Computer-assisted 3D terrain analysis using high-resolution imagery and digital elevation data

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ABSTRACT
3D terrain analysis from stereoscopic viewing of contact air photo prints has long been a staple tool for engineers and geoscientists working on a wide range of engineering, geoscience and resource development applications. However, advances in the availability and quality of digital air photos and satellite images, coupled with increasingly improved digital elevation models (DEMs), have led to the development of new techniques for viewing the landscape in three dimensions. Two relatively easy to apply techniques are the creation of 3D colour anaglyphs from digital stereo pairs and from imagery "draped" over digital elevation data. The usefulness of these techniques for different applications depends largely on the spatial and spectral resolution of the datasets and study objectives. Case study examples drawn from recent consulting projects illustrate the level of terrain detail and interpretive indicators that can be derived from digital products. These range from regional scale multispectral satellite images to high resolution aerial images, and from widely available regional digital elevation data to detailed bare earth LiDAR data. While most 3D views built from digital datasets do not match the level of terrain detail available from stereoscopic examination of traditional film contact prints, significant advances have been made in recent years. As a result, working in digital formats provides strong incentives for utilizing these formats. These advantages include an array of tools to aid 3D visualization (e.g., oblique 3D images, 2D cross-sections, simulated flythroughs), the ability to utilize spectral analysis for specialized applications, immediate access to up-to-date high resolution views of areas of interest, and efficiencies gained from mapping within a GIS environment.

RÉSUMÉ
Pour longtemps les ingéniers et géoscientifiques ont utilisé les photos aériennes pour l'analyse de terrain en trois dimensions. Ces techniques sont utilisées pour divers applications en ingénierie, geoscientifiques et le développement des resources. Cependant, les avances en disponibilité et qualité des photos aériennes numériques et images satellite, et aussi des modèles numerique d'élévation améliorés, ont amené à la développement de nouvelles techniques pour examiner le paysage en trois dimensions. Il y a deux techniques qui sont relativement facile à appliquer. Premièrement, c'est la création d'anaglyphe en trois dimensions, utilisant des couples stéréoscopiques numériques et deuxièmement , c'est l'analyse des images superposées sur données numeriques d'élévations. L'utilité des ces techniques pour divers applications dépend sur la résolution spatiale et spectrale de l'ensemble de données, et sur les objectifs de l'étude. Les examples d'études de cas pris de projects de consultation recent montrent le niveau de détail de terrain, et les indicateurs d'interprétations qui peuvent être dérivés des produits numériques. Il peut s'agir des images satellite multispectrale à l'échelle régionale, jusqu'à des photographies aériennes haute resolution. Aussi, il peut s'agir de données numériques d'élévation qui sont largement disponibles, jusqu'à des données de LiDAR montrant une image détaillée de terre nue. Tandis que le plupart de vues en trois dimensions construits de données numériques n'égale pas le niveau de détail disponible par l'examen stéréoscopique de photos aériennes traditionnel, pendant ces dernières années nous avons vu des avancées significatives. À la suite, le travail en format numérique donne de fortes incitations pour utiliser ces formats. Les avantages comprendent divers outils pour aider avec la visualisation en trois dimensions (par exemple, les images en trois dimensions obliques, les coups transversals en deux dimensions, les vols simulés), l'abilité d'utiliser l'analyse spectral pour des applications spécialisées, l'accès immediate au vues, à jour, en haute resolution pour les domains d'intérêt et l'éfficacité atteint par travailler dans un environnement de SIG.

1 INTRODUCTION

Terrain analysis from stereoscopic (3D) viewing of contact air photo prints has long been a staple tool for engineers and geoscientists working on a wide range of engineering, geoscience and resource development applications. However, advances in the availability and quality of digital air photos and satellite images, coupled with increasingly improved digital elevation models (DEMs), have led to the development of new techniques for viewing the landscape in three dimensions.

The purpose of this review is to evaluate available techniques that can be most easily and cost effectively applied with common desktop computers and readily available software. Available techniques have been reviewed and those with the most promise were investigated in more detail to determine the degree of variability in the quality of the digital product and its usefulness for several common types of applications in different terrain settings.

