

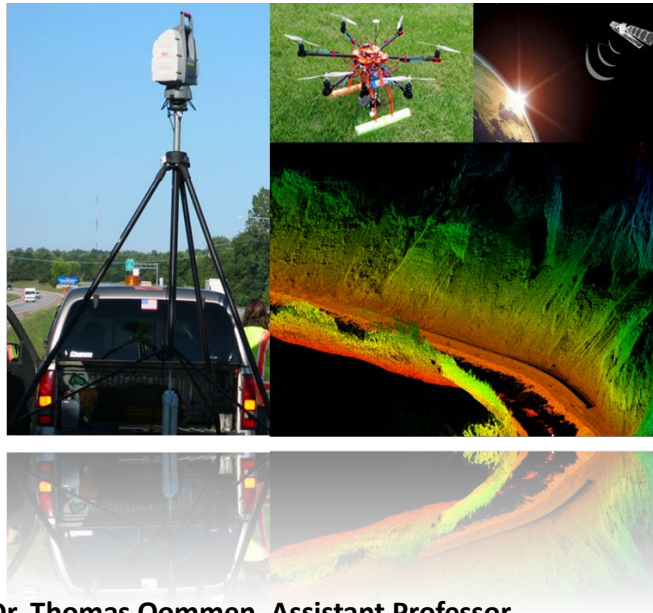
Deliverable 6-A: Cost benefit analysis of a proactive geotechnical asset management system using remote sensing

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GLOSSARY OF TERMS

ALOS	Advanced Land Observing Satellite
AASHTO	American Association of State Highway and Transportation Officials
COSMO-SkyMed	Constellation of small Satellites for the Mediterranean basin Observation
DEM	Digital Elevation Model
DSLR	Digital single-lens reflex
DSS	Decision Support System
ENVISAT	Environmental Satellite
ERS	European Remote Sensing Satellite
FAA	Federal Aviation Administration
GAM	Geotechnical Asset Management
GB	Giga-byte
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
InSAR	Interferometric Synthetic Aperture Radar
LiDAR	Light Detection and Ranging
Meteor-3M	Russian polar orbiting satellites
PALSAR	Phased Array type L-band Synthetic Aperture Radar
RADARSAT-1 and 2	Radar Satellite 1 and 2
RAM	Random access memory
RMSE	Root mean squared error
RTK	Real-time kinematic
Sentinel-1A and 1B	European Space Agency radar imaging satellites
SEOSAR/Paz	Satélite Español de Observación SAR (Spanish SAR observation satellite)
SFM	Structure from Motion
TerraSAR-X	German radar earth observation satellite
UAV	Unmanned aerial vehicle
USDOT/OST-R	US Department of Transportation, through the Office of the Assistant Secretary for Research and Technology
USGS	United States Geological Survey
VTOL	Vertical takeoff and landing

EXECUTIVE SUMMARY: DELIVERABLE 6-A

Overall Goal of this Deliverable: To present a summary of the costs and benefits of applying three technologies to monitor geotechnical assets: Satellite base Interferometric Synthetic Aperture Radar (InSAR), Light Detection and Ranging (LiDAR), and Structure from Motion (SFM) Photogrammetry. Costs are estimated from different sources, including costs reported in the literature and costs directly assessed as part of the project's data collection and analysis. Benefits will be assessed in the context of the value that can be assigned to the information content produced by the different methods. Specifically, the information content is defined in reference to geotechnical assets surface displacement, and the relative value is judged in terms of its accuracy and data point density. Different scenarios that consider various in-house versus outsourcing of service, and higher versus lower precision data acquisition setups are considered and discussed. Comparisons between the different scenarios and their impact on cost, accuracy and data point density are included at the end.

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1. The cost and benefit analysis framework

The adoption of new technologies, like the remote sensing methods proposed for geotechnical asset management and monitoring, requires the evaluation of the potential benefits they offer, versus the potential costs of implementing them (Ye et al. 2014). The assessment of the potential costs and benefits of the new technology is crucial to decide whether it is worth adopting it compared with other alternatives, including monitoring methods currently in place, or in some cases no monitoring at all. We will use the framework of costs and benefits for similar technologies and applications laid out in the literature, particularly for LiDAR applications, e. g. Ye et al. (2011, 2014), Vincent and Ecker (2010), Olsen et al. (2013), Chang et al. (2014), and Williams et al. (2013).

Commonly the term “cost-benefit analysis” is used for assessing the net societal benefit of large projects that have a direct impact on the broader public, and is therefore considered a public policy assessment tool (e. g. Boardman et al., 2006; Zerbe and Bellas, 2006). The assessment of the costs and benefits of remote sensing technologies for geotechnical asset management has to be framed within the wider context of transportation asset management. In such a context, the monitoring technology only corresponds to a small component of the whole asset management system. Therefore, our goal for this report is rather modest, we only aim to provide a discussion of the relative costs of the technologies and compare some of their potential benefits, within the context of their use for geotechnical asset management.

In the case of remote sensing technologies applied to monitor the state of geotechnical assets, the main product obtained from their use is the information on the asset's conditions, e. g. if a slope shows movement. It is the value of that information what determines the potential benefits of the technology. The value of this information is dependent on the use that will be given to it. In the particular case of geotechnical asset management, the information's value depends on the use of the information for decision making related to the assets maintenance, repair or replacement, as part of a geotechnical asset management system (Sanford-Bernhardt et al., 2003; Vessely, 2013; Stanley, 2011). If there is an adequate decision making platform where the information generated by remote sensing techniques is a critical input the value of that information will be high, resulting in a significant benefit, otherwise the information has no value.

To compare the costs with the benefits, and assess whether the benefits outweighs the costs, it is necessary to reduce both to a common metric, usually in terms of economic value through the monetarization (i. e. assigning a dollar value) of each item that will contribute to the potential cost and benefits (Boardman et al., 2006; Zerbe and Bellas, 2006). In our case, rather than monetary values for particular cases of the technological applications, we will give a range of examples and broad estimations of costs, and a qualitative description of benefits from using the proposed remote sensing technologies. Two main types of scenarios regarding costs will be presented, the cost of developing “in-house” capabilities to use the technology, and the cost of contracting a service provider who can apply the technology and will deliver a final product, similar to what would be obtained if the technology capacity was built “in-house”.

The benefits will be discussed in the context of the value of information generated by each specific technology. The main product of the remote sensing technologies explored in this project is the detection and measurement of changes in the surface (displacements, deformation or movement in general) of the assets being monitored (e. g. cut slopes, retaining walls, etc.). Tracking such changes through time and considering them in the relevant geotechnical context (e. g. what are the slope stability implications for a movement of a given magnitude measured on a cut slope) is the basis for using the information in a decision support system, which is also currently in development as part of the project. A synthesis of the cost and benefit will be presented, comparing costs and benefits between the different technologies, but keeping in sight the differences in the outputs and potential applications of each technology.

Given the large range of possible applications, the variability in costs depending on such applications, and the even more significant complexity of the potential benefits that could be attached to the information produced by the remote sensing techniques, we will also present and discuss the uncertainties in our analysis and the relevant limitations of the available information. Part of this uncertainty is related to the state of development of other components in this project, including the testing and validation of the remote sensing methods, and the development of a decision support system, in which the information would actually be an input. We will make some assumptions about these components, but an update may be necessary after the corresponding project products are completed.

2. Estimating costs of different technologies and platforms

2.1 Defining unitary costs

When possible, the general cost estimation and discussion will be based on the assumption of two scenarios: first we consider an “in-house” capacity building scenario, in which all the hardware and “know-how” is acquired by the user of the technology (e. g. a State Transportation Agency). Second, we consider the outsourcing scenario, in which the costs correspond are those of contracting a service provider, who applies the technology and provides the user with a final product (e. g. surface displacement measurements). For the “in-house” scenario we will consider the initial investment costs, as well as long term operation costs. The outsourcing costs are compiled from market value costs reported in the literature and by the project partners.

The in-house scenarios includes initial costs related to an initial investment, necessary to buy the hardware and software, as well as procuring the training for operators and analysts that will be necessary to apply the technology, and the long term, sustained cost for the operation or recurrent use of the technology. The long term cost will be discussed on an annualized basis, and no discount analysis of present value will be performed, but the impact of long term payoff of the initial investment will be discussed in section 3, when integrating cost and benefit considerations (e. g Ye et al. 2014; Chang et al. 2014).

The outsourcing scenario only considers the recurrent use of the contractor's service. Whether in-house or outsourcing is a better alternative will depend on several factors, but usually the in-house capacity will be justified by a higher demand for the technology, i. e. more frequent or extensive use, while the outsourcing tends to be more cost effective for lower work volumes. According to this reasoning, agencies dealing with extensive geotechnical assets, distributed over large areas of very active (e. g. relatively steep and often unstable) terrain may find the in-house capacity building more cost efficient, than agencies dealing with a smaller volume of such assets and their corresponding workload.

Some of the technologies and platforms may not be available in both in-house and outsourcing scenarios. The case of aerial LiDAR surveying is presented in section 2.3, discussing the reasons that make developing an in-house capacity unfeasible for most cases in section 2.3.1, and

therefore only a quick overview of that case is presented. The opposite happens in the case of structure from motion (SFM) photogrammetry discussed in section 2.6; in that case only the in-house scenario is considered (section 2.6.1), given the current state of development of the technique and the corresponding lack of commercial service providers (section 2.6.2). Because the fundamental differences in the methods, the cost of traditional photogrammetric services are unlikely to be representative of market costs for SFM photogrammetry, and therefore are not considered here as a proxy for the UAV based platform.

