debris area toe of North Peak rock wall	>38.0	-
F	Mid to lower vegetative rock wall	-	-
G	Debris zone run out area	24.4 to 25.6	-

Table 8. LiSAmobile measured displacement for the period from June 20, 2014, to December 20, 2016 (913 days) with observations specific to Q10.

Region	Point of Interest (POI)	Displacement (mm)	Displacement Descriptions Specific to Q10
A	P_1	4.0 to 160.0	Increased acceleration observed until late November 2016, followed by deceleration until the end of Q10. Acceleration to the entire region (not just P_4) was observed.
	P_2		
	P_3		
	P_4		Movement trend continued from Q9 until mid-November 2016, after which the rate of displacement is significantly slowed and remains unchanged until the end of Q10.
B	P_5	≤21.4	Rate of displacement fluctuates throughout Q10. Results are affected by persistent snow cover observed in Q10.
C	P_6	≤46.6	A small acceleration observed in late October at P_7. Persistent snow cover is observed in Q10.
	P_7		
D	P_8	-	Debris zone exhibited a stabilized trend with small fluctuations until the end of Q10.
E	P_9	-	Small fluctuations observed throughout Q10, similar to Q8 and Q9.
	P_10		Rate of displacement unchanged displaying stable behaviour until the end of Q10, when a small positive displacement is observed similar to Q9. Persistent snow cover and accumulation is observed in December 2016.
F	P_11	-	POI data is omitted due to errors introduced by snowfall.
G	P_12	-	Rate of displacement is unchanged, similar to Q9 with small fluctuations.

Generalized displacement in Q10 for all seven regions accelerated minimally from Q9, with the exception of region A; P_1 to P_4. Ellegi noted that displacement at these POIs had increased compared to the previous reports and followed the same trend until mid-November until stabilizing likely due to the winter months. Ellegi states in Q10 that P_1 to P_4 are individual points selected during the initial preliminary testing in 2014 and therefore can be representative of an area displaying greater movements. Measured displacements at some POIs were subject to errors due to atmospheric moisture, such as heavy rainfall, fog, and accumulating snow cover. The Q10 summary report from Ellegi noted that the system was operational from the installation date in June 2014, with minimal interruptions.

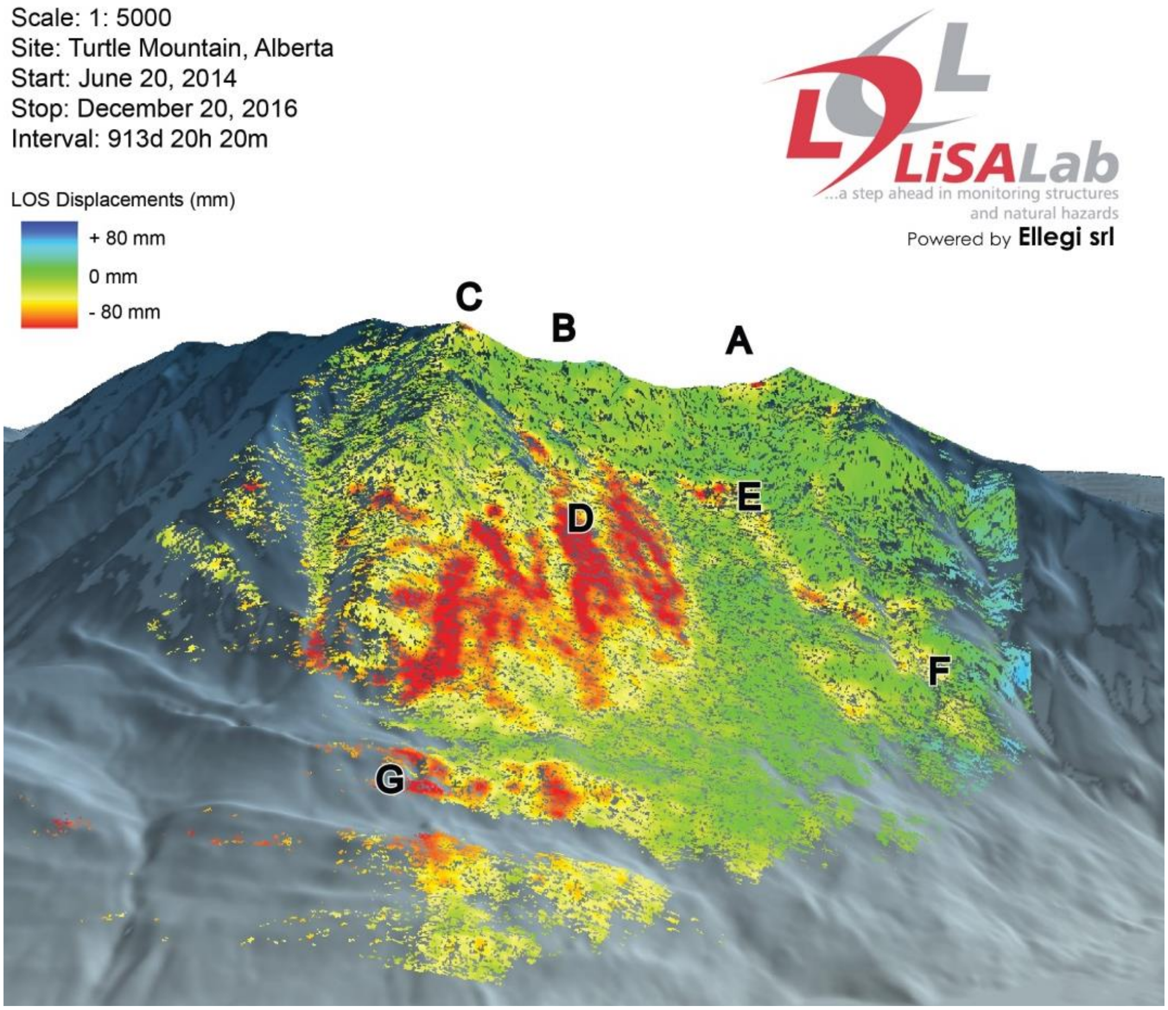

Figure 9. Line of sight 3D displacement map of Turtle Mountain measured from June 20, 2014, through December 20, 2016 (913 days).

4 Supporting Studies and Research

Throughout 2016, AGS completed three secondary monitoring campaigns. The AGS selects secondary campaigns based on monitoring frequency and additional monitoring predetermined on an annual basis. During 2016, AGS preselected photogrammetry, LiDAR, and RADARSAT-2 campaigns to be run throughout the year.

4.1 Photogrammetry

Photogrammetric monitoring is a process of determining relative deformation of the mountainside by analyzing the locations of targets. Targets are made of thin aluminum sheets, which are cut into circles with a diameter of 10”. The inner circle, with a diameter of 4” is painted white, while the rest of the target is painted black. The contrast in colour makes it easier for an airplane to find, focus, and take a precise three-dimensional measurement of the targets.

Once measured, data points are analyzed and compared to the data from previous fly-overs. Any changes in the data represent a relative displacement of the target, which suggests a potential movement of the area. However due to potential uncertainty in the data caused by the environment and/or inconsistencies of the images taken as well as a sparse collection of the data, this method of analysis is used as a secondary monitoring method, rather than a primary monitoring system on Turtle Mountain.

To improve the results from the photogrammetric monitoring, during the summer of 2016, a group of AGS employees updated the locations of the targets on the mountain. Several pre-made targets were designed before the trip, in the event of discovery of broken or missing targets. Standard matte finish paint was used, to minimize the reflection from the surrounding environment and make it more visible for the camera. These replacement targets were made to match the ones on the mountain, except they were made out of plywood instead of aluminum to eliminate unnecessary costs, without reducing the accuracy of the process at the recommendation of the company providing the imagery services. With continuously changing technology and methods, the photogrammetric targets may become obsolete before the next photogrammetry monitoring campaign.

Once on the mountain, AGS staff located and took GPS coordinates of the targets using the Leica Viva GS14 survey equipment that was rented in Edmonton. The coordinates of each target were stored on a memory card and later processed in Edmonton. No targets were replaced due to time constraints because of extreme weather and the overall excellent condition of the found targets.

With more accurate coordinates and based upon experience from previous measurements, a new flight plan was chosen and flown in August 2016. In total, nineteen targets were used during this measurement, and the results were organized into the data groups (i.e., epochs). The results of Epoch 5 were compared with the previous ones.

A total of ten points were found to be stable while the remaining ones had minor deformations. Six of the previously measured targets were not included in Epoch 5 since they were not visible in the imagery due to possible vegetation growth, faded targets, or new camera technologies.

A report by M.E. Chapman detailing the methods used, a full analysis of this data, and suggestions for future research, can be found in Appendix 1.

4.2 LiDAR

A LiDAR DEM was acquired from Orthoshop Geomatics Engineering as part of the photogrammetry survey. This LiDAR campaign was pre-selected as part of the secondary monitoring for 2016. The imagery is a bare-earth DEM where vegetation on the surface is removed to expose the rocky surface below (Figure 10).

The extent of the LiDAR coverage includes Third and South Peaks, the upper part of the anticline hinge, and elevation ranges between 1715 and 2206 m asl (above sea level). This dataset was captured on August 13, 2016, with

- an average flying height of 600 m agl (above ground level),
- a camera's focal length at 83 mm,
- a point density of approximately 50 points/m^2, and
- a pixel size of 4 cm.