2 DEVELOPING DIGITAL 3D IMAGES

Computer monitors, like traditional contact air photo prints, display images on a flat, two-dimensional plane. In order to create a three-dimensional image on such media, the user requires two important components. First, a *stereo pair* of images must be obtained or created. Second, some method of forcing the user to view the stereo pair simultaneously but separately (*stereo separation*) is required. The viewer's mind then fuses the two stereo pair images into a single three-dimensional view.

Traditional air photo interpretation uses overlapping vertical air photos to provide the stereo pair, and special viewing instruments called stereoscopes to force the stereo separation in the viewer. The challenge in computer-assisted 3D has been to duplicate both processes in a digital environment without the use of extremely complicated, bulky and expensive peripheral devices.

2.1 Digital Creation of Stereo Pairs

A stereo pair of images is essential for creating realistic three-dimensional images for use in computer-assisted 3D terrain analysis. A stereo pair is a set of two images in which objects, features or terrain common to the two images exhibit a discernable level of *parallax*. Parallax is the apparent shift in the position of an object relative to a static background due to changes in viewing position and distance from the viewer. In the case of vertical air photos, the change in viewer position is kept at a fixed amount; the degree of parallax exhibited by the objects, features and terrain in the stereo pair is thus due to changes in distance to the viewer (or, more precisely, the distance to the focal plane of the camera capturing the aerial photo). The closer the object, feature or terrain moves to the viewer, the greater the amount of parallax exhibited in the stereo pair. If the aircraft from which the air photos are taken maintains a constant altitude during the photography then the changes in distance to the viewer can be ascribed to variation in elevation (for terrain) and height (for objects) in the stereo pair.

In computer space, the stereo pairs can come from two distinctly different processes. One method is to import a set of overlapping vertical aerial imagery from an outside source, such as scanned versions of traditional air photo contact prints or frames captured directly by a digital aerial camera. This method represents the closest approximation to the use of traditional stereo contact air photos. The parallax exhibited by objects, features and terrain in the common area of these stereo images is a built-in function of the internal geometry of the images themselves, so no additional software processing is required at this stage.

A second method of deriving stereo pairs is to use a digital elevation model (DEM) to build a three-dimensional representation of the underlying terrain. Imagery of the area, from either digital aerial photography or high-resolution satellite imagery, is 'draped' over the 3D representation to produce a three-dimensional terrain model. Specialized software routines then calculate the necessary amount of parallax for each terrain feature and create a stereo pair of images from the terrain model.

The underlying DEM can come from several sources. The most common are raster DEMs, in which the digital number of each pixel in the DEM directly corresponds to elevation above sea level. Regional-scale DEMs covering all of Canada, such as the Canadian Digital Elevation Database (CDED) dataset are available to the general public free-of-charge. The DEM products derived from NASA's Shuttle Radar Topography Mission (SRTM) are also freely available, and cover the entirety of the world's landmass from 60° south to 60° north latitude. Provincial mapping agencies may offer more detailed DEM data sets of a given area derived from survey data, contour data, or even photogrammetric techniques. LiDAR is another potential source of DEM data, and terrain models built on LiDAR data can often create impressively realistic 3D views of the surface.

Each method of digitally creating a stereo pair has its own strengths and weaknesses. Imported stereo pairs from scanned air photo prints or digital cameras contain parallax information on every surface and object within the stereo pair, meaning features such as trees, buildings, fence lines and even vehicles will be perceived in 3D, just as they are when traditional contact prints are viewed with a stereoscope. By contrast, stereo pairs derived from terrain models tend to contain parallax information on the underlying terrain only. Features such as trees and buildings will appear 'flat' against the otherwise three-dimensional terrain. As well, subtle or very small alterations in topography may or may not be present in such a view depending on the resolution of the underlying DEM.