Cost estimates are presented as either total costs per project (or site) location, costs per linear transportation corridor unit (dollars per mile) or costs per day of operation, depending what units are more relevant to the specific application. Long term costs included in the in-house scenarios, like the initial investment in equipment, are distributed over time on an annual basis.

2.2 Satellite based InSAR costs

2.2.1 Building in-house InSAR analysis capacities

Initial investment cost to build in-house capacities to use InSAR as a monitoring tool include buying the software and hardware necessary for data analysis. The main hardware consists of computer equipment with enough processing power to operate the software, and electronic storage volume for hosting the data files. Computer hardware requirements vary depending on the software used, but high power commercial desktop models are usually sufficient e. g. a desktop computer with an Intel Core i7 series processors, 16 GB of RAM and 1 to 2 TB of storage space. Such hardware has a cost ranging between \$ 1,500 and \$ 2,500.

Software license costs vary over a large range, depending on the type and brand of software used, from \$ 8,000 up to \$ 65,000. We used the commercial Sarmap software (Sarmap, 2009), which provides capabilities to process single interferograms from pairs of satellite images, and persistent scatterer points from image stacks (for more details see Deliverable 2-A: report “Candidate remote sensing techniques for the different transportation environments, requirements, platforms, and optimal data fusion methods for accessing the state of geotechnical assets”). Sarmap falls in the lower end of software prices and delivers most of the products considered in this project for InSAR.

Sustained costs include the computer time cost, and the analyst time costs. If a computer is bought for the sole purpose of InSAR data analysis, as a dedicated resource, no further computing time cost considerations are necessary, but the cost of maintaining the equipment, and most significant, the cost of hosting the data on server, etc., may represent an additional cost, as part of the agency's IT operations. We estimate an IT cost for storage and backup of ~ 20 TB of data. Using current hard drive storage costs from commercial, including space for multiple periodic backups, we estimate an annual cost of \$ 0.2 per GB, which gives a total cost of \$ 4,000 per year.

Dedicated analyst time cost will vary depending on how much the analyst has to interact with the software (e, g, how complex and challenging the data set is) and the amount of data that need to be processed. The analyst time also includes the time spent searching the datasets to be used, in image catalogues. Processing a single stack of several tens of images can take several hours to more than a week of continuous processing for the software, but will only require a few hours of work by the analyst for preparing the input, starting the processing sequence of the software, and evaluating the software output at the end.

A conservative estimate for the analyst time devoted to a single site analysis, using a large stack of images (e. g. 40 images), is 8 hours on average. Considering a cost of \$40 per hour for a trained analyst, we get a rough estimate of \$320 per site analyzed. This can vary significantly, increasing if the terrain is challenging and further interaction from the analyst is required. It is difficult to estimate the number of sites, or image stacks that would have to be analyzed in a year, but it could be between a low of 10 sites and a high of 50, which would translate to annual labor costs between \$ 3,200 and \$ 16,000.

Data acquisition costs depends on the type of satellite imagery being acquired. Cost for commercial applications imagery range from free available images for Sentinel 1B, to > \$ 7,000 for RADARSAT-2 per image, but usually fall on the lower end of the cost range, e. g. hundreds of dollars per image (see table 1). It becomes obvious that the imagery cost can be significant, especially when stacking techniques that use tens of images are applied. Using a high average estimate of \$ 1,000 per image, a single interferogram analysis using an image pair would imply a

\$ 2,000 cost, and an image stacking analysis, like that performed for persistent scatterers, using 20 to 40 images would amount to \$ 20,000 to \$ 40,000 in costs. The number of images used depends on the extension of geotechnical assets that need to be monitored, the ground location of the image footprint, and the image size (see figure 1, for an example). The tendency in the near future for agencies that produce and deliver such images, is to reduce the cost or even provide them for free, like in the case of the Sentinel 1b imagery, but this consideration does not apply to historical data necessarily. Assuming that each image footprint contains 100 miles of transportation corridor, and that a transportation agency needs to analyze 100 to 1,000 miles every year, the agency would have to analyze 1 to 10 locations, costing a total of between \$ 20,000 and \$ 200,000.

Table 1. InSAR satellite images characteristics.

Satellite	Mission Timespan	Revisit Period (days)	Ground Resolution (meters)	Price Per Image (US Dollars)**
ERS-1	1991 - 2000	35	25	\$212 - \$354
ERS-2	1995 - 2011	35	25	\$212 - \$354
RADARSAT-1	1995 - 2013	24	10-100	\$3,047 - \$3809
ENVISAT	2002 - 2013	35	25-150	\$354 - \$591
ALOS PALSAR	2006 - 2011	46	7-100	\$42 - \$709
RADARSAT-2	2007 -	24	3-100	\$3,047 - \$7,110
COSMO-SkyMed	2007 -	16	1-100	\$680 - \$2,268
TerraSAR-X	2007 -	11	1-16	\$875 - \$7,972
Meteor-3M	2009 -	3	400-1,000	\$30/\$40 - ?
ALOS PALSAR-2	2014 -	14	1-100	\$1,257 - \$4,191
Sentinel-1A	2014 -	12	4-80	Free of cost
SEOSAR/Paz	2015 -	11	1-15	Will be publically available
Sentinal-1B	2016 -	6	4-80	Will be publically available
COSMO-SkyMed 2 nd Generation	2016 -	1.5-10	1-35	Will be publically available

**US Dollar exchange rates (January 2015). NA = not available for commercial or educational use. Prices and data availability listed for users in the United States.

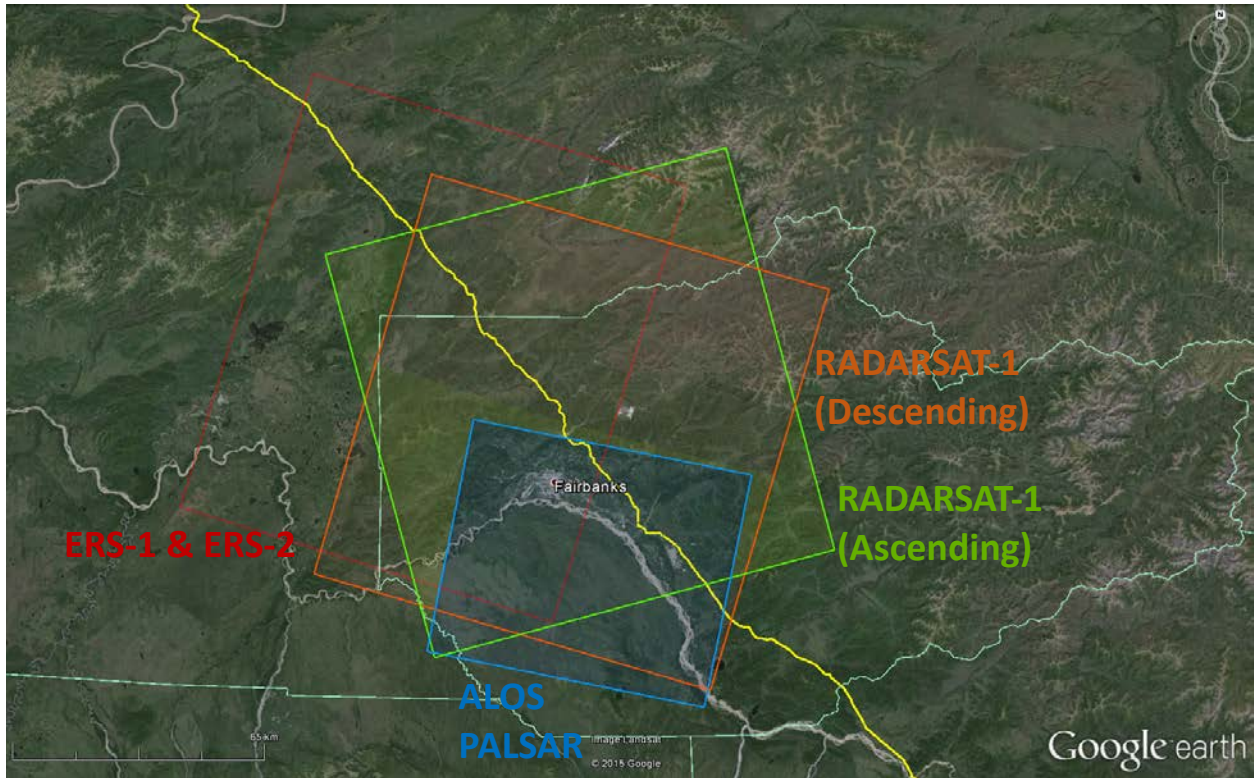


Figure 1. Example of different InSAR images area coverage over Fairbanks, Alaska.

From the above discussion we see that the cost of commercial InSAR applications developed “in-house” will be dominated by data acquisition costs, especially for longer time trend analysis like those performed with stacking techniques.

Table 2. Summary of costs for in-house InSAR analysis capacities

Item	Cost estimate	
	Low	High
Computer hardware	1,500	2,500
Software	8,000	65,000
Annual data storage	4,000	4,000
Annual analyst labor	3,200	16,000
InSAR images	20,000	200,000
Total	36,700	287,500

2.2.2 Outsourcing the InSAR analysis

Commercial service providers for analyzing InSAR imagery are also available. The costs of such services will also depend on the requested products and the availability of satellite imagery. As a comparison within the aims of the project, a commercial InSAR analysis service provider performed a similar analysis to that done with our “in-house” developed capacities, and although the outputs were not entirely comparable, as discussed in sections 3 and 4, the costs can broadly be compared as an indicator of similar services. For a single site and using the same imagery (e. g. 90 images acquired at no cost for research purposes) as our “in-house” test, the reported costs by the commercial provider ranged between \$ 20,000 and \$ 50,000. The addition of the imagery cost could increase the final price of the commercial service, for cases outside of the research test. As with the scenario described in section 2.2.1, we assume that between 1 and 10 locations, corresponding to between 100 and 1,000 miles, need to be analyzed, which would add to an annual costs between \$ 20,000 and \$ 250,000.