The LiDAR DEM has horizontal and vertical accuracies of 0.20 m and 0.15 m, respectively, at a 95% confidence interval.

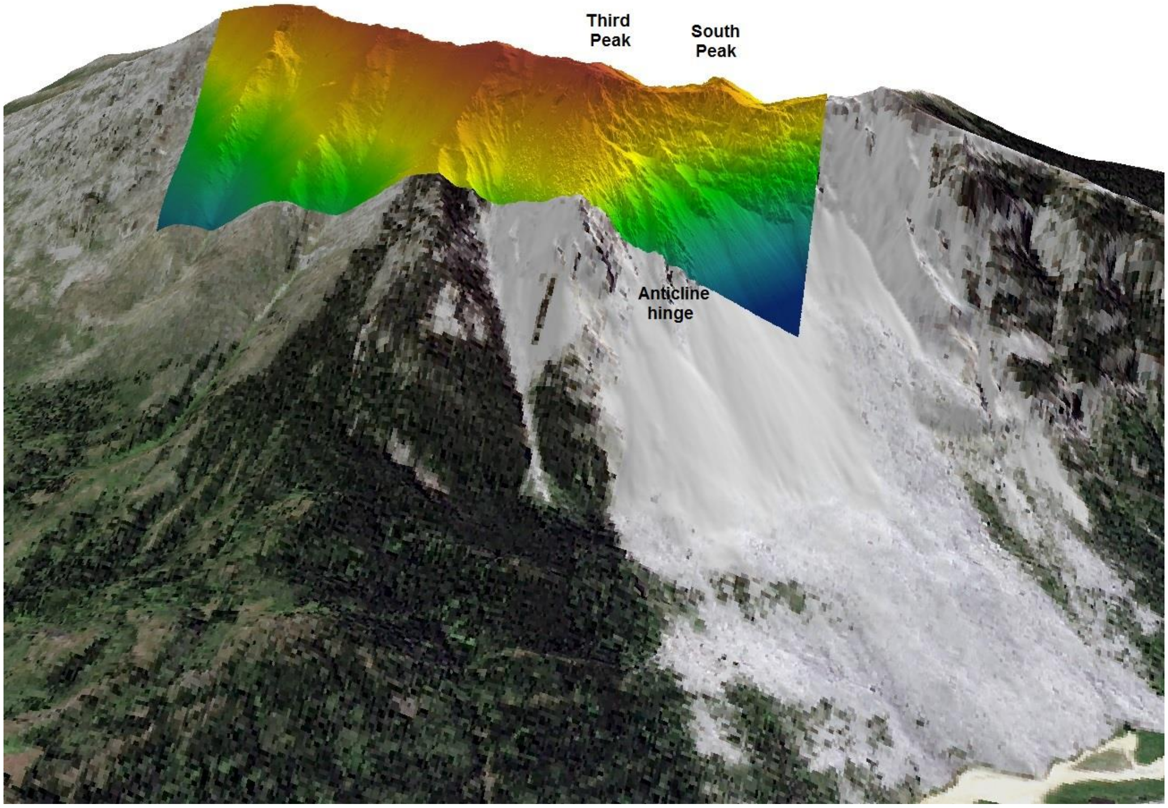

Figure 10. LiDAR DEM obtained in 2016 draped over Turtle Mountain.

4.3 RADARSAT-2

As a secondary monitoring campaign, SAR images were collected and analyzed in 2016. Thirteen high-resolution spotlight RADARSAT-2 synthetic aperture radar (SAR) images were collected between June 26, 2015, and October 18, 2016. The spotlight mode of RADARSAT-2 has the highest pixel resolution of 1 m x 3 m. To achieve stable coherence, each SAR image pre-processed with 4x8 multi-look averaging, which renders an effective resolution of 8 m x 12 m.

The SAR interferograms are processed using GAMMA InSAR processing suites. The stacked deformation over time and linear deformation rate are subsequently computed using a linear least square inversion technique (Samsonov et al., 2011). Figure 11 shows the observed surface deformation relative to the LiDAR DEM for 2015 and 2016. Through the InSAR, we do not observe any anomalous deformation of more than half a centimetre between each year. The computed linear deformation rate (Figure 12) shows a very slow deformation rate with the maximum rate observed on the front side of Turtle Mountain at less than ~0.3 cm/year. Due to the look angle of the satellite, InSAR does not provide the deformation information for the back of the mountain.

These SAR image results agree with the displacement results measured by the ground-based InSAR, LiSAmobile, and show very slow deformation rates in 2016.

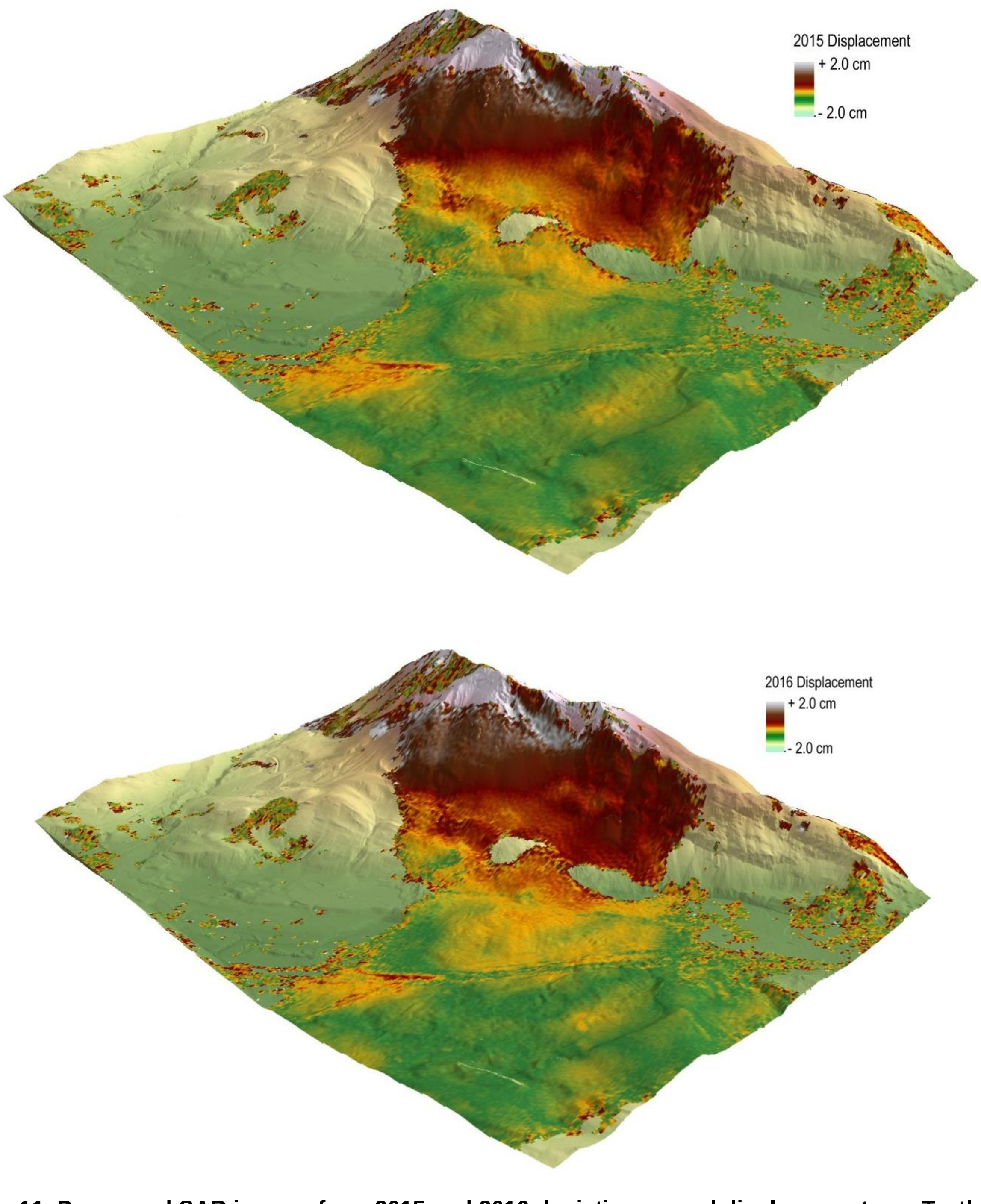

Figure 11. Processed SAR images from 2015 and 2016 depicting annual displacements on Turtle Mountain.