Stereo pairs from DEMs, however, can be created from single air photos or satellite images, or even from topographic or thematic maps overlain on the terrain model. Factors such as scale and the amount of vertical exaggeration present in the view can easily be adjusted when the software is calculating the parallax for the final stereo pairs, whereas when the stereo pairs are imported from an outside source such factors tend to be fixed. Specialized software can even render stereo pairs of a terrain in orientations other than vertical, to produce three-dimensional oblique representations of a surface. At its most sophisticated, this technology could be used to render 3D animations and flythroughs of a given area. Users will have to carefully consider their terrain analysis objectives and needs before choosing which of these two methods is most suitable (or best suited) for them.

2.2 Obtaining Stereo Separation

Creating a stereo pair of images is only the first step in rendering a three-dimensional view. What`s needed next is some method of forcing the user to view each half of the stereo pair simultaneously yet separately, a process termed *stereo separation*. When viewing traditional air photo contact print stereo pairs, a terrain analyst will use a pair of specialized glasses called a stereoscope. The stereoscope physically forces the user to view the halves of the stereo pair separately; the left eye views the left half of the stereo pair, while the right eye views the right half of the stereo pair. The user`s mind then fuses the two images back into a single view, using the levels of parallax exhibited by each surface in the stereo pair to develop a three-dimensional perspective of the image.

A number of technologies have been developed over the years to force stereo separation in the creation of three-dimensional views on a otherwise flat computer monitor. Perhaps one of the simplest and most familiar methods is the use of red-blue or red-cyan anaglyphs. This is essentially the same technology used to create "3D" movies back in the 1950s, and is still a popular means of creating 3D views in movies and video games today. One half of the stereo pair is displayed as shades of red, the other half as shades of cyan. The viewer wears a pair of anaglyph glasses containing one red lens and one cyan lens. The red lens filters out the red image of the stereo pair, while the cyan lens filters out the cyan image. This forces each eye to view a separate image, with the resulting fusion back into a 3D view. Anaglyphs can also be done using other colours, such as red-green and yellow-blue, but the red-cyan anaglyph process is most common.

In addition to colour anaglyphs, similar processes using different forms of filtered light have also been developed to produce stereo separation. One example is the use of vertical and horizontal polarization to produce the stereo pair and special polarized glasses to achieve stereo separation. Some polarization systems use clock-wise and counter-clockwise polarity to create the same effect.

Although simple to create, anaglyphs can experience colour casts and a phenomenon known as *ghosting*, the presence of subtle halos around certain features in the anaglyph, which some viewers find uncomfortable or distracting. Fortunately, most anaglyph software have processes to remove or minimize casts and ghosting in the final anaglyphs in all but the most extreme cases.

Some advanced photogrammetric and 3D modelling software utilize a different method of achieving stereo separation. Each half of the stereo pair is alternately projected on a high-speed computer or TV screen. The halves of the stereo pairs alternate up to hundreds of times a second, producing what appears to be a steady image. The viewer wears special glasses that synchronize with the alternating images on screen. As each half of the stereo pair is projected, the lens on the opposite eye is darkened or shuttered to prevent that eye from viewing the image. LCD shutter glasses are perhaps the best known of these methods, especially as TV manufacturers have recently begun to introduce 3D-capable televisions that utilize this technology.

3 CASE STUDY EXAMPLES

The following case studies give some idea of how 3D visualization using simple red-cyan anaglyph technology can be incorporated into terrain analysis studies. Of the various techniques available the authors have found red-cyan anaglyphs often provide the best combination of ease-of-use and suitable 3D image quality. LCD shutter glasses and polarization filters provide superior 3D image quality but require specialized (and often expensive) equipment. Red-cyan anaglyphs use only low cost red-cyan glasses. Moreover, red-cyan anaglyphs developed on a computer screen can be rendered to common image storage formats such as JPEG and TIFF and will work when printed on regular paper, allowing them to be integrated into technical reports and presentations. Figure 1 shows a typical red-cyan anaglyph generated from colour air photo digital imagery. Note that a pair of red-cyan glasses will be needed to view all the anaglyph images in this paper.