Table 3. Summary of costs for outsourcing the InSAR analysis

Item	Cost estimate	
	Low	High
Outsourcing InSAR analysis	20,000	250,000
Total	20,000	250,000

2.3 Aerial LiDAR costs

2.3.1 Building in-house capacities for aerial LiDAR analysis

Developing in-house aerial LiDAR capabilities is usually very expensive and will not be a feasible option for the majority of users, except the largest agencies, which may have to deal with extensive geotechnical asset inventories and challenging conditions (e. g. steep and geologically active terrain). The use of aircraft equipped with special adaptations to carry the LiDAR instruments, and a high accuracy navigation system to geolocate the LiDAR data, makes the use of non-dedicated (e. g. rented) aircraft complicated. The high power LiDAR instruments used for aerial data acquisition are also more expensive than the terrestrial LiDAR scanners discussed in the next section (Shan and Toth, 2009), and the expertise involved in operating such

aircraft and instruments leads to most or all of the data acquisition steps being outsourced to specialized commercial providers (Chang et al. 2014).

Vincent and Ecker (2010) present a detailed aerial LiDAR cost estimate of \$ 8321 per mile of corridor, for a transportation corridor survey in Missouri, when all the costs for the operation of the aircraft and other logistics are taken into account (see also discussion of this case in Chang et al. 2014). This estimation is however for a very high point density and accuracy survey, comparable to the point densities and accuracies that can be obtained by mobile and static LiDAR collects. We assume that most agencies that end up using aerial LiDAR data will outsource the data collection and analysis to a commercial service provider, and the costs are therefore expected to be similar.

Table 4. Summary of costs for in-house capacities for aerial LiDAR analysis*

Item	Cost estimate	
	Low	High
Total (non-itemized) cost	25,200	541,000
Total	25,200	541,000

*Taking the same total values as in table 5.

2.3.2 Outsourcing the aerial LiDAR analysis service

The amount that the aerial LiDAR service providers charge for their services depends on the specifications defined by the user (e. g. ground point density and accuracy), the data processing level at delivery (e. g. raw point clouds, “last return” classified point clouds, DEMs, etc.), the complexity and level of difficulty of the terrain (e. g. relief, slope, forest cover, etc.), site locations, (e. g. remoteness), and size of the survey job (e. g. larger areas have a smaller unit area cost). Costs are usually quoted per covered area unit, for a given “level of quality”.

A study for the USGS National Data Elevation Assessment from 2012 reports cost for large area (> 5000 sq. mi) ranging from \$ 90 to \$ 521 per square mile, depending primarily on the “quality level”, which defined in terms of data point density, nominal pulse spacing, vertical RMSE, and equivalent contour accuracy (Dewberry, 2012). Aerial LiDAR costs for the State of Michigan (for 2013) range from \$ 100 per square mile, for surveys of areas larger than 5,000 square miles,

to ~ \$ 250 per square mile, for survey areas smaller than 100 square miles (State Of Michigan Center For Shared Solutions, 2013). Specifying higher or lower quality levels for the data can increase the cost by more than a factor of 2. These values are comparable to the aerial LiDAR costs of \$ 335 per square mile estimated for Wisconsin in 2014 (McDougal, 2014) and \$ 344 per mile, estimated for Vermont in 2015 (Vermont Center for Geographic Information, 2015), in both cases a standard USGS “quality level” 2 was specified.

Because in this project we assume that the primary targets for the LiDAR survey are transportation corridors, it is more meaningful to give the costs as unit length costs (i. e. dollars per mile of corridor), rather than unit area costs (dollars per square mile of terrain). Assuming a wide enough buffer zone to include the transportation corridor and all relevant geotechnical assets (e. g. natural and cut slopes), and considering the limitation of the minimum altitude above the terrain that the aircraft can fly and the footprint size of the LiDAR scans, one can convert from the unit area cost to a unit length cost. Additionally, the limitations of the flight path, which may not be able to follow a highly sinuous transportation corridor layout, also has to be considered. For a swath width of half a mile and using the areal costs discussed in this section we get linear unit costs in the range of \$ 45 to \$ 250 per mile of surveyed corridor. However, the requirement of a minimum survey area, sometimes imposed by surveying companies, may drive the actual cost per surveyed mile up.

The length of the transportation corridors that need to be surveyed will depend on the type of asset monitoring. Agencies with extensive geotechnical assets in very active terrain, and which require close monitoring (e. g. in areas with rugged and steep terrain) may want to survey thousands of miles of their transportation network. While agencies with less complex terrain and more stable or simpler asset inventories may focus on shorter stretches of their transportation network. Assuming that the total corridor length to be surveyed in any given year is somewhere between 100 and 1,000 miles, the annual cost would be between \$ 25,000 and \$ 521,000. Once the data have been delivered to the user (e. g. a transportation agency), a data archiving and management process is necessary, and that basically involves planning for data storage. Data storage space could potentially be much larger compared to InSAR, if a similar area (or corridor length) is being surveyed with aerial LiDAR. Storage space requirements of up to 10 GB per

mile could be expected. Assuming an annual cost of \$ 0.2 per GB and an annual transportation corridor surveying length of 100 to 1,000 miles, a total annual cost between \$ 200 and \$ 2,000 has to be considered.

Table 5. Summary of costs for outsourcing the aerial LiDAR analysis service

Item	Cost estimate	
	Low	High
Outsourcing LiDAR analysis	25,000	521,00
Annual data storage	200	20,000
Total	25,200	541,000

2.4 Mobile LiDAR costs

2.4.1 Building in-house mobile LiDAR expertise

Detailed cost, and cost-benefit analyses for developing in-house mobile LiDAR capabilities are presented and discussed by Vincent and Ecker (2010), Yen et al. (2011 and 2014), and Chang et al. (2014). These cases assume that cost of initial investment in equipment, can be distributed over a long time period (up to 6 years).

Initial investment to build in-house capacities include the investment in LiDAR instruments for data acquisition, as well as computer hardware and software for data processing and analysis. Commercially available LiDAR equipment costs vary between \$ 5,000 and \$200,000 at 2011 prices (Yen et al. 2011). Initial investment in software include the license for the data analysis software, which can range from \$ 500 to \$ 80,000, depending on the capabilities and functionality (Yen et al. 2011). For our project we used software on the lower end of the pricing scale (\$ 3,500), but had to resort to other in-house coding software (i. e. Matlab®) to do some of the processing. Initial investment in hardware include computers for data processing and data storage space, and we assume similar computer costs to those previously described for the InSAR processing, i. e. between \$ 1,500 and \$ 2,500.

Although virtual storage space needs for the collected data would be expected to be larger than for aerial LiDAR, given the higher point densities for achieved for mobile LiDAR collection, the area covered by such surveys will typically be much smaller. Annual data storage costs reported

by Yen et al. (2014) seem exaggerated, at \$ 7.3 per GB, as physical hard drives with periodical backup functionality may be a much cheaper option. Using their estimate of 3 GB per mile of data, the memory cost would amount to \$ 21.9 per mile. If instead we use the annual cost of \$ 0.2 per GB used for the InSAR data storage in section 2.2.1, we obtain an annual data storage cost of \$ 0.6 per mile of surveyed corridor. Assuming that transportation corridor lengths that will be surveyed any given year are somewhere between 100 and 1000 miles, the annual cost of data storage would amount to \$ 60 to \$ 600.

Data collection costs vary greatly depending on the type of data collected, and particularly the required accuracy, which determines the requirement to establish ground control, etc. These costs include the time of all the field personnel, vehicle and gasoline costs, and very importantly, the cost of establishing accurate ground control, which may be much more costly than the LiDAR data collection *per se*.

For data collections using high accuracy ground control Vincent and Ecker (2010) estimated a cost of \$ 9,933 per mile of corridor, while Yen et al. (2014) estimate costs between \$ 385 and \$ 531 per mile of corridor, for data collects without external ground control (their options 4 and 6 on table 4). These values cover a similar range of costs compared to the aerial LiDAR costs presented in section 2.3. The differences between the costs estimates by Vincent and Ecker (2010) and those estimated by Yen et al. (2014), is in large part due to the high cost of establishing ground control using traditional surveying methods in the first study. For surveyed transportation corridor lengths of 100 to 1000 miles, the annual costs would be somewhere between \$ 38,500 and \$ 531,000 for the type of survey described by Yen et al. (2014), and somewhere between \$ 993,300 and \$ 9,933,000 for the type of survey described by Vincent and Ecker (2010).

LiDAR data collected for monitoring surface displacement would be required to be highly accurate, with errors not larger than a few centimeters. With the current technology this would require processing methods that rely on precise ground control, shifting the costs to the upper end of the range reported here. However, new technology, and particularly RTK GPS and INS

technology coupled to the LiDAR instruments, may allow users to rely less on ground control in a near future (Olsen et al., 2013; Williams et al. 2013).

Data processing costs include an average of 2 hours of labor per GB of collected data, and taking the estimate of 3 GB of data per mile, and a cost of \$ 40 per hour for the technician doing the analysis, the cost of processing the data would be \$ 240 per mile. Surveying an annual corridor length of 100 to 1,000 miles would cost somewhere between \$ 24,000 and \$ 240,000.