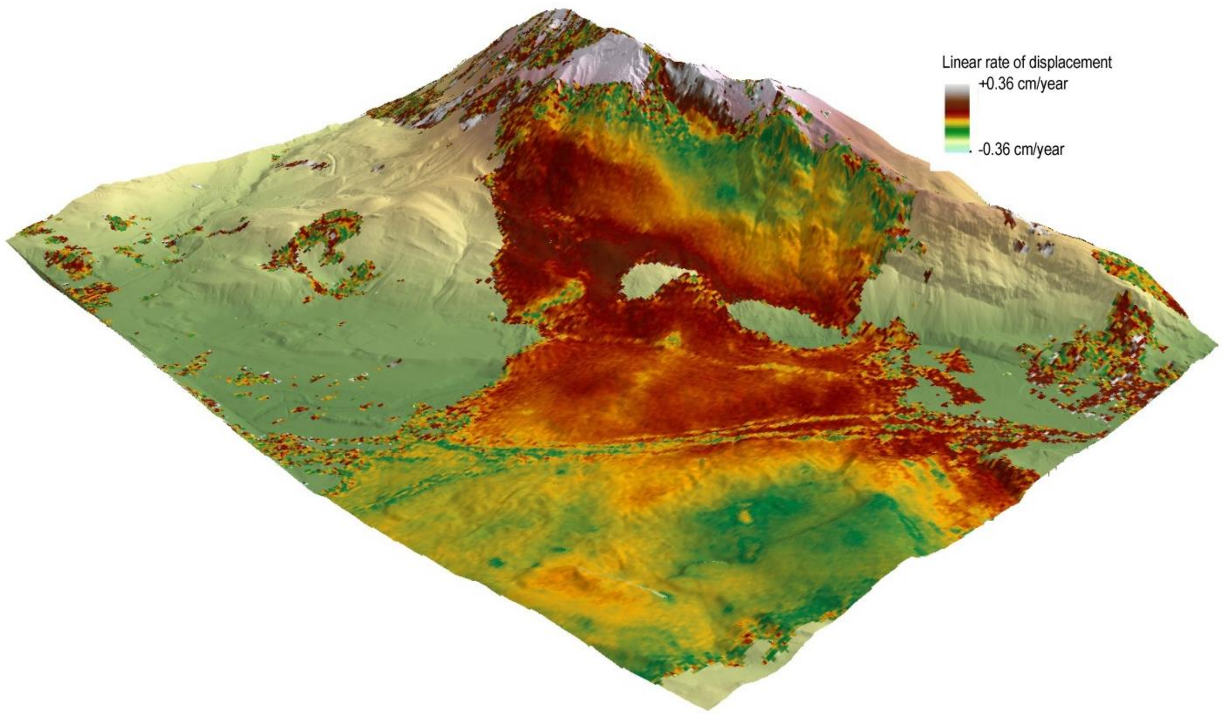

Figure 12. Linear deformation rate calculated for Turtle Mountain.

5 Turtle Mountain Monitoring Program Transition

In 2015, the TMMP began the transition to a near-real-time remote monitoring system, as recommended by the 2014 expert panel report (see Wood et al., 2016 and 2017a, for additional details). This transition includes

- lowering the current level of response readiness (i.e., 24/7 continual on-call status) as it is not warranted by the hazard as observed and evaluated throughout the last decade of monitoring,
- making the GB-InSAR the primary monitoring sensor, and
- removing some of the evaluated non-operational equipment that is not considered vital to the long-term monitoring.

In July 2015, a letter of support was obtained and signed by the Municipality of Crowsnest Pass (MCNP) council members to formally support this transition. In January 2016, the AGS approached the Alberta Emergency Management Agency (AEMA) requesting a review of our proposed transition. If the AEMA agreed with this change, the AGS asked for a similar letter seeking support for this transition. In late February, the AGS received correspondence from the AEMA endorsing the transition, removal of non-operational monitoring equipment, and the termination of the early-warning system. This final endorsement allowed the AGS to move forward to continue to collaborate with the AEMA and MCNP throughout 2016 to ensure changes made to the program are reflected in the *AER/AGS Roles and Responsibilities Manual for the Turtle Mountain Monitoring Program* (Wood et al., 2017b).

The purpose of this manual is to provide information about the AGS's ownership of the TMMS and the specific roles and responsibilities of AGS/AER staff during normal operations, for long-term monitoring. All internal roles and responsibilities pertaining to the TMMS are also referenced to the same four-stage alert system to maintain consistency for all parties involved. This alert system was reviewed and presented to external agencies' emergency response groups (ERGs) for evaluation. Feedback from the ERGs is reflected in Wood et al. (2017b).

During Spring 2016, all non-operational equipment previously identified in prior Turtle Mountain reports (Wood et al., 2016 and 2017a) were reviewed internally and evaluated. A list was compiled of all non-operational equipment to be inspected during the field season planned for Summer 2016.

In June 2016, a team surveyed all the equipment located on South Peak installed by the AGS over the previous decade. Each piece of equipment was inventoried with a note whether it will be decommissioned or remain on the mountain. Equipment remaining on the mountain would commemorate the historical examples of monitoring provided by the AGS. This equipment would join the historical exhibition of monitoring including Dr. John Allan’s markings from the 1930s (Allan, 1931), geophones, and Moiré crackmeters from the 1980s, as an example. This equipment is intended to be left as educational material for the public on South Peak.

For each station with equipment identified to be decommissioned in 2017 coordinates were taken. Photographs of the stations were collected to allow the team to plan the logistics of the upcoming fieldwork. The AGS proposed to decommission approximately 70% of the equipment located on the mountain installed only by AGS. Equipment installed by other agencies or universities was inventoried and will not be included in the decommissioning plan.

The AGS plans to collaborate with the Frank Slide Interpretive Centre (FSIC) in 2017 to produce a series of historical, informative signs to educate the public on previous monitoring equipment located on South Peak. These signs are proposed to follow a storyline from the historic landslide to historical monitoring equipment and finally current modern monitoring practices on Turtle Mountain. In addition, approximate locations for the installation of these future historical signs were discussed with the FSIC staff during a site visit in June 2016.

The TMMP transition procedures were completed in 2016, with all changes outlined in the *AER/AGS Roles and Responsibilities Manual for the Turtle Mountain Monitoring Program, Alberta* (Wood et al., 2017b). The decision to officially transition to a near-real-time remote monitoring system took effect on July 20, 2016, with approval from AER’s executive leadership team. This decision is based on collaborative work starting in 2015, with the endorsement and assistance of the AEMA and MCNP. For more information on the specific roles and duties of the AER/AGS and outside agencies, the reader is referred to Wood et al. (2017b).

Based on a review of the sensor thresholds, a system of four alert levels (green, yellow, orange, and red) was developed by AMEC (2005) and subsequently incorporated into the AEMA’s emergency response protocol for Turtle Mountain. This protocol establishes that the AER, through the AGS, is responsible for determining the appropriate alert level for a potential emergency at Turtle Mountain. The AER/AGS developed its own internal emergency response protocol which was updated in 2016. The emergency response protocol is revised as often as is required to ensure that it is current version reflects best practice and is fit for its purpose. As a minimum, one review is done every year. The AGS reviewed this document based on AGS’s evaluation and recommendations from the expert panel review. The AGS received input from the AEMA, MCNP, and other outside agencies. An update of this plan will reflect changes as a result of the transition to a near-real-time remote monitoring system.

6 Conclusions

Recent application of modern characterization, monitoring, and modelling technologies has greatly increased our understanding of the existing rock-slope hazard at Turtle Mountain. The rate of displacement is low and has remained essentially constant over the last decade of monitoring.

The AGS will continue to work with Ellegi for maintenance and upgrades to LiSAmobile. The contract with Ellegi was reviewed at the end of 2016 and will be renewed during the next fiscal year. The AGS will complete an internal review of the monitoring equipment at the end of 2016 and will assess the inventory of equipment for decommissioning in 2017. This assessment will help AGS plan for the 2017 field season. The AGS will continue to investigate different forms of monitoring systems.

Communication of the risks associated with these hazards to the affected population is also ongoing. We publish the most recent results annually (Moreno and Froese, 2006, 2008a, 2008b, 2009, 2011, 2012; Moreno et al., 2013; Warren et al., 2014, 2016; Wood et al., 2016 and 2017a) and present them in public meetings. AGS continues to collaborate with the MCNP council members and staff to provide information on the TMMP. Updates are also available on the "Turtle Mountain Monitoring Program" page of the Alberta Geological Survey website (http://ags.aer.ca/turtle-mountain-monitoring-program.htm).

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Appendix 1 – Photogrammetric Deformation Monitoring of Turtle Mountain, Alberta - Consultant Report

Photogrammetric Deformation Monitoring of Turtle Mountain, Alberta

by

Michael A. Chapman, Ph.D., P. Eng.
Independent Consultant Report

March 2017

1. PHOTOGRAMMETRIC DEFORMATION MONITORING

1.1 Imagery

As a requirement of the high accuracy nature of this deformation monitoring project, stringent guidelines were put in place to ensure precise three dimensional coordinate determinations of existing targets on the top of Turtle Mountain. It was not possible to use the same aerial camera since the previously used film-based cameras had been retired and a new high resolution digital camera was selected for the image acquisition. The digital camera had a nominal focal length of 53 mm compared to the focal length of the previously used film-based camera which was 152 mm. The digital camera has a pixel size of 5.2 µm by 5.2 µm, a 53.7° field of view and employs a RGB charge coupled device (CCD) array sensor with dimensions 10320 by 7788 pixels (active). The previously used film-based camera with a had a field of view of 74.2°. The film camera had a nominal image format of 230 mm by 230 mm.

Based upon the experiences of Epochs 1, 2, 3 and 4, a flight plan was chosen with multiple lines comprised of multiple exposures/images and was flown in August 2016. The specification for image overlap (longitudinal/forward overlap and lateral/sidelap) should yield an average of nine (9) images for each target. The actual flight recorded 255 images along seven (7) lines with an average of 36 exposures per flight line (see Figure 1).