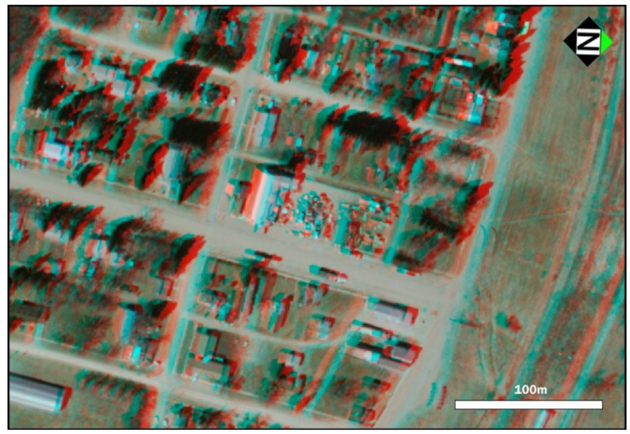

Figure 1. Red-cyan anaglyph created from a stereo pair of overlapping 0.6m colour digital air photos

Both imported stereo pairs and 3D views generated from imagery 'draped' over DEMs are regularly used. Both approaches have advantages and disadvantages that must be considered when deciding which method to use for a particular study area. Using existing stereo pairs of air photos, either scanned from contact prints or captured via digital aerial camera, often provides sharper, more realistic looking 3D views. Every conceivable surface in the image will have its unique level of parallax and thus every feature in the final anaglyph will have a true 3D appearance. The anaglyph in Figure 1, for example, was generated from a stereo pair of 0.6m colour aerial digital photos taken as part of the FlySask program carried out by the Saskatchewan Government. Trees, buildings and even vehicles appear in 3D in addition to regular variations in terrain.

In contrast, stereo pairs built from draped high-resolution imagery do not capture the parallax on all possible surfaces within an image, but rather calculate parallax for each part of the image based on an underlying digital elevation model. Typically features such as trees, cars, fence lines and buildings appear 'flat' in these types of anaglyphs. Figures 2a and 2b show an example of the difference between an anaglyph created from an existing stereo pair of overlapping air photos and one created by draping air photo imagery over a DEM. The image created by using overlapping air photos creates a more accurate representation of the relief than does the image created with the DEM (*e.g.,*note the point of land that extends northwestward from the east side of the reservoir)

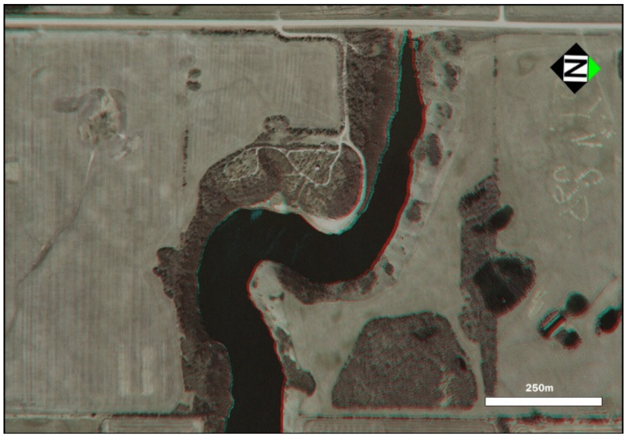

Figure 2a. Anaglyph of a small reservoir in eastern Saskatchewan, built from an existing stereo pair of overlapping 0.6m colour digital air photos

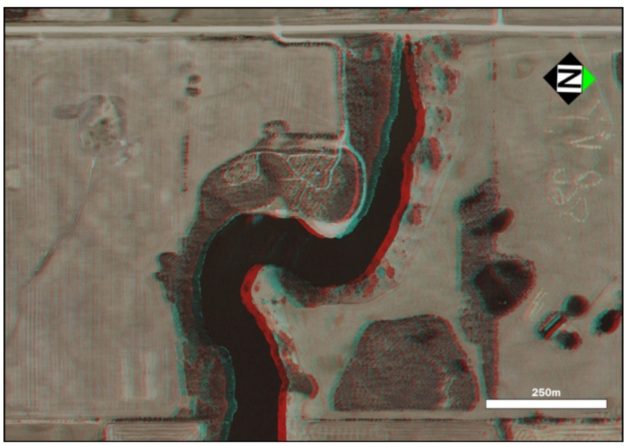

Figure 2b. Anaglyph of the same reservoir, built from a 0.6m colour digital air photo draped over SRTM 3arcsecond DEM data.