Table 6. Summary of costs for in-house mobile LiDAR expertise

Item	Cost estimate	
	Low	High
LiDAR instrument	5,000	200,000
Analysis software	500	80,000
Computer hardware	1,500	2,500
Annual data storage	60	600
Ground control surveying (rapid) ¹	38,500	531,000
Ground control surveying (high accuracy) ¹	993,300	9,933,000
Data processing labor	24,000	240,000
Total (with rapid control)¹	69,560	1,054,100
Total (with high accuracy control)¹	1,024,360	10,456,100

¹Two sub-scenarios are considered here, depending on whether rapid or high accuracy ground control is used.

2.4.2 Outsourcing the mobile LiDAR analysis service

The range of costs given by Yen et al. (2014) for the outsourcing case is very similar to the in-house option. Some of the cases presented by them are mixed cases, where some of data acquisition and analysis process is outsourced, but other parts are done in-house, and would require building such a capability by the user. Completely outsourcing the service resulted in a cost of \$ 476 per mile (their option 1 in table 4), and mixed options spanning a wider range of costs, from \$ 422 per mile for renting the LiDAR equipment and assuming the costs of the survey (their option 3 in table 4), to \$ 717 per mile for their “partial ownership” of the equipment case (their option 7 in table 4). All these estimates correspond to data collection without accurate external ground control. Much higher costs, similar to those presented by Vincent and Ecker (2010) for the in-house case, would be expected if high accuracy external control had to be set up, driving up costs to as much as 10,000 per mile. Annual costs for 100 to 1,000 miles of

surveyed transportation corridor would then fall between \$ 42,200 and \$ 717,000 for the lower accuracy survey, and between \$ 1,000,000 and \$ 10,000,000 for the higher accuracy survey of control points, but such high accuracy ground control surveys are never used for mobile LiDAR surveys in practice.

Table 7. Summary of costs for outsourcing the mobile LiDAR analysis service

Item	Cost estimate	
	Low	High
Outsourcing mobile LiDAR service (rapid control)	42,200	717,000
Outsourcing mobile LiDAR service (high accuracy control)	1,000,200	10,000,000

2.5 Terrestrial LiDAR costs

2.5.1 Building in-house terrestrial LiDAR expertise

Terrestrial LiDAR collections are typically done for projects where high accuracy is necessary, and the use of precise external ground control is required. We assume that this is the case for both the in-house and the outsourced terrestrial cases discussed here. Vincent and Ecker (2010) give an estimate cost of \$ 29,258 per mile of terrestrial LiDAR survey. Given the high cost and large data volumes produced by this method, it is usually not applied to large stretches of transportation corridors, but rather focused on smaller areas of interest, like unstable slopes or other deteriorating geotechnical assets. This is the use envisioned for the geotechnical asset management in this project, and the discussion will follow that concept.



Figure 2. Riegl LMS-Z210ii instrument used to collect terrestrial LiDAR points at the field site in Nevada.

Using the unit cost estimates given by Vincent and Ecker (2010) in their table 8 (page 56) and adjusting the times for a single work day, we get an estimate cost of \$ 10,000 per day of terrestrial LiDAR surveying, including setup of external control, and data processing and analysis. Depending on the geotechnical asset size and the potential extension of the problem (e. g. slope instability) it may take less or more than a day to survey it. The use of terrestrial LiDAR may be reserved to the most critical cases, which require a more intensive monitoring, e. g. slopes that show movement and which would have a large impact if they failed. The total number of days that would be used for this kind of survey on a given year depend, as in previously discussed cases, on the extension and size of the geotechnical asset inventory managed by each agency, and the complexity and challenges of the terrain in which they are located. Assuming 10 to 100 days of survey data collection and processing that will be required each year for monitoring critical assets, the total annual costs could be somewhere between \$ 100,000 and \$ 1,000,000.

If the required ground control accuracy is less than the accuracy that would be obtained with standard, high precision surveying instruments, a less accurate “rapid” method, based on a high performance, hand held GPS receiver can be used (see section 2.6.1 for a detailed explanation). The rapid version for georeferencing the ground control points has an estimated cost between \$ 400 and \$ 800 per day of fieldwork, depending on the number and distribution of the control points. When we substitute these values in the surveying corresponding budget item given by Vincent and Ecker (2010) and recalculate the daily costs we obtain a cost value between \$ 7,200 and \$ 7,600 per day. Using the same figures of 10 to 100 days of data collection we obtain annual costs of \$ 72,000 and \$ 760,000.

Additionally, data archiving and management needs to be considered. Taking the annual cost of \$ 0.2 per GB, and assuming a daily data collection volume of 100 GB, we estimate a cost of \$ 20 per work day, and annual totals between \$ 200 and \$ 2,000, assuming 10 to 100 days of survey data collection and processing.

Table 8. Summary of costs for in-house terrestrial LiDAR expertise

Item	Cost estimate	
	Low	High
LiDAR data collection and analysis (high accuracy control) ¹	100,000	1,000,000
LiDAR data collection and analysis (rapid control) ¹	72,000	760,000
Annual data storage	200	2,000
Total (with high accuracy control)¹	100,200	1,002,000
Total (with rapid control)¹	72,200	760,000

¹Two sub-scenarios are considered here, depending on whether rapid or high accuracy ground control is used.

2.5.2 Outsourcing the terrestrial LiDAR service

The cost of contracting commercial service providers will depend on the characteristics of the project, but are expected to fall within the range of costs outlined for the in-house scenarios from section 2.5.1 (Chang et al. 2014), i. e. \$ 10,000 per day of data collection and analysis, and similar (\$ 100,000 to \$ 1,000,000) annual costs for a 10 to 100 days per year of survey data collection and processing scenario.

Table 9. Summary of costs for outsourcing the terrestrial LiDAR service

Item	Cost estimate	
	Low	High
Outsourcing terrestrial LiDAR service	100,200	1,002,000
Total	100,200	1,002,000

*Taking the same total values as in table 8. Only the high accuracy case is shown.

2.6 UAV SFM photogrammetry costs

2.6.1 Building in-house UAV SFM photogrammetry expertise

Our cost estimates are based on past projects experience (e. g. Brooks et al. 2013) and our experience with the current project. Initial investment in hardware includes the cost of the UAV, the photographic camera and lenses, and other peripheral equipment (e. g. intervalometer for automatic picture acquisition). UAVs can be of several different types, but here we will consider two types: multi-rotorcraft and fixed wing. Multi-rotorcraft UAVs allow for greater flexibility in deployment due to the VTOL capabilities, e. g. they don't need much space for takeoff or landing, but can have lower payload capacities, and usually cannot cover as large areas as the

fixed wing UAVs. Which type is more appropriate for a given task will depend on how these characteristics influence the UAV performance for the task.

UAVs vary in cost from about \$ 500 to more than \$ 10,000. This project has taken advantage of the capabilities that can be provided by UAVs in the \$800 to \$10,000 range. Cost differences reflect the size and complexity of the UAVs, and therefore their functionalities and capabilities. Larger and more expensive UAVs can carry heavier payloads and stay longer on the air, but may be less maneuverable. We have used a 6 rotor (hexacopter) UAV produced by Bergen R/C Helicopters. The cost of this UAV, fully equipped with batteries and navigation hardware and software is \$ 5,400.



Figure 3. Hexacopter UAV used for SFM photogrammetry in the project.

The camera used was a Nikon D800 DSLR camera, with a 36 megapixel sensor, a 50 mm f/1.4 lens and a built in GPS and intervalometer. The total cost of the camera and accessories was \$ 3,600. Data storage requirements of point cloud products will be comparable to those for terrestrial LiDAR, but additional storage space is needed for the high resolution (e. g. 36 megapixel) photography. Total data volumes (photographs and cloud point products) may amount to 250 GB collected per day. Using the annual cost of \$ 0.2 per GB we have assumed in

previous calculations, would give a cost of \$ 50 per day for data storage. Assuming 10 to 100 days of data collection in any given year, the annual cost for data storage would be between \$ 500 and \$ 5,000. Analysis software costs range between \$ 2,000 and \$ 15,000, and for this project we are using software (AgiSoft ® Photoscan) on the lower end of the price range.

Maintenance and operation costs for the UAV and camera system are expected to be on the order of \$ 710 per year, assuming a similar work load (~ 63 days for data collection and 21 days for processing) as presented by Brooks et al. (2013). Following those assumptions, the annual operation costs would amount to a total of \$ 20,160 for data collection labor and \$ 6,720 for data processing. If instead we assume 10 to 100 days of data collection per year, as in previous examples, the adjusted annual cost for data collection would be \$ 32,000, and the annual cost for data processing would amount to \$ 10,667.

External ground control can be established in different ways for the UAV photogrammetry, and at the moment this process is still subject to experimental testing as part of the project. We have used a high performance hand-held Trimble GeoExplorer GNSS receiver to survey ground control point locations. We only use the internal antenna and collect data for 10 to 20 minutes, to get < 10 cm geolocation accuracies. Such rapid geolocation strategy reduces the time for deployment of the groundcontrol targets, therefore reducing the costs involved in fieldwork, but it also reduces the accuracy of the control points, impacting the overall quality of the data. A more in depth discussion of that impact on the information value of data will be given in section 3. It is also possible to do a much higher accuracy survey of the control points, e. g. through static differential GPS or total station surveying of the control points. Such high accuracy methods would increase the costs by a large amount, similar to what happens in the case of terrestrial LiDAR surveys presented in section 2.5.