An average photo scale of 1:4 200 was achieved for Epoch 5 which is a smaller scale than the photo scales used in Epoch 1, 2, 3 and 4. A comparison of the five epochs of photography and their statistical results can be seen in Table 1.

1.2 Object Point Targets

A total of 19 photogrammetric targets were visible on the photography of Epoch 5. Six of the previously used targets (i.e., 4, 12, 14, 17, 101 and 181) were not measured since they were not visible in the imagery. However, they would have assisted in the photogrammetric adjustment and should be visited and replaced for future measuring epochs. Point number 131 was weighted lower in the photogrammetric adjustment due to the uncertainty of its actual location on the ground. With the absence of these six points, Epoch 5 had 19 points in common with Epoch 1, 3 and 4. Unfortunately, only 18 images (in three central lines) of the 255 exposures available were used since a sufficient number of targets (four or more) were available only on these selected images over the targeted field (see Figure 1). In fact, each target was measured on average 6 times which was considerably less than previous epochs. This reduction in images of targets was primarily due to the flown image overlap (i.e., longitudinal and lateral). In Figure 1, the points in light orange (18) represent the exposure/images used in photogrammetric adjustment. The points in dark orange (19) represent the used target points and the points in blue (237 total) are the unused exposures/images. The axes are in metres and express local coordinates.

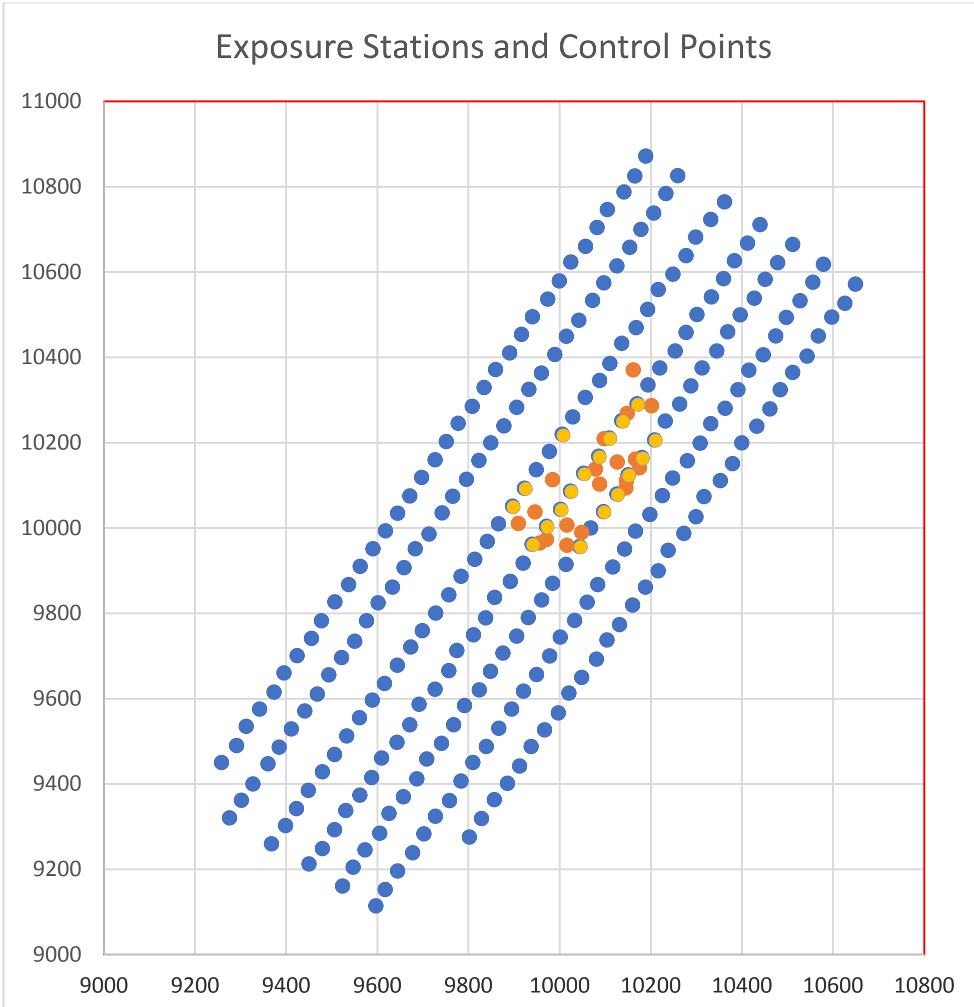

Figure 1: All Exposure Stations, Selected Exposure Stations and Control Points

The photogrammetrically determined ground coordinates (X, Y and Z) for these targets as obtained from the adjustment of Epoch 1, Epoch 3, Epoch 4 and Epoch 5 image data and are given in Tables 2, 3, 4 and 5, respectively.

1.3 Photogrammetric Point Measurement

An important contributor to the accuracy of deformation monitoring is the quality of the image coordinate measurements. Several factors influence the quality of image coordinates:

1. measuring device
2. film deformation (not present in digital cameras)
3. lens distortion
4. atmospheric refraction

The digital images used for Epoch 5 were measured on a softcopy workstation located at The Orthoshop, Calgary. As in the cases of Epochs 1, 2, 3 and 4, precise image measurements were made at each point. The lens distortion characteristics of the new digital camera were such that a maximum of 0 µm of radial distortion was present. This distortion-free characteristic of the lens was reported in the camera calibration report from the manufacturer (see Appendix A) and was clearly evident during the photogrammetric adjustment process. Errors due to atmospheric refractions were deemed negligible for this low flying height and were not corrected.

The photogrammetric residuals of the image coordinates indicate that the 19 targets that were measured had errors that were within acceptable tolerances and are compatible with the results of the previous epochs. However, it is strongly recommended that the next set of photography be taken with greater overlap (longitudinal and lateral) and during the summer season to prevent the presence of long shadows as was the case previous epochs of photography.

Table 1. Summary of Photogrammetric Free-Network Adjustment Results for Epoch 1, 2, 3 and 4.

	Epoch 1	Epoch 2	Epoch 3	Epoch 4	Epoch 5
Average Image Scale	1:2,300	1:2,680	1:2,500	1:2,200	1:4,200
Number of Photographs	11	15	16	18	18
Number of target points	20	19	22	21	19
Average number of images per point	9	12	11	10	6
RMS value $s_{x,y}$ of image coordinate residuals	± 2.2 µm	± 2.1 µm	± 2.2 µm	± 2.2 µm	± 1.2 µm
Mean standard errors: σ_c	± 4.1 mm	± 3.9 mm	± 3.9	± 4.0	± 5.0
$\sigma_{x,y}$	± 2.9 mm	± 2.7 mm	± 2.3	± 2.6	± 3.5
σ_z	± 5.8 mm	± 5.6 mm	± 5.9	± 5.8	± 5.5
Square root of the ratio of the Largest over small eigenvalue of $\underline{C}\, x^2$	8.7	9.1	8.8	8.9	2.0
Statistical degrees of freedom	223	312	342	360	211

1.4 Photogrammetric Adjustment

A free-network bundle adjustment was used to process the photogrammetric data of Epoch 5. This technique employs the method of inner constraints as was also used to adjust the data of Epochs 1, 2, 3, and 4. Table 1 summarizes the results of all five photogrammetric adjustments. The consistency of the five sets of results can be explained in terms of the similarity of the design of the data groups (i.e., epochs). Slight differences can be attributed to variation in the photo scale, the number of photographs and the number of images per object point. The reduced redundancy indicated by the statistical degrees of freedom (see Table 1) of Epoch 5 is mainly due to the lower number of images per target point. Epochs 1, 2, 3 and 4 had average of 9, 12, 11 and 10 images per target, respectively. Epoch 5 had an average 6 images per target point. Point 8 had 2 images, Points 6 and 15 had only 4 images each, Points 11, 97 and 98 had 5 images each, Points 1, 9, 13, 19, 22, 24, 25 and 131 had 6 images each, Points 10, 16, 18 and 20 had 7 images each while Point 21 had images.

1.5 Deformation Analysis

The primary objective of this investigation is the detection and subsequent localization of any deformations which might be revealed by the object point control field. Based upon the object point coordinates established using Epoch 1 data, the results obtained from Epoch 2, 3, 4 and 5 data can be compared in a relative manner. This comparison can be sequential or global in nature. A sequential approach compares successive epochs while a global comparison uses the first epoch as a basis for comparison. The results of both these methodologies are discussed in this report.

1.5.1 Congruency Testing

As stated in Fraser (1983) the congruency test examines the null hypothesis that the object point network is stable between successive epochs. The quadratic form of the deformations in conjunction with the a posteriori variance factor is tested using a standard F test. Five separate congruency tests were performed using the results of Epoch 1 versus Epoch 3, Epoch 2 versus Epoch 3, Epoch 1 versus Epoch 4, Epoch 1 versus Epoch 5 and Epoch 4 versus Epoch 5, The results of these tests shown in Tables 4, 5, 6 7, 8 and 9, respectively. Vector d indicates the spatial magnitude of deformations given by the three coordinate differences. It is important to note, however, that this vector must be used along with the variance-covariance matrix of the coordinate differences to identify possibly deformations.