3.1 Case Study - Sand dune terrain near Vanscoy, Saskatchewan

Figure 3a shows a red-cyan anaglyph of an area of stabilized sand dunes approximately 12km southwest of Saskatoon, Saskatchewan, near the community of Vanscoy. The image was created from stereo air photo pairs. The dune terrain is developed on a large area of fine-grained glaciodeltaic sands that were deposited near the southern margin of Glacial Lake Saskatchewan (*ca.* Phase 5 of Christiansen, 1979). The dunes are vegetated with grass, shrubs and trees and are no longer actively moving. However, the fine soils are still subject to wind erosion if the vegetation is disturbed. The terrain is uncultivated and is used primarily for pasture and for residential acreage development. Thickness of surficial stratified drift deposits is in the order of 15m, and the dunes in the image exhibit a maximum relief of approximately 8 to 10m (as measured from the SRTM DEM dataset).

Figure 3a. Red-cyan anaglyph of dune terrain near Vanscoy, SK

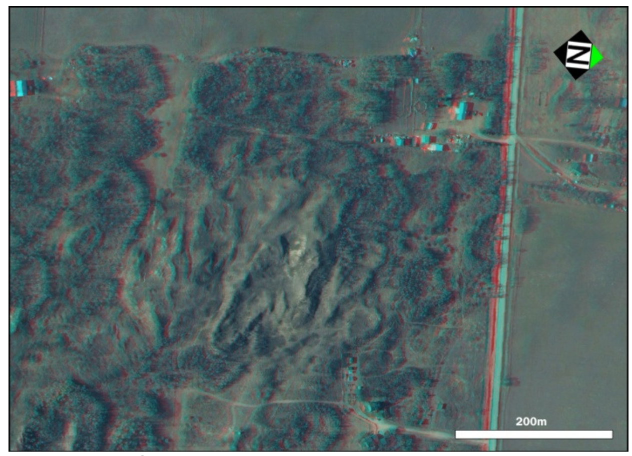

Figure 3b. Sand dune terrain anaglyph, built by draping FlySask 0.6m color orthoimagery over a 30m DEM derived from photogrammetric measurements.

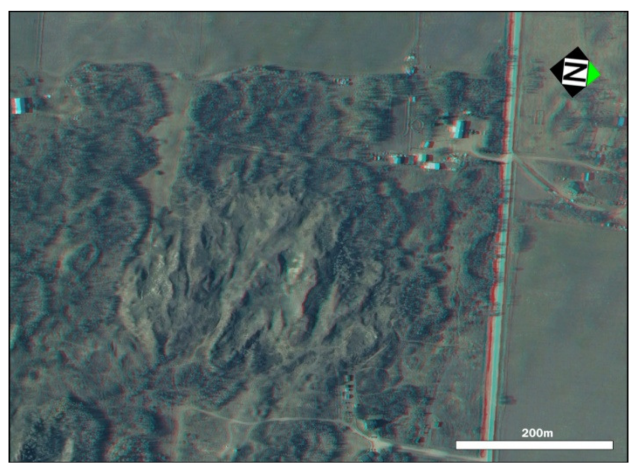

Figure 3c. Anaglyph of same dune terrain, but built by draping the FlySask 0.6m colour orthoimagery over NASA SRTM 3arcsecond DEM data

The degree to which anaglyphs created from imagery draped over elevation datasets accurately show the subtle variations in terrain that can occur in such an area depends on the resolution of the underlying DEM. The finer the spatial resolution, the more accurate the representation of the terrain in the final anaglyph. Figure 3b is an close-up anaglyph of the dune terrain, created by draping 0.6m FlySask colour orthoimagery over a DEM developed from photogrammetric methods. Figure 3c is an anaglyph of the same terrain, with the same 0.6m colour orthoimage, but draped over SRTM 3arcsecond DEM data. The photogrammetric DEM has a spatial resolution of 30m; the SRTM 3arcsecond DEM has a spatial resolution of 3 arcsecond, which in this part of Canada is equivalent to approximately 55m east-west by 90m north-south.