Deploying and surveying the ground control points is usually the most labor intensive and time consuming part of the fieldwork. The amount of work and time it can take to set up the ground control points depends on the terrain conditions and the density or spacing between the points. The density of control points should be as high as possible, but hiking on very rugged or steep terrain will significantly limit the access in some cases, and even in easily accessible terrain,

practical time constraints will finally put a limit to the number of points that can be surveyed. Since the targets for the proposed applications will be at, or near transportation corridors, the access issue will usually not be a major concern. UAVs with RTK GPS capability, which have become available in 2015, would reduce or eliminate the need for ground control points.

In our field tests the average spacing between control points has ranged from a few tens, to more than a hundred meters. We estimate that on average it takes 1 hour of labor to deploy and survey each control point, using the hand-held sub-meter accuracy GPS with occupation times of 10 to 20 minutes, described earlier. This would result in 10 to 20 work hours per mile, which would cost \$ 400 to \$ 800. Higher accuracy surveying, using differential GPS or total station would increase that cost to \$ 1,000 to \$ 2,000 dollars per mile. Alternatively, for a typical day of data acquisition it would be necessary to deploy a similar number (10 to 20) of ground control points resulting in a similar cost of \$ 400 to \$ 800 per day for the lower accuracy (hand-held GPS) surveying type. Annual costs, considering 10 to 100 days of surveying for the data acquisition, would amount to \$ 4,000 to \$ 80,000, a cost that would need to be added to the cost previously considered in this section. The physical targets consist of plastic sheets with a distinct black and white pattern and a well-defined center that can easily be recognized in the photographs. Each target costs \$ 17 and they are reusable. For 10 to 20 control points, the resulting cost would be between \$ 170 and \$ 340.



Figure 4. Plastic sheet field target for the ground control point. Left: target displayed on a road at the Alaska test site. Right: target displayed on a slope at the Nevada site.

Additionally, the cost of the surveying equipment would have to be considered, which for a GPS similar to the Trimble GeoExplorer used in the field tests would be on the order of \$ 5,000. Differential GPS and total station equipment costs for more accurate ground control surveys could range from \$ 5,000 to \$ 50,000.

Table 10. Summary of costs for in-house UAV SFM photogrammetry expertise

Item	Cost estimate	
	Low	High
UAV	500	10,000
Camera	1,000	4,000
Computer hardware	1,500	2,500
Analysis software	2,000	15,000
Surveying equipment	5,000	50,000
Annual data storage	500	5,000
Data collection labor	20,160	32,000
Data processing labor	6,720	10,667
Ground control surveying (rapid ground control) ¹	4,000	80,000
Ground control surveying (high accuracy control) ¹	10,000	200,000
Total (with rapid ground control)¹	41,380	209,167
Total (with high accuracy ground control)¹	47,380	329,167

¹Two sub-scenarios are considered here, depending on whether rapid or high accuracy ground control is used.

2.6.2 Outsourcing the UAV SFM photogrammetry service

Both the SFM photogrammetric methods and the UAV platforms are emergent technologies. Additionally, UAV commercial applications face strict operation regulations by the FAA, which has contained its expansion and adoption as a widespread commercial practice. The regulatory burden is expected to change in the near future, allowing for a much larger expansion in commercial UAV applications, but for now the information relative to costs of such commercial applications is difficult to assess. At least one company, Pix4D, is now offering cloud-based processing of UAV-collected imagery using SFM methods; this option could develop into a common solution for those that do not want to process the imagery themselves. Our expectation is that the costs will be comparable to our estimates presented for the in-house scenario discussed in section 2.6.1.

Table 11. Summary of costs for outsourcing the UAV SFM photogrammetry service

Item	Cost estimate	
	Low	High
Outsourcing UAV SFM photogrammetry service	47,380	329,167
Total	47,380	329,167

*Taking the same total values as in table 10. Only the high accuracy case is shown.

2.7 Terrestrial SFM photogrammetry costs

2.7.1 Building in-house terrestrial SFM photogrammetry expertise

The hardware needed for terrestrial SFM photogrammetry is essentially the same as for the UAV case, minus the actual UAV. Field and processing methods are also similar, therefore the annual costs for collecting data would be in the range of \$ 20,000 to \$ 32,000. Ground control points surveying could increase that cost significantly, by as much as \$ 4,000 to \$ 80,000.

Table 12. Summary of costs for in-house terrestrial SFM photogrammetry expertise

Item	Cost estimate	
	Low	High
Camera	1,000	4,000
Computer hardware	1,500	2,500
Analysis software	2,000	15,000
Surveying equipment	5,000	50,000
Annual data storage	500	5,000
Data collection labor	20,160	32,000
Data processing labor	6,720	10,667
Ground control surveying (rapid control) ¹	4,000	80,000
Ground control surveying (high accuracy control) ¹	10,000	200,000
Total (with rapid control)¹	40,880	199,167
Total (with high accuracy control)¹	46,880	319,167

¹Two sub-scenarios are considered here, depending on whether rapid or high accuracy ground control is used.

2.7.2 Outsourcing the terrestrial SFM photogrammetry service

As described for the case of outsourcing the UAV SFM photogrammetry service in section 2.6.2, commercial services are at this time not well established, and for that reason it is difficult to estimate what the potential costs from contracting commercial service providers in a near future may be. In any case, the costs are expected to be similar to those reported for the in-house scenario reported in the past section.

Table 13. Summary of costs for outsourcing the terrestrial SFM photogrammetry service

Item	Cost estimate	
	Low	High
Outsourcing terrestrial SFM photogrammetry service	40,880	199,167
Total	40,880	199,167

*Taking the same total values as in table 12. Only the high accuracy case is shown.

2.8 Mobile SFM photogrammetry costs

2.8.1 Building in-house mobile SFM photogrammetry expertise

Mobile SFM photogrammetry requires a different type of camera, due to the speed at which the platform is moving. Field tests for this project have used an Epic-X camera produced by commercial developer RED, which allows for high resolution (12 megapixels) and high frame capture rates (30 frames per second) simultaneously. Such cameras have a market value of \$ 40,000 to \$ 50,000. Other hardware and procedures are the same as for the UAV SFM photogrammetry case, minus the UAV and the Nikon D800 camera, and those costs are expected to be similar.

Table 14. Summary of costs for in-house mobile SFM photogrammetry expertise

Item	Cost estimate	
	Low	High
RED Epic-X Camera	40,000	50,000
Computer hardware	1,500	2,500
Analysis software	2,000	15,000
Surveying equipment	5,000	50,000
Annual data storage	500	5,000
Data collection labor	20,160	32,000
Data processing labor	6,720	10,667
Ground control surveying (rapid control) ¹	4,000	80,000
Ground control surveying (high accuracy control) ¹	10,000	200,000
Total (with rapid control)¹	79,880	245,167
Total (high accuracy control)¹	85,880	365,167

¹Two sub-scenarios are considered here, depending on whether rapid or high accuracy ground control is used.



Figure 5. Photographs mosaic and hillshade representation of the digital elevation model generated from mobile SFM photogrammetry, at the Cincinnati site.

2.8.2 Outsourcing the mobile SFM photogrammetry service

As described in section 2.7.2, the outsourcing of this emergent technology is only in its infancy, and as such, the costs and market value of services are difficult to establish, but are expected to be comparable to the costs estimated for the in-house case presented in section 2.8.1.

Table 15. Summary of costs for outsourcing the mobile SFM photogrammetry service

Item	Cost estimate	
	Low	High
Outsourcing mobile SFM photogrammetry service	79,880	245,167
Total	79,880	245,167

*Taking the same total values as in table 14. Only the high accuracy case is shown.

3. Benefits from each technology and comparison with their costs

3.1 Defining information goals and expected performance in the context of GAM

Assessing the benefits and quantifying them in monetary terms is a challenging but necessary step in formal cost-benefit analysis (e. g. Boardman et al., 2006; Zerbe and Bellas, 2006). As mentioned before, the benefits of the technological applications discussed in this report can only be evaluated in the context of geotechnical asset management, as an input for monitoring the performance of the assets. A general justification for the need of transportation asset management has been discussed extensively by several authors, e. g. Cambridge Systematics, Inc. (2002), and AASHTO (2011). Explicit examples of cost benefit analysis studies for the implementation of

transportation asset management systems at the State transportation department level are given by Dye Management Group, Inc. (2009), and Amekudzi et al. (2011). More specifically, the case for the implementation of geotechnical asset management has been discussed extensively by Sanford Bernhardt et al. (2013), Stanley & Pierson (2013), and Vessely (2013).

In the context of those studies we assume in general that the implementation of transportation asset management systems, and in particular geotechnical asset management systems is justified in a significant number of cases, from a cost-benefit perspective. We limit the goal of this report to presenting the relative benefits provided by the remote sensing methods to the geotechnical asset management system, based on the information content value of the products generated from them. The rationale behind the analysis will be the need for monitoring information by the geotechnical asset management system, as explained in the rest of this section. Based on the characteristics of their information value, we will discuss their strengths and weaknesses and determine what applications the different methods are most appropriate for.

Geotechnical asset management incorporates monitoring and assessment of the assets conditions and performance into a decision making process, to allocate resources for the purpose of maintaining the assets optimal performance, and extending its service life (Sanford Bernhardt et al., 2013; Stanley and Pierson, 2013; and Vessely, 2013). Ideally the monitoring and condition assessment would happen within a model for the expected life-cycle deterioration curve of the asset (Sanford Bernhardt et al., 2013; and Vessely, 2013), but in practices such models are not well established, and other proxies and heuristic approaches are taken instead, such as asset condition rating systems (Stanley and Pierson, 2013).