When applying the congruency test at the 95% significance level it was found that all but two points (i.e., Points 20 and 131) passed when comparing Epoch 1 and Epoch 5. This would suggest that there are potential movements occurring at these two points. The magnitude of the movement associated with Point 131 is 39.3 cm. This apparently significant movement warrants further investigation. However, when viewed on the images, Point 131 was partially obscured by vegetation and it possible that this point was moved by some one or by the wind for example. Point 20 exhibited a movement (6.3 cm) when comparing Epoch 1 and Epoch 5. This point ws physically moved by 6.2 cm between Epoch 1 and Epoch 4 No significant movement was seen when comparing Epoch 4 and Epoch 5.

Table 2. Adjusted X, Y and Z Co-ordinates of the 20 Photogrammetric Target Points at Epoch 1 with their Standard Errors.

Point Number	X(m)	Y(m)	Z(m)	(mm)	(mm)	(mm)
1	10016.674	10006.200	2204.127	2	3	5
4	10195.978	10243.798	2153.191	2	2	4
6	10201.773	10286.164	2129.265	2	2	5
8	10162.152	10370.385	2104.589	2	4	5
9	10148.800	10268.684	2132.489	2	2	4
10	10097.946	10209.111	2163.681	2	2	4
11	9984.492	10112.868	2143.837	3	3	7
12	10040578	10210.573	2125.842	2	2	5
13	10079.280	10138.006	2167.485	2	2	5
16	10147.228	10111.499	2179.751	2	2	4
17	10178.166	10128.012	2185.017	2	2	4
18	10166.891	10161.266	2198.923	2	3	3
19	10174.923	10141.120	2195.725	2	2	4
20	10126.477	10154.491	2186.368	2	2	4
21	10088.142	10102.707	2190.093	2	2	5
22	9945.846	10037.151	2171.486	4	2	6
24	10145.691	10093.396	2168.053	3	2	6
25	10048.690	9989.617	2182.681	2	3	6
101	10016.898	10006.916	2203.758	3	4	8
181	10169.198	10157.598	2199.370	2	3	4
14	Not found	-	-	-	-	-
15, 97, 98, 131	New point in Epoch 3	-	-	-	-	-

Table 3. Adjusted X, Y and Z Co-ordinates of the 22 Photogrammetric Target Points at Epoch 3, with their Standard Errors.

Point Number	X(m)	Y(m)	Z(m)	(mm)	(mm)	(mm)
1	10016.665	10006.200	2204.182	2	2	5
4	10195.981	10243.814	2153.173	2	2	5
6	10201.774	10286.169	2129.269	2	2	6
8	10162.154	10370.370	2104.589	2	4	7
9	10148.806	10268.681	2132.486	2	2	7
10	10097.948	10209.107	2163.683	2	2	5
11	9984.511	10112.830	2143.899	2	2	5
12	10040.592	10210.547	2125.866	2	2	5
13	10079.283	10138.005	2167.489	2	2	5
14	10145.695	10093.383	2168.058	2	2	5
17	10178.166	10128.023	2185.008	2	2	5
18	10166.885	10161.290	2198.904	2	3	5
19	10174.917	10141.137	2195.720	2	2	5
20	10126.423	10154.524	2186.352	2	2	5
21	10088.132	10102.697	2190.093	2	2	5
22	9945.839	10037.128	2171.528	3	2	5
25	10048.690	9989.608	2182.748	2	2	6
181	10169.188	10157.613	2199.341	2	3	5
15*	9909.656	10010.043	2148.453	4	3	8
97*	9956.413	9964.793	2186.677	3	3	8
98*	9971.483	9973.037	2196.423	3	3	7
131*	10016.267	9959.643	2177.758	2	3	7
16,24, 101	Not found	-	-	-	-	-

*new point

Table 4. Adjusted X, Y and Z Co-ordinates of the 21 Photogrammetric Target Points at Epoch 4 with their Standard Errors.

Point Number	X(m)	Y(m)	Z(m)	(mm)	(mm)	(mm)
1	10016.659	10006.186	2204.148	2	2	5
4	10195.976	10243.824	2153.180	2	2	5
6	10201.770	10286.153	2129.298	2	2	6
8	10162.161	10370.341	2104.564	2	4	7
9	10148.803	10268.682	2132.484	2	2	7
10	10097.959	10209.115	2163.683	2	2	5
11	9984.503	10112.881	2143.858	2	2	5
12	10040.582	10210.584	2125.856	2	2	5
13	10079.288	10138.021	2167.499	2	2	5
17	10178.164	10128.013	2185.017	2	2	5
18	10166.901	10161.299	2198.922	2	3	5
19	10174.924	10141.130	2195.734	2	2	5
20	10126.431	10154.513	2186.347	2	2	5
21	10088.138	10102.720	2190.102	2	2	5
22	9945.831	10037.128	2171.520	3	2	5
25	10048.694	9989.609	2182.733	2	2	6
98	9971.476	9973.019	2196.351	3	3	7
131	10016.281	9959.645	2177.712	2	3	7
181	10169.222	10157.578	2199.334	2	3	5
16	10147.224	10111.490	2179.720	2	3	5
24	10145.690	10093.393	2168.071	2	3	6
14, 15, 97, 101	Not found	-	-	-	-	-

Table 5. Adjusted X, Y and Z Co-ordinates of the 19 Photogrammetric Target Points at Epoch 5 with their Standard Errors.

Point Number	X(m)	Y(m)	Z(m)	(mm)	(mm)	(mm)	No. of Images
1	10016.677	10006.210	2204.129	3.4	3.6	4.8	6
6	10201.770	10286.160	2129.263	4.0	4.2	5.0	4
8	10162.155	10370.390	2104.589	4.6	4.8	5.0	2
9	10148.802	10268.690	2132.490	3.5	3.7	4.9	6
10	10097.951	10209.110	2163.683	2.9	3.0	4.8	8
11	9984.500	10112.860	2143.838	4.2	3.9	5.0	6
13	10079.277	10138.020	2167.483	2.8	2.7	4.7	7
15	9909.656	10010.040	2148.453	4.4	4.1	5.0	4
16	10147.226	10111.490	2179.742	2.7	2.7	4.7	7
18	10166.907	10161.280	2198.922	2.9	2.9	4.7	7
19	10174.920	10141.120	2195.731	2.9	2.8	4.7	6
20	10126.437	10154.510	2186.368	2.6	2.5	4.6	7
21	10088.146	10102.710	2190.095	3.2	3.1	4.7	7
22	9945.849	10037.150	2171.487	3.2	3.1	4.9	6
24	10145.697	10093.390	2168.055	3.0	3.2	4.8	6
25	10048.689	9989.605	2182.681	3.6	3.6	4.9	6
97	9956.412	9964.792	2186.678	3.5	3.4	4.8	5
98	9971.483	9973.040	2196.420	3.5	3.4	4.8	5
131	10016.254	9959.641	2177.707	3.9	4.7	17.7	6
4, 12, 14, 17, 101, 181	Not found	-	-	-	-	-	-

1.5.2 Localization of Deformations

After determining that significant deformations occurred between the four epochs, the process of localizing the point movements follows. Point movements can be singular in nature or they may occur in groups. The latter is usually identified by the method of strain analysis where point groups of homogeneous strain are isolated.

A sophisticated procedure for localizing point deformations was established at the Technical Institute of Stuttgart by Dr. Lothar Gruendig. This method is described in Fraser (1983) and Fraser and Gruendig (1984). Using a software package incorporating this methodology, the four epochs of data were examined. The first combination comprising differences between Epoch 1 and Epoch 2 was evaluated by Fraser (1983). A summary of the results of the deformation localization for this pair of epochs is given in Table 4. It was found that 11 points had significant deformations with three of these only having marginally significant deformations. The subsequent application of a t-test showed that the deformations of two of these three marginal points were not significant. Consequently a total of ten points were found to be stable. Of the unstable points, one point in particular, Point 20, was identified as having the most significant deformation present. It was subsequently revealed that this pint had been physically moved by 6.2 cm. The localization process impressively revealed a deformation at point 20 of 6.3 cm in approximately the same direction. When comparing the data from Epoch 1 and Epoch 4 a similar deformation was localized at Point 20. In this instance a deformation at 6.6 cm was detected in the same general direction. Deformations between Epoch 2 and Epoch 3 did not reveal the same shift for Point 20 since the target had not been intentionally moved between these two epochs.

Table 5. Summary of Deformation Analysis Results for Epoch 2 Versus Epoch 1. Point Movement Magnitudes are indicated by d. (Fraser, 1983)

Point Number	ΔX(cm)	ΔY(cm)	ΔZ(cm)	d(cm)	Significant deformation?	
					Localization	t-test
8	-.6	-.8	.4	1.1	no	no
181	.6	.1	-.9	1.1	no	no
19	-.2	.1	.2	.3	no	no
10	.7	.2	.8	1.1	no	no
1	-.1	.1	1.4	1.4	no	no
18	.3	.4	-.6	.8	no	no
21	.1	.2	.4	.4	no	no
22	-.9	-.3	-1.6	1.8	no	no
9	-.1	-.1	-2.2	2.4	yes	yes
12	.4	.4	-2.9	3.0	yes	no
11	.1	.1	-3.8	3.8	yes	no
4	-1.2	-.3	-2.4	2.7	yes	yes
13	.4	.9	-3.5	3.6	yes	yes
16	.1	.1	-4.4	4.4	yes	yes
25	-1.8	.5	.4	1.9	yes	yes
17	-1.4	.	-2.9	3.3	yes	yes
6	-2.4	-.2	-2.0	3.2	yes	yes
24	-1.3	.1	-5.2	5.3	yes	yes
20	-5.0	2.1	-3.2	6.3	yes	yes

Table 6. Summary of Deformation Analysis Results for Epoch 3 versus Epoch 1. Point Movement Magnitudes are indicated by d.