The SRTM derived anaglyph shows less terrain detail and a flatter appearance than the anaglyph derived from the 30m photogrammetric DEM, due to the coarser spatial resolution of the SRTM DEM. Both anaglyphs, in turn, show much less detail on the individual morphology of the dunes than that shown in the anaglyph is Figure 3a (which was derived from a stereo pair of overlapping air photos). However, the basic structure of the dune complex itself is still visible, as is the topography of the surrounding area.

3.2 Case Study - Key Lake, northern Saskatchewan

Figure 4 shows a red-cyan anaglyph of an area east of Key Lake, in northern Saskatchewan. The area is characterized by drumlinized moraine overlain in places by windblown sandy glaciolacustrine sediments, extensive ice-contact and outwash deposits, permafrost-affected peatlands, lakes and rivers (Schreiner 1984). Relief on the drumlins reaches 106m while large eskers are up to 10m in height. As a result of the diversity of landscapes and associated terrain materials, terrain mapping from aerial and satellite imagery is an important component of infrastructure development projects to avoid unstable foundation conditions and excessive cuts, plan site access and location construction material sources.

The anaglyph was built by draping panchromatic 2.5m SPOT orthoimagery over a DEM from the 1:50,000 series Canadian Digital Elevation Data (CDED) set. The CDED DEM has a spatial resolution of 0.75 arcseconds, which at the latitude of the image is equivalent to a spatial resolution of approximately 12.5m east-west by 23m north-south. Northeast-southwest oriented drumlins easily stand out in this anaglyph. A large esker and associated outwash deposits can be seen in the lower right-hand corner of the image.

One of the main advantages of draping satellite orthoimagery over a regional DEM dataset such as the CDED is the ability to show large areas of remote terrain in three-dimensions quickly and at a variety of scales. The image is approximately 20km across, and all parts of the anaglyph are displayed in correct 3D at the same time. Such a view would be impossible to create from stereo pairs of overlapping air photos unless the photos were taken at an extremely small scale. Regional scale