Geotechnical asset performance reduction and deterioration may happen in many different ways, and will be dependent on the type of asset and the type of damage or wear to which the asset is subject too. Surface damage and wear will be evident from visual inspections, but for many geotechnical assets the most critical types of deterioration will be due to internal damage, leading in some cases to the asset failure, and in extreme circumstances in a catastrophic way. For instance, cut slopes adjacent to transportation corridors may suffer from surficial degradation (e. g. rill erosion, etc.), but they could also experience changes in the internal stress and strength of

the rock or soil mass, resulting in large deformation and potentially a catastrophic failure. The risk approach to geotechnical asset management aims to manage such kind of performance degradation (Vessely, 2013).

Through timely intervention in response to the asset performance degradation, the asset management system aims to extend the service life. Based on the continuous monitoring of the assets behavior, the required maintenance and periodic repair of the asset is provided. Such intervention is intended to happen before irreversible damage makes asset replacement the only option, or even worse, a catastrophic failure cause loss of human lives and extensive damage to infrastructure and private property. The strategic goal of a GAM system is to minimize the long term cost related to maintaining an operational transportation corridor, and at the same time maximize the benefits obtained from the corridor, e. g. maximizing users' safety, reducing economic costs, minimizing congestion, and minimizing environmental impacts.

For an efficient intervention in terms of maintenance and repairs, it is necessary to judge when the benefit of the intervention outweighs its cost, considering the possible outcomes of the alternatives (e. g. investing in a given level of maintenance and repairs, vs. not doing so). The monitoring of the asset by itself will not provide a decision on this issue, it will only give information on the assets state. To make an efficient decision it is necessary to consider the possible outcomes in terms of the agency's or program performance goals, in a risk and uncertainty framework. The process can be framed within a "decision support system" (DSS): a system that facilitates the organization of the monitoring information as an input into the decision process, provides decision rules or criteria to the user, and guides the decision making process to a final decision outcome, without limiting the user's autonomy of choice and interpretation of the information. Such a system is currently under development as part of the project, and will be presented as a deliverable product in a later stage.

The remote sensing methods studied in this project can provide a wealth of data on the surficial characteristics of the geotechnical assets being monitored. Surface geometry, texture, and spectral (visible from the photography, microwave from InSAR, and infrared from the LiDAR) reflectivity properties can be recovered from the surface being analyzed. However, for the

purpose of assessing the assets state, the main focus will be on the geometric or shape changes of the asset surface over time. Such changes will correspond to surface deformation or displacement of different types. As mentioned previously, the interpretation of the significance and possible implications of the surface deformation for the asset's state and performance, will depend on the asset type, the deformation characteristics, and the specific model that is being used to interpret the deformation information. All this aspects will be covered in detail in other parts of the project, and will be reported accordingly in the respective deliverable product reports.

For the general purpose of describing the merits and benefits of the different remote sensing methods here evaluated, we will focus on a few information content criteria that are relevant to the deformation characterization of the assets surface. For LiDAR and photogrammetry methods the information retrieved from the surface can be described as a discrete sampling of points, although the sampling process is finite and the samples in reality correspond to small areas instead of infinitesimal points (Shan and Toth, 2009). The sampling set will always consist of a finite number of samples, and will therefore always represent an incomplete sampling.

The accuracy with which the different methods represents the surface is fundamental for measuring displacements over time, low accuracy and high noise levels will hide small displacements (the signal) in the errors and noise. The accuracy of the point locations in three dimensional space will in part determine how well the dataset represents the real surface. Highly accurate locations of the sampling points in space will result in a highly accurate representation of the surface geometry or shape. Comparing that surface geometry or shape at different times will allow us to characterize and quantify the surface movement (Shan and Toth, 2009).

In contrast to LiDAR and photogrammetric methods, InSAR methods measure the surface displacement directly, by measuring the phase difference of radar waves reflected by the target surface (Cutrona, 1990; Zebker et al., 1994; Bürgmann et al., 2000), and therefore the expected errors are those directly involved with this process, instead of errors related to the representation of surface geometry by a sample of points.

The fidelity with which the sampling points represents the surface depends also on the point density: the closer the point spacing is, the more information of the surface has been sampled. Denser point clouds allows to resolve finer details and therefore to detect smaller changes that may occur over time, i. e. smaller deformations. From this discussion, two main criteria can be defined to represent the relative benefits of the different methods:

- a. Geometric or shape accuracy of sampling points, measured by some metric of the expected location error in three dimensional space.
- b. Spatial point or information density, measured by the average distance between points, or conversely, by the number of points per unit surface area.

We will use these criteria in the next section to characterize the information content of the different technologies and compare their strengths and weaknesses, and find the best applications for them.

3.2 Evaluation of information content and benefits from each remote sensing method.

3.2.1 Point location and surface displacement accuracy

The accuracy of surface displacement or deformation for each of the remote sensing methods discussed in section 2 will depend on partially controlled (e. g. instrument to target distance or flight height for LiDAR and photogrammetry) and virtually non-controllable (e. g. random measurement noise for LiDAR and photogrammetry) factors. A range of “optimistic” accuracy values that can be considered typical of each method will be considered, assuming data acquisition under relatively good conditions. Accuracy reporting varies across different sources, but here we are going to report comparable measure of dispersion or error, like the 2 standard deviations width of the error distribution, the width of the 95% confidence interval for point measurements, or the RMSE of the point positions with respect to a standard.

The accuracy with which InSAR can measure surface displacements in the line-of-sight from the sensor to the surface can be measured in millimeters (Crosetto et al., 2010; Ferretti et al., 2011), as illustrated by figure 6. Such extremely high accuracies are very difficult to match by LiDAR and SFM photogrammetry. The position accuracy of aerial LiDAR, as quoted by (Shan and Toth,

2009), can range from 3 cm for low altitude flying aircraft (~ 500 magl), to ~ 25 cm for higher altitude flying aircraft (4,000 magl). Terrestrial LiDAR can achieve very high position accuracies, reaching an accuracy of 3 mm for short (50 m) instrument to target distances, but the accuracy falls to 5 cm at long (700 m) distances. Mobile LiDAR equipment can achieve accuracies between 5 and 30 cm, similar to aerial LiDAR surveys (Shan and Toth, 2009). The differences in accuracy between the different LiDAR platforms are influenced mainly by the instrument to target distance (usually larger for aerial LiDAR and shorter for terrestrial LiDAR), and the georeferencing error introduced to mobile platforms by their movement.

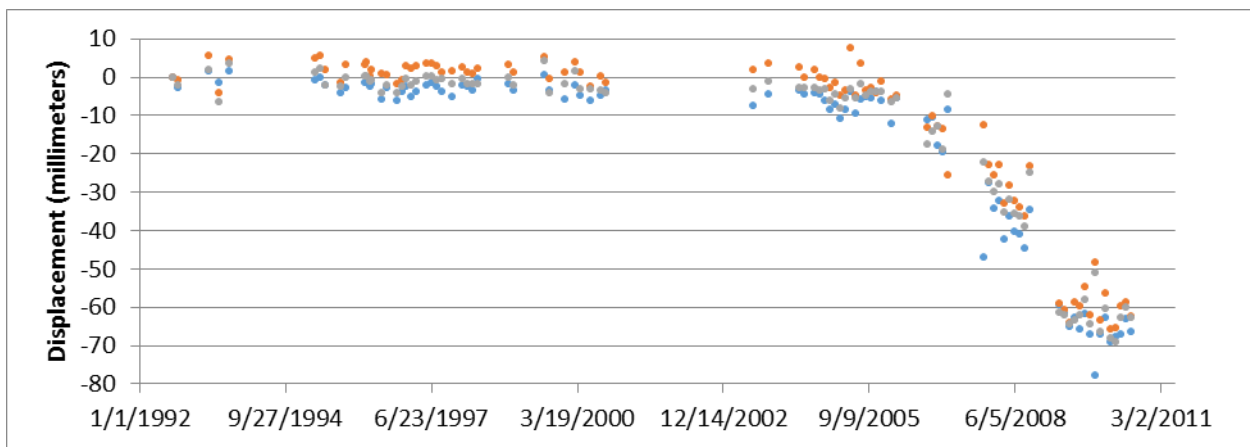


Figure 6. InSAR derived displacement on an unstable slope at the Nevada test location. The dispersion of data is on the order of only a few millimeters.

Typical values for UAV SFM photogrammetry errors reported in the literature by authors using the same software we are using for this project (Photoscan by AgiSoft ®) range between 3 cm and 5 cm in non-vegetated areas, flying at elevations between 130 m and 165 m above the target (Pavelka and Sedina, 2015). These errors were obtained by comparing point locations to ground control points surveyed with high precision differential GPS. Precision testing performed as part of our project include fitting planar and quadric surfaces to sets of points collected on “plane” building walls, and using the fitting errors to quantify the overall precision of the dataset. This was compared with simultaneous terrestrial LiDAR acquisitions on the same target walls. Figure 7 shows the residuals for the both the SFM photogrammetry and LiDAR point cloud fits.

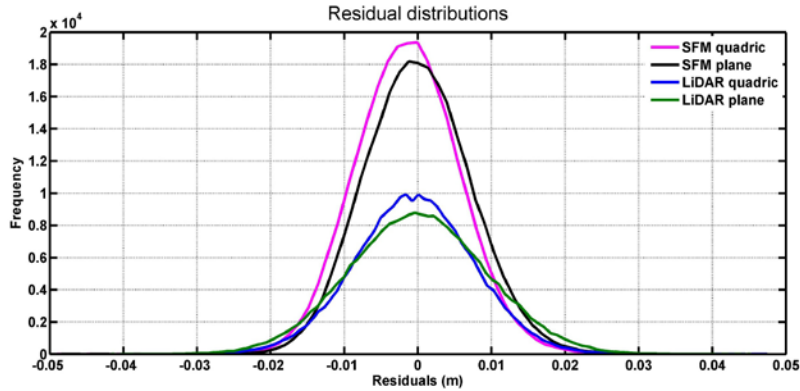


Figure 7. Residuals obtained from fitting planar and quadric surfaces to SFM photogrammetry and LiDAR point clouds obtained from large “planar” building walls.