Point Number	ΔX(cm)	ΔY(cm)	ΔZ(cm)	d(cm)	Significant deformation? Localization t-test	
8	-.3	.0	.2	.3	no	no
24	-.1	.0	.4	.4	no	no
4	.0	.1	.0	.1	no	no
21	.1	-.2	.5	.5	no	no
9	.3	.0	-1.1	1.2	no	no
19	-.2	-.9	1.9	2.1	yes	no
6	-1.0	.9	2.9	3.2	yes	no
17	.6	-.7	1.8	2.0	yes	yes
181	-.2	-2.0	.1	2.0	yes	yes
18	-1.4	-.2	1.1	1.8	yes	yes
13	1.5	-1.4	-1.3	2.4	yes	yes
25	.7	3.1	9.2	9.7	yes	yes
1	.7	3.0	8.3	8.9	yes	yes
10	-.3	.9	4.1	4.3	yes	yes
12	1.3	-.1	2.8	3.1	yes	yes
11	1.7	-.9	5.1	5.4	yes	yes
22	.4	1.1	6.8	6.9	yes	yes
20	-5.0	2.8	3.3	6.6	yes	yes

Table 7. Summary of Deformation Analysis Results for Epoch 2 versus Epoch 3. Point Movement Magnitudes are indicated by d.

Point Number	ΔX(cm)	ΔY(cm)	ΔZ(cm)	d(cm)	Significant deformation? Localization t-test	
13	-.1	.0	.0	.1	no	no
9	-.4	-.1	-.5	.6	no	no
6	.4	-.1	.3	.5	no	no
12	.1	.1	.2	.2	no	no
4	-1.5	1.7	-1.0	2.5	yes	yes
18	-2.5	1.0	-1.8	3.3	yes	yes
20	-5.3	.6	-2.3	5.8	yes	yes
21	-4.1	1.8	-4.7	6.5	yes	yes
17	-4.6	2.5	-3.8	6.4	yes	yes
24	-4.4	1.9	-.9	4.9	yes	yes
10	-4.8	3.3	-3.5	6.8	yes	yes
25	.2	-.4	.8	.9	yes	yes
181	-5.0	-.4	-4.1	6.4	yes	yes
19	-5.1	.0	-5.5	7.5	yes	yes
8	-2.0	1.5	-.6	2.6	yes	yes
1	-3.3	1.0	.6	3.4	yes	yes
22	-2.7	-1.1	.1	2.9	yes	yes
11	-2.6	-2.4	-1.2	3.7	yes	yes

Table 8. Summary of Deformation Analysis Results for Epoch 1 versus Epoch 4. Point Movement Magnitudes are indicated by d.

Point Number	ΔX(cm)	ΔY(cm)	ΔZ(cm)	d(cm)	Significant deformation? Localization t-test	
17	-.2	.0	- .4	.4	no	no
9	.4	.2	.2	.5	no	no
21	-0.4	-1.0	-.3	1.1	no	no
10	1.3	.4	.0	1.4	no	no
19	-.2	1.0	1.1	1.5	no	no
12	.6	1.2	0.8	1.6	no	no
13	.3	1.3	.4	1.6	no	no
24	.0	-.4	1.7	1.7	no	no
11	1.4	1.2	0.1	1.8	yes	no
1	-1.4	-2.1	-.6	2.6	yes	no
4	-.2	2.8	-.3	2.8	yes	no
25	.7	-1.2	2.6	2.9	yes	no
22	-1.2	-2.8	.5	3.1	yes	no
18	.8	3.0	-0.2	3.1	yes	yes
16	-.5	-1.0	-3.2	3.4	yes	yes
8	.9	-3.8	-.7	4.0	yes	yes
6	-.3	-.6	4.6	4.6	yes	yes
181	2.2	-2.3	-3.8	5.0	yes	yes
20	-4.7	2.0	-2.6	5.7	yes	yes

Table 9. Summary of Deformation Analysis Results for Epoch 3 versus Epoch 4. Point Movement Magnitudes are indicated by d.

Point Number	ΔX(cm)	ΔY(cm)	ΔZ(cm)	d(cm)	Significant deformation? Localization t-test	
10	.6	.6	0.4	.9	no	no
25	.6	.1	.9	1.1	no	no
20	.6	-1	-.1	1.2	no	no
17	-.4	-.8	.9	1.3	no	no
9	-1.3	-.2	-.8	1.5	no	no
19	.6	-.4	1.4	1.6	no	no
1	-.2	-1.4	-.7	1.6	no	no
4	-1.3	1.0	-.2	1.7	no	no
131	1.6	.1	-1.6	2.3	yes	no
18	1.5	1.2	1.7	2.6	yes	no
13	.2	1.5	2.1	2.6	yes	no
22	-.8	-.4	2.5	2.7	yes	no
6	-1.6	-1.8	1.6	2.9	yes	no
21	.6	2.4	2.1	3.2	yes	no
12	-1.9	3.2	.1	3.7	yes	yes
98	-.3	-1.9	-3.8	4.3	yes	yes
181	3.3	-3.2	-.8	4.7	yes	yes
11	-1.3	4.6	-1.8	5.1	yes	yes
8	-.9	-3.4	-3.9	5.3	yes	yes

Table 10. Summary of Deformation Analysis Results for Epoch 1 versus Epoch 5. Point Movement Magnitudes are indicated by d.

Point Number	ΔX(cm)	ΔY(cm)	ΔZ(cm)	d(cm)	Significant deformation? Localization t-test	
1	0.4	-0.4	3.7	3.7	no	no
6	0.5	-3.1	0.3	3.2	no	no
8	-2.0	-1.2	1.7	2.9	no	no
9	1.1	2.7	-2.0	3.5	no	no
10	-0.1	2.2	-0.8	2.3	no	no
11	.6	-.4	1.4	1.6	no	no
13	-1.7	0.8	-0.7	2.0	no	no
15	-0.1	1.3	-1.3	1.8	no	no
16	0.2	-1.8	-3.9	4.3	no	no
18	2.9	2.3	0.7	3.8	no	no
19	0.7	0.7	4.3	4.4	no	no
20	-5.1	2.9	-2.3	6.3	yes	yes
21	-1.6	-0.8	1.2	2.2	no	no
22	0.9	-0.4	0.1	1.0	no	no
24	0.8	-1.6	1.2	2.2	no	no
25	-1.2	-1.9	-2.4	3.3	n	no
97	0.7	0.8	0.5	1.2	no	no
98	1.2	0.8	-0.5	1.5	no	no
131	-38.2	0.1	-9.4	39.3	yes	yes

Table 11. Summary of Deformation Analysis Results for Epoch 4 versus Epoch 5. Point Movement Magnitudes are indicated by d.

Point Number	ΔX(cm)	ΔY(cm)	ΔZ(cm)	d(cm)	Significant deformation? Localization	t-test
1	0.1	-0.1	0.1	0.2	no	no
6	-0.1	-0.1	-0.1	0.1	no	no
8	-0.8	2.6	0.7	2.8	no	no
9	0.1	0.1	o.0	0.1	no	no
10	-0.1	2.2	-0.8	2.3	no	no
11	1.2	-4.8	-0.5	5.0	no	no
13	-0.5	-0.8	-2.0	2.2	no	no
16	1.7	0.8	-2.4	3.0	no	no
18	1.3	0.0	3.2	3.5	no	no
19	-0.3	1.5	2.8	3.2	no	no
20	0.3	1.1	1.7	2.0	yes	yes
21	1.4	-0.7	4.0	4.3	no	no
22	0.1	0.1	0.0	0.1	no	no
24	2.6	0.2	0.5	2.7	no	no
25	-0.7	-4.5	-1.8	4.9	n	no
98	-3.5	-0.2	-5.2	6.3	no	no
131	-4.9	-4.8	-9.2	11.5	yes	yes

Two point group movements were initially identified when comparing Epochs 1 and 2. These groups consisted of Points 4, 6 and 9 and 16, 17 and 24 where settlements of 2 cm and 3 – 5 cm, respectively, were found.

The results of the deformation localization between Epoch 1 and 4 revealed that 11 points showed significant deformations. Of these two points, numbers 11, 1, 4, 25 and 22, were only marginally significant. Subsequently, a t-test was applied to these two points revealing their deformations not to be significant. Consequently a free-network adjustment was performed using the 8 stable points. The corresponding horizontal deformation can be seen in Figures 2 and 3.

Upon examining the deformations in Figures 2 and 3 several patterns become evident. The first group included Points 8, 18, 181 and 20 for which significant horizontal movement was evident. Points 1 and 25 moved horizontally as a group as did Points 17, 18, 19 and 181. In the vertical direction, points 6 and 25 moved upward while 181 and 20 moved downward but not as groups. During the comparison of Epochs 1 and 2, Points 1 and 25 demonstrated an upward trend.

Deformation localization between Epochs 3 and 4 indicated that 11 points had significant deformations. Six of these points passed the t-test and were subsequently added to the list of stable points (see Table 9).

Using these 11 stable points a free-network adjustment was computed. Figures 4 and 5 show the resulting deformations computed for Epoch 3 versus Epoch 4. Two point groups were found to be statistically significant in the horizontal plane. The first group consisted of Points 11 and 12. Points 18 and 181 comprised the second group of points moving in a similar horizontal direction. These same two point groups did not show similar trends in the vertical direction. Although, a downward movement was evident for point 8 while the others did not appear to exhibit a trend.

EPOCH -1 – 5 deformations

HORIZONTAL Ellipses at 95.00%

DEFORMATIONS

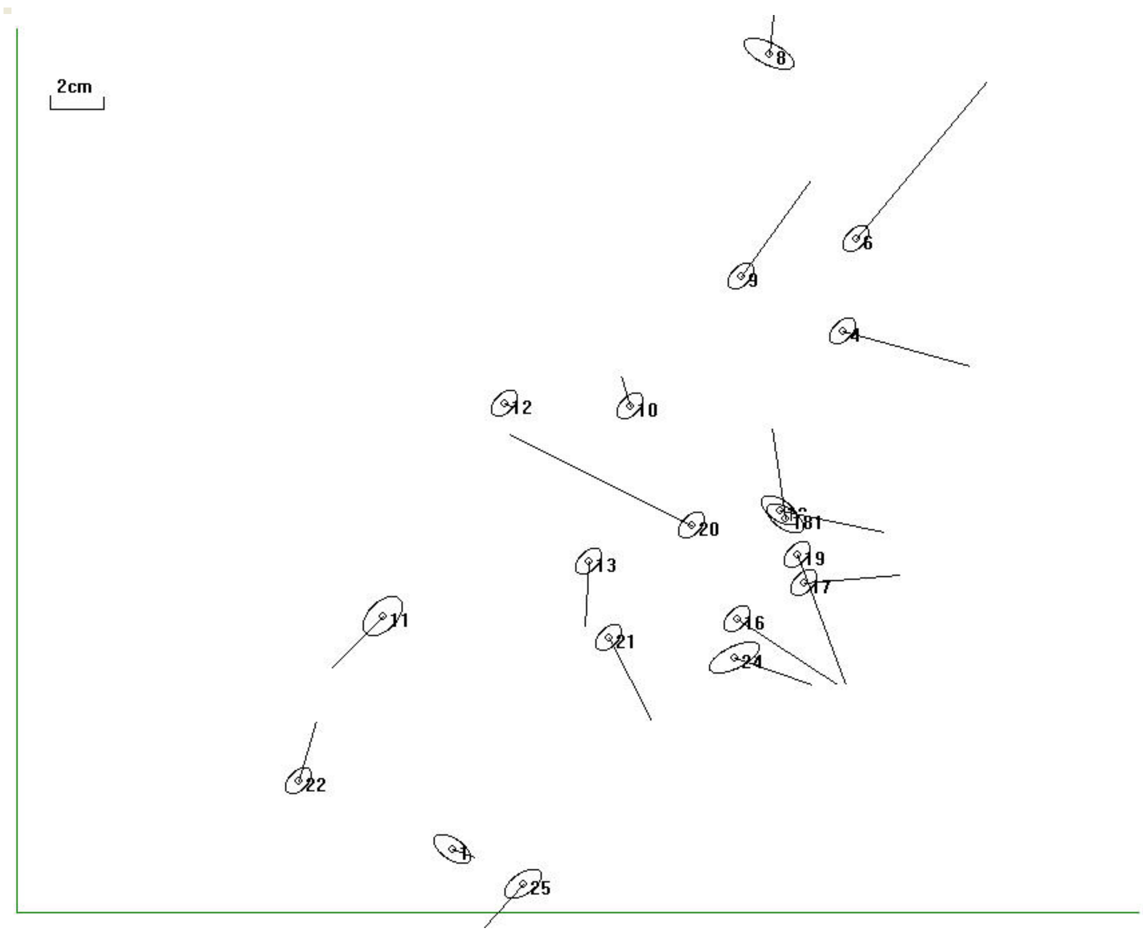

Figure 2. “Deformations” in the Horizontal Plane, as Determined by the Localization Procedure for Epoch 4 versus Epoch 1.

EPOCH -1 – 5 deformations

VERTICAL intervals at 95.00%

DEFORMATIONS

UP: Postion

DOWN: Negative

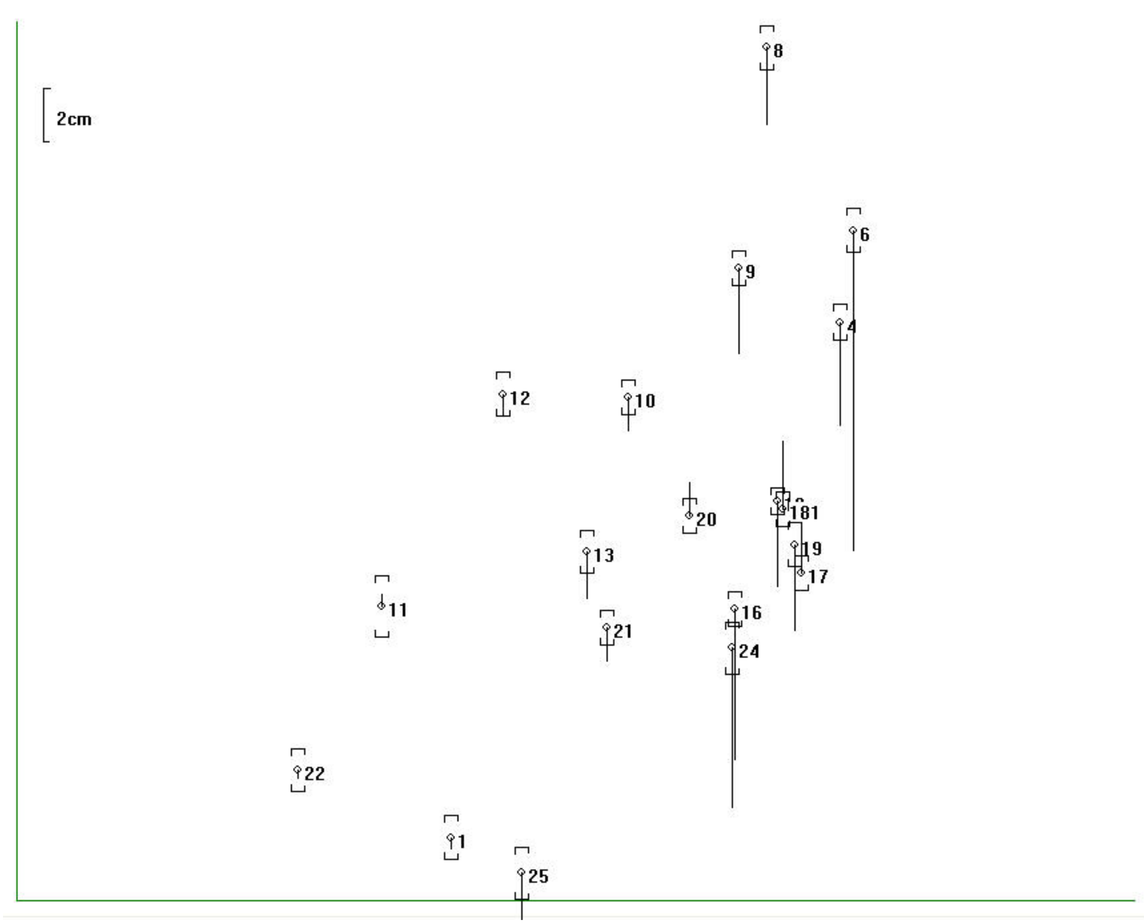

Figure 3. “Deformations” in the Vertical Direction, as Determined by the Localization Procedure for Epoch 34 versus Epoch 1.