Errors obtained from this test show that SFM photogrammetry and LiDAR produce comparable results, but SFM photogrammetry slightly outperforms the LiDAR dataset. When the dispersion measure is plotted against the distance from the instrument a tendency of increasing error is seen in the data (see figure 8). This dataset again confirms that for distance as far as ~ 65 m the SFM photogrammetry dataset seems to outperform the LiDAR dataset.

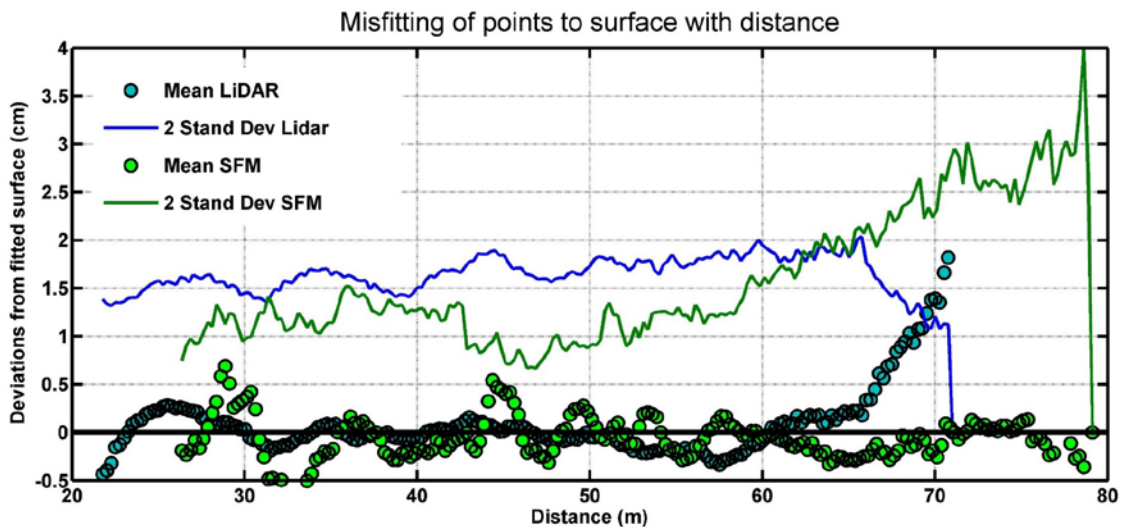


Figure 8. Deviations of the SFM photogrammetry and LiDAR points from the fitter planar and quasi-planar (quadric) surfaces, and the variation of dispersion with distance.

These data indicate that errors are typically between 1 and 2 cm, for distances up to 65 m. A note of caution is however needed at this point. The apparent better fit of the SFM photogrammetry

data with respect to the LiDAR dataset may be an artifact, due to the ability of the SFM photogrammetry algorithm to adjust the point to simple planar or quasi-planar surfaces. Ongoing testing with more complex surfaces, including the natural terrain surfaces from out field test sites may help to either confirm the tendency seen in the building wall tests, or show a discrepancy and possibly pointing at a more complex behavior of the SFM photogrammetry error behavior.

Finally, the accuracy of the control points will have a significant impact in the accuracy of the measured LiDAR and SFM photogrammetry data. We present two scenarios, a high accuracy control scenario in which the control points are surveyed with high precision methods (e. g. differential GPS, total station, etc.), and a rapid control scenario, in which the control points are surveyed with high performance hand-held GNSS receivers. In the high accuracy scenario the errors are expected to be less than 10 mm, and therefore are not expected to contribute significantly to the measurement errors of the different technologies. In the rapid control scenario the errors are expected to be on the order of a few centimeters, impacting the overall accuracy of the measured point positions of the LiDAR and SFM photogrammetry datasets. In the high accuracy control scenario we do not include extra errors in the measurements, but in the rapid control scenario errors in range of 5 to 10 cm are added to our estimation of uncertainty.

3.2.2 Point density

InSAR processing can produce high point density datasets in the form of interferograms, or low point density datasets in the form of persistent scatterers. Obtaining interferograms may not be possible when decorrelation affects a majority of the pixels, but persistent scatterers may still be an option in those cases, allowing to extract information from the SAR images (Ferretti et al., 2011). Because many of the SAR sensors cannot penetrate through a vegetation cover, leading to decorrelation of pixels, persistent scatterers may be the only option in those cases. And in heavily vegetated areas, not even persistent scatterers may be a viable option to extract surface displacement information.

Over areas where it is possible to generate interferograms the point density will be limited by the image pixel size (see table 1), which ranges from 1 to 1,000 m, but typically falls between 1 and 100 m, giving point densities between 10^{-2} to 1 points per m^2 . In the case of persistent scatterers

the point density is highly dependent upon the presence of scatterers on the ground, and may be as low as zeros, but is typically on the order of several thousand per scene, for areas that include abundant exposed rock, human build artifacts, and other objects that can act as persistent scatterers. Figure 9 shows the location of persistent scatterers over the Nevada field site. The point density in that case the point density is $\sim 7 \times 10^{-4}$ points per m^2 . We can expect that point densities will be between the orders of 10^{-5} to 10^{-2} points per m^2 .

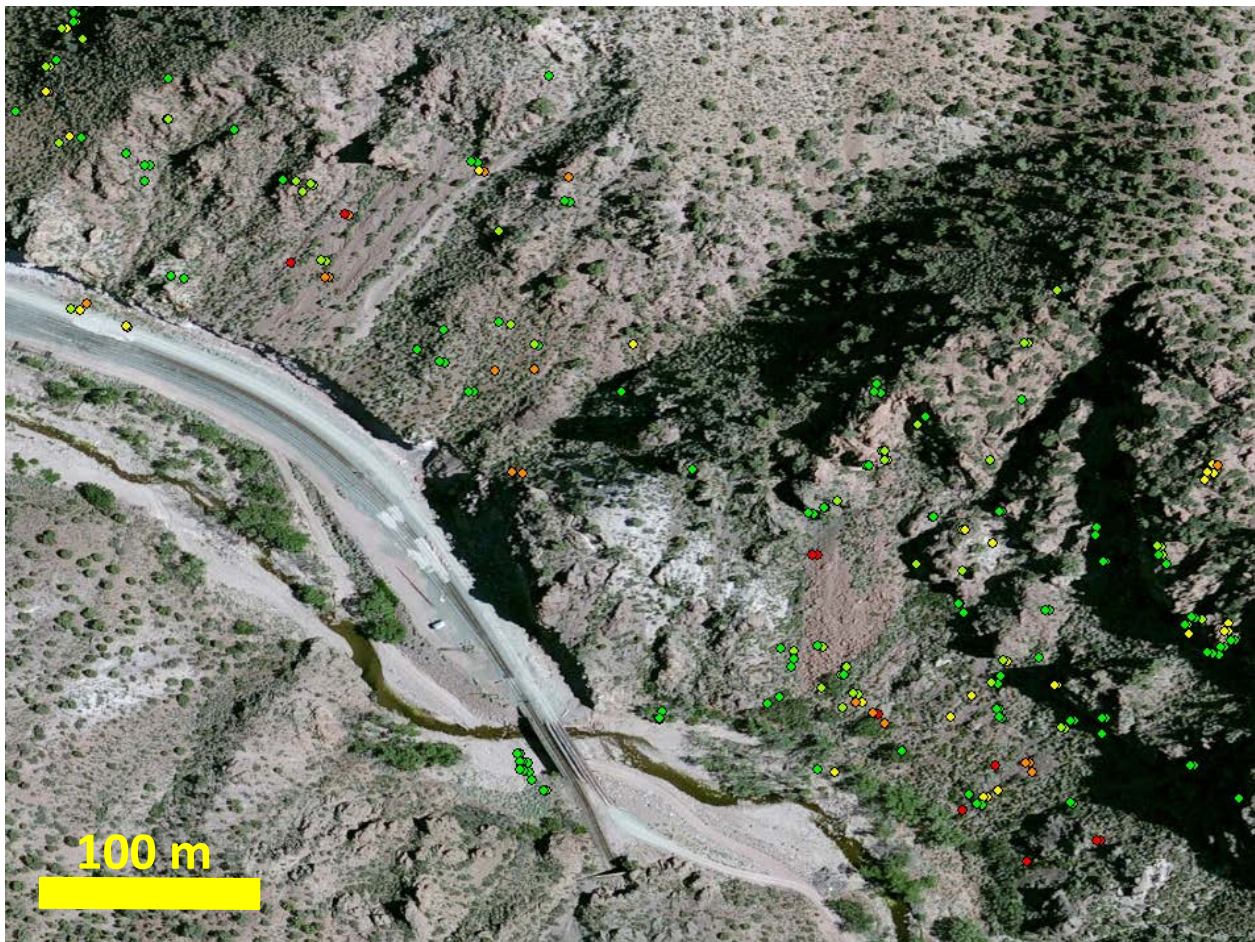


Figure 9. Distribution of persistent scatterer points on the slopes near the Nevada field test site.

Point separations for LiDAR datasets will depend from three variables, the scanning angle increment, the beam divergence angle, and the distance to the target surface. Minimum scanning angle increments are usually on the order of 0.01° . At that angle increment and for an instrument to target distance of 100 m the separation between points will be 1.7 cm (see figure 10). Using

large scanning angle increments, point separations on the order of a few cm will result. Large angle increments may be using to speed up the field data collection.