EPOCH -4 – 3 deformations

HORIZONTAL Ellipses at 95.00%

DEFORMATIONS

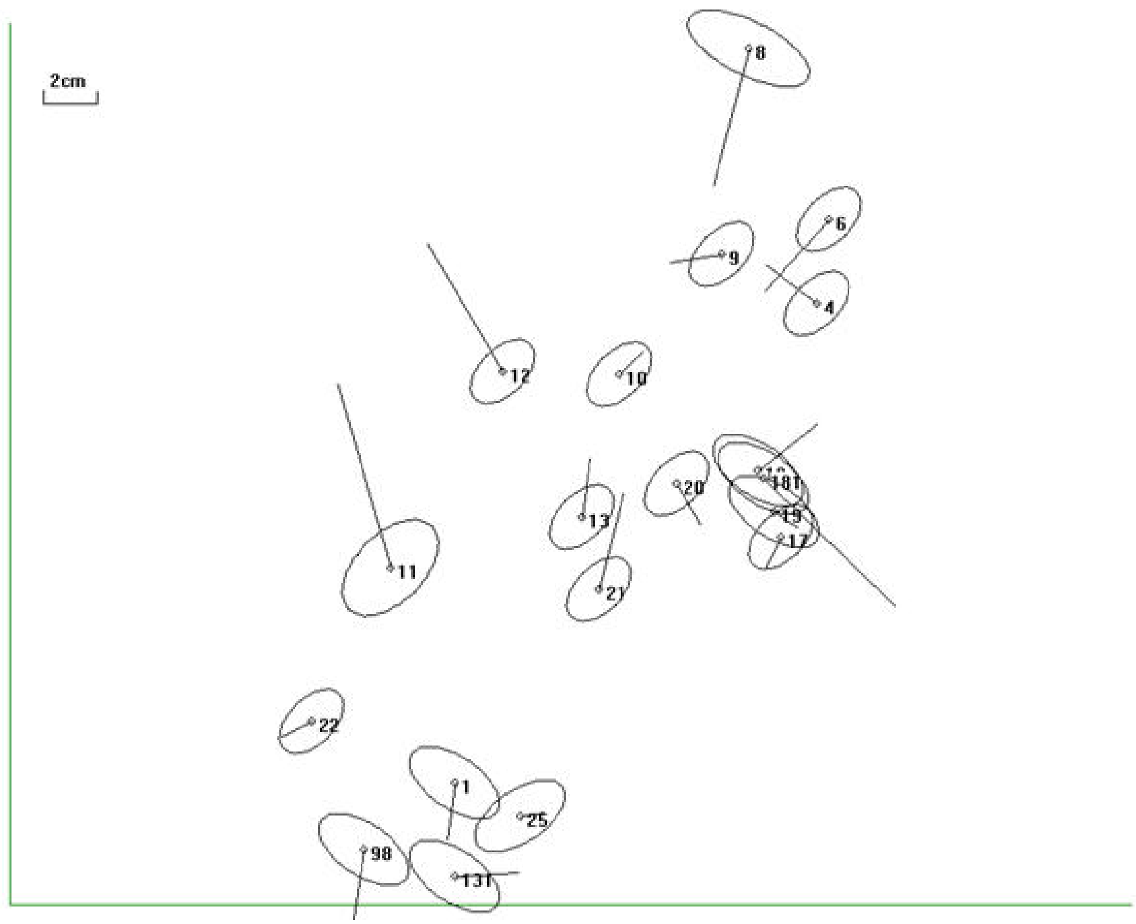

Figure 4. “Deformations” in the Horizontal Plane, as Determined by the Localization Procedure for Epoch 4 versus Epoch 3.

EPOCH -4 – 3 deformations

VERTICAL intervals at 95.00%

DEFORMATIONS

UP: Postion

DOWN: Negative

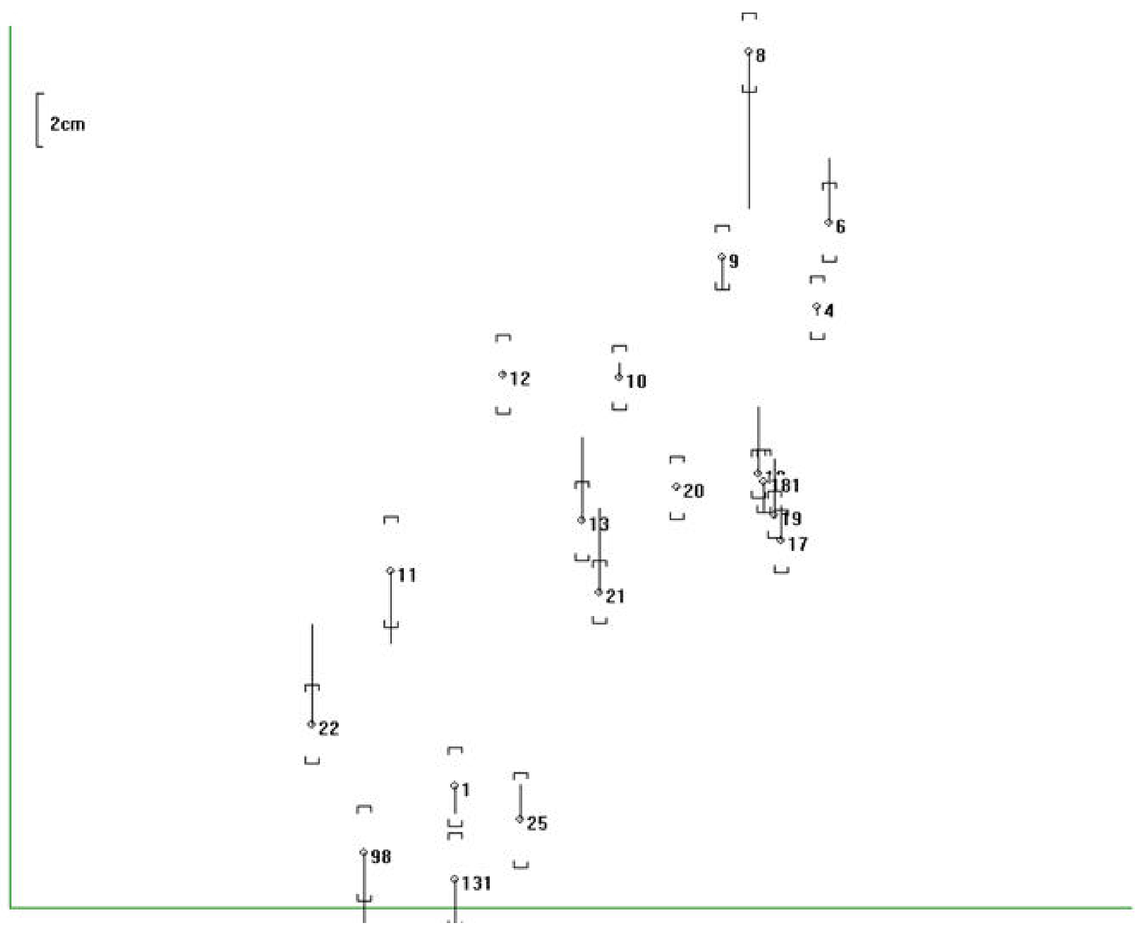

Figure 5. “Deformations” in the Horizontal Plane, as Determined by the Localization Procedure for Epoch 4 versus Epoch 3.

1.5.3 Interpretation of the results

Using the results from Epoch 5, comparisons were made to the results from Epoch 1 and 4. As identified earlier, Point 20 exhibited a 6.3 cm movement when comparing the results from Epoch 1 and Epoch 4. The same magnitude of movement was detected when comparing Epoch 1 and Epoch 5. This movement was due to the fact that Point 20 was physically moved 6.2 cm. No significant movement was reported at Point 20 when comparing the results from Epoch 4 and Epoch 5. Point 131 (the target consisted of a circular white panel) appeared to have a significant movement (39.3 cm) when comparing Epoch 5 to Epoch 1. While this point movement warrants further inspection, it is possible that this point was moved by the wind or by an individual passing through the site.

The results of the comparisons of Epoch 4 with both Epochs 1 and 3 indicate that portions of the South Peak area of Turtle Mountain are deforming as noted in previous analyses. More particularly, it appears that several point groups are exhibiting trends in their movements. These trends are evident in both horizontal and vertical directions.

An apparent settling occurred at Points 4, 6 and 9 and 16, 17 and 24 between Epochs 1 and 2. A less pronounced settling occurred at Points 20 and 181 between Epochs 1 and 4 and at points 4 and 9 between Epochs 1 and 4. At Points 13 and 21 an upward trend was obvious between both Epochs 3 and 4.

In planimetry, an outward shift seemed to place at Points 11 and 12 over the nineteen year period separating Epochs 3 and 4 as previously reported. Between Epochs 1 and 4 there were both horizontal and vertical movements but no distinct trend was evident. A common vertical displacement was evident at Points 20 and 181. In this case, the movement was in a downward direction.

In analyzing these results, it is important to remember that apparent movements are relative in nature and are based upon the choice of stable point sub-groups.

2. CONCLUSIONS

The results of this most recent measuring epoch confirm the practicability of using high-precision photogrammetry as a deformation monitoring tool. With the inclusion of the data from the fourth measuring epoch several trends are becoming evident. Both sequential and global testing were found to be useful in localizing point movements as well as short and long term trends, respectively. However, none of these support the hypothesis that the rock wedge bordered by Crack 1 is moving as a unit.

As a result of the time of year of the photography acquisition, several targets were missed due to shadows. These missed targets corresponded to points 14, 15, 97 and 101.

3. RECOMMENDATIONS

During the course of this investigation some problems were identified. Most prominent are the somewhat less than optimal object point targets. To minimize the likelihood of misidentifying targets in the future, a target-centred cross should be painted on the rock surrounding the target. Where possible, each leg of the cross could be a metre long and as wide as the target itself.

Many of the problems associated with target identification could be resolved with another site visit and the acquisition of the photography earlier in the season and at mid day. Despite the long time span between epochs 3 and 4 and the need to replace some of the targets, there seemed to be reasonable agreement between the results. However, a site revisit with a thorough examination of the targets is recommended.

A measuring epoch during the cold winter months should be planned to examine the thermal and ice effects taking place on Turtle Mountain. This would necessitate good coordination to ensure the targets were free of snow at the time of photography.

Finally more research is still needed to fully incorporate the techniques of strain analysis into this deformation monitoring scheme.

4. REFERENCES

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