Point separations for the SFM photogrammetry depend on the camera optics (i. e. the focal length), the camera sensor size, and the distance from the camera to the target. Figure 10 also shows the separation between points for different lenses used with the Nikon D800 camera. The final point separation will be lower than the values shown in the graph, because the SFM photogrammetry software will not be able to locate all the pixels from the photograms in three dimensional space. How many pixels end up being used depends in part from the setting the user chooses when processing data in the SFM photogrammetry software, but it also depends on the quality of the images and the ability of the software to match the pixels and assign them a position in three dimensional space. From the figure it becomes evident that typical point separations at distances of less than 150 m from the target are on the order of a few cm.

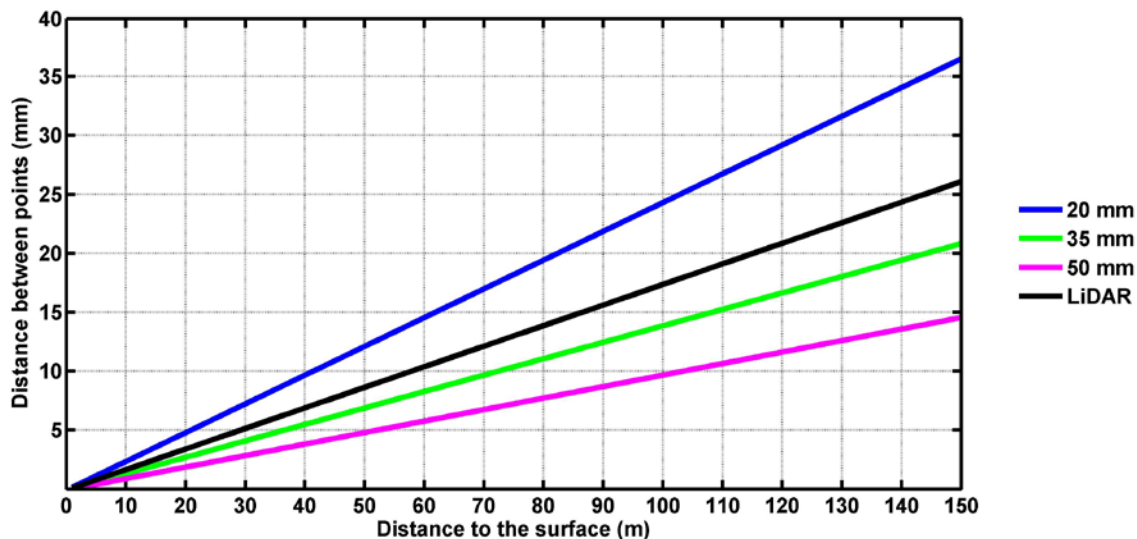


Figure 10. Point separation for different camera lenses and compared to the LiDAR point spacing using an incremental angle step of 0.01° . The camera point separations shown assume that all the pixels in the images have been location in the three dimensional space, which is usually not the case.

3.3 Synthesis of costs and benefits.

To integrate the analysis of the costs and benefits from all the technologies and methods we compile the information on accuracy, point density and costs in table 16. Cost are taken from the total cost in tables 2 through 15, and accuracies and point densities are taken from section 3.2.

Table 16. Comparison of costs and information content from each technology

Type of survey	Cost estimate (\$)		Accuracy range (mm)		Point densities range (per m ²)	
	Low	High	Low	High	Low	High
InSAR (In-House, persistent scatterer)	36,700	287,500	2	10	10 ⁻⁵	10 ⁻²
InSAR (In-House, interferogram)	36,700	287,500	2	10	10 ⁻²	1
InSAR (Outsourced, persistent scatterer)	20,000	250,000	2	10	10 ⁻⁵	10 ⁻²
InSAR (In-House, interferogram)	36,700	287,500	2	10	10 ⁻²	1
Aerial LiDAR	25,200	541,000	50	250	10 ²	10 ⁴
Mobile LiDAR (In-House, rapid control)	69,560	1,054,100	50	300	10 ²	10 ⁴
Mobile LiDAR (Outsourced, rapid control)	42,200	717,000	50	300	10 ²	10 ⁴
Terrestrial LiDAR (rapid control)	72,200	760,000	10	50	10 ²	10 ⁴
Terrestrial LiDAR (High accuracy control)	100,200	1,002,000	3	20	10 ²	10 ⁴
UAV photogrammetry (rapid control)	41,380	209,167	80	100	10 ²	10 ⁴
UAV photogrammetry (High accuracy control)	47,380	329,167	30	50	10 ²	10 ⁴
Terrestrial photogrammetry (In-House, rapid control)	40,880	199,167	70	100	10 ²	10 ⁴
Terrestrial photogrammetry (In-House, high accuracy control)	46,880	319,167	20	50	10 ²	10 ⁴
Mobile photogrammetry (In-House, rapid control)	79,880	245,167	70	100	10 ²	10 ⁴
Mobile photogrammetry (In-House, high accuracy control)	85,880	365,167	20	50	10 ²	10 ⁴

Table 16 shows a wide variety of accuracies, point densities and costs for all the methods. Although broad, the costs ranges for the different technologies cover similar order of magnitude, which shouldn't be surprising considering that our scenario selection in section 2 was purposely wide. Narrowing down the cost ranges would require defining much more specific scenarios, and

that can only be done by defining factors like the geographic, the type of assets being consider, etc. This is something an agency could more easily do for their area of operation, using the unit costs discussed in section 2. In-house versus outsourced costs also have similar cost ranges, and in some cases this was an explicit assumption used in section 2.

The higher costs for in-house scenarios in many cases reflect the fact that initial investment costs (e. g. buying hardware and software for data collection and analysis) are implicitly spread over the one year basis assumed for all the calculations, which in a very short time period for the return on investment in most cases. Spreading the cost related to initial costs for the in-house scenarios over a period of 3 or 6 years may be a more realistic approach; however, changing the cost calculations for such cases will not significantly affect the cost ranges shown in table 16, as most of the costs for those cases comes from the long term components (e. g. data collection and analysis labor) rather than the initial investment. In summary, as it would be expected, the costs of developing in-house capacities for data collection and analysis will only be justified if the work load is large, and over a long enough period of time to recover that investment. For smaller operations which make less use of the technologies it will could be more economically efficient to outsource such services.

There is also a clear difference in costs depending on what methods is used to establish control points for the survey. As it would be expected, the more precise surveying will be more expensive, especially for large areas. The type of survey used for the control points will also have an impact on the accuracy, resulting in a tradeoff between cost and accuracy. To achieve very high accuracies will increase the cost of the survey, but higher accuracies may be needed to detect very subtle movements or changes in the geotechnical asset surface. Defining the required level of precision will depend on the asset type and its possible degradation or failure mechanisms.

The accuracy information given on table 16 also covers overlapping ranges, from a few millimeters in the case of InSAR, to a few centimeters in the case of LiDAR and SFM photogrammetry. As discussed in section 3.2.1, there is a noticeable difference between the high accuracy control and thee rapid control methods, and this is reflected in table 16, by adding 5 to

10 cm of error to the rapid control cases. As discussed previously, there is a tradeoff between the accuracy of the survey and its cost, and the difference in costs can be substantial; evaluating if such a cost is justified will depend on how important it is to get very high accuracy data, e. g. in the case where small deformations could have large consequences.

Point density data in table 16 show a very wide range, from the relatively low point densities of InSAR data, to the very high point densities of LiDAR and SFM photogrammetry. Applications over large swaths of a transportation corridor aimed to identify potential problematic areas that are showing displacement, will not require high point densities, but may require high accuracies to detect small movements. In such cases InSAR may be the best methods of choice.

Applications over smaller areas, where the details of movement over the scale of a few meters are relevant, could benefit mostly from the high point densities achieved by LiDAR and SFM photogrammetry.

LiDAR and SFM photogrammetry methods provide comparable data in terms of cost, accuracies, and point densities. The initial high cost of LiDAR equipment makes the SFM photogrammetry attractive for smaller work volume cases. The versatility given by the UAV platform can be an important advantage for the SFM photogrammetry in some cases, although this does not become immediately evident from the data here presented. In general the SFM photogrammetry seems to present a valuable alternative to the LiDAR technology in some cases, but given the status of LiDAR as a well-tested and established surveying technology, it will take more development and testing of the SFM photogrammetry methods for its wider adoption as a comparable surveying technology.

4. Conclusions

Cost estimates for the application of the different remote sensing techniques discussed in this report vary over a large range of values, mainly because of the wide choice of scenarios chosen for the analysis. A narrower range of costs can be estimated by choose more specific application conditions, something a potential user could do using the unit costs given in section 2 as a guide. Although the estimated costs cover similar ranges in some cases, important differences arise in

between other cases, due to the choice of in-house or outsourcing of the service, as well as the required level of accuracy.

The choice on whether it is cost effective to develop in-house capabilities or outsource the service will depend largely on the amount of surveying done by the user. The tradeoff between cost and accuracy or point density will depend on the specific application of the survey, particularly, the type of asset being assessed and the type of deterioration or possible failure mechanism.

The SFM photogrammetric methods seem to deliver results comparable to LiDAR technology, and in some cases outperform LiDAR products (e. g. the precession test shown in figure 8) for a lower cost. The viability of SFM seems promising, but we expect that it will requires further testing and validation before it can be adopted widely as a surveying technology, at the level of the well-established LiDAR technology. Further testing and validation throughout this project aims to contribute to this goal.

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