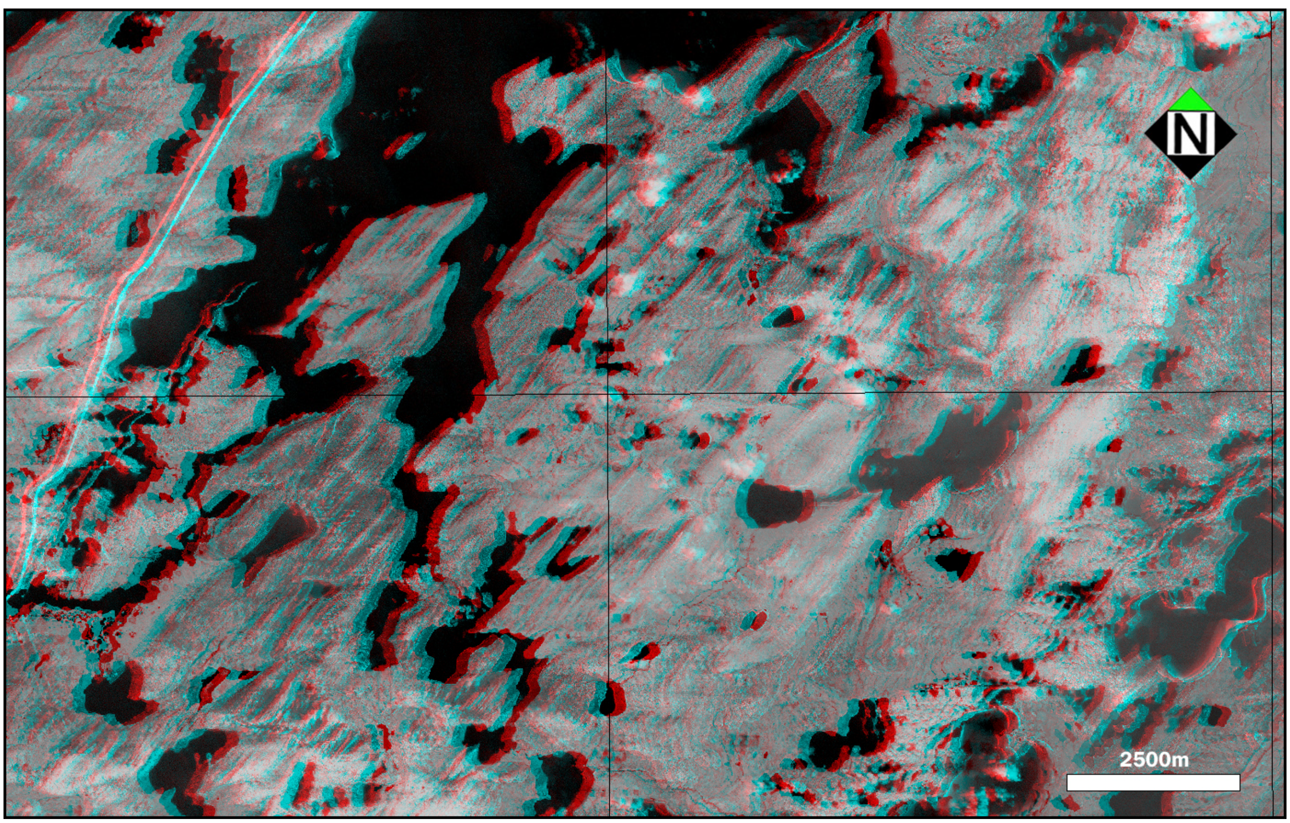

Figure 4. SPOT 2.5m orthoimagery draped over CDED DEM to create a small-scale anaglyph view of the Key Lake area.

3D views of terrain covering hundreds or even thousands of square kilometres can be generated and viewed instantly using such datasets.

Because both the SPOT orthoimagery and the CDED DEM are georeferenced objects within a GIS system the resulting 3D view can also be overlain with vector data to assist with terrain analysis and interpretation. In Figure 4 the anaglyph has been overlain with a 10,000-metre UTM grid (thin black lines). Since the UTM grid is drawn after the anaglyph is generated the lines appear to 'float' over the terrain.

3.3 Case Study - Peace River Landslides, BC

The Peace River valley in northeastern British Columbia cuts through variable depths and lithologies of glacial deposits, preglacial gravels, and deep sections of underlying interbedded sandstone and shale units that include the Dunvegan Sandstone, Shaftesbury Shale, Moosebar and Gates formations. Valley sides in this geological setting are prone to instability and slope movements as evidenced by a large number of historical landslides visible in 3D air photo and satellite images and shaded relief images created from DEMs. Some of the more notable and well-documented failures include the 1973 Attachie slide, a flow slide in overconsolidated glaciolacustrine clay and silt (Fletcher *et al.* 2002), and the Cache Creek slide, a large deep seated bedrock failure.

Figure 5a shows a red-cyan anaglyph of the Attachie slide failure along the Peace River. The anaglyph was created by draping 1m colour digital orthoimagery over a 1m DEM generated from LiDAR scans, and shows the level of detail possible with these anaglyph views when the underlying DEM layer has a very high spatial resolution. The slide itself can be differentiated from the surround area both by its shape in the 3D view as well as by changes in vegetation pattern on the failure surface.

Figure 5b shows the same area as Figure 5a, but this time the colour orthoimagery has been replaced by a hill-shaded raster rendered from the 1m LiDAR data. Because the parallax required for the anaglyph is calculated from the underlying DEM, it does not matter what raster is used for the drape layer(s). Use of raster datasets other than aerial or satellite imagery may give new or different insights into the nature of the terrain being analysed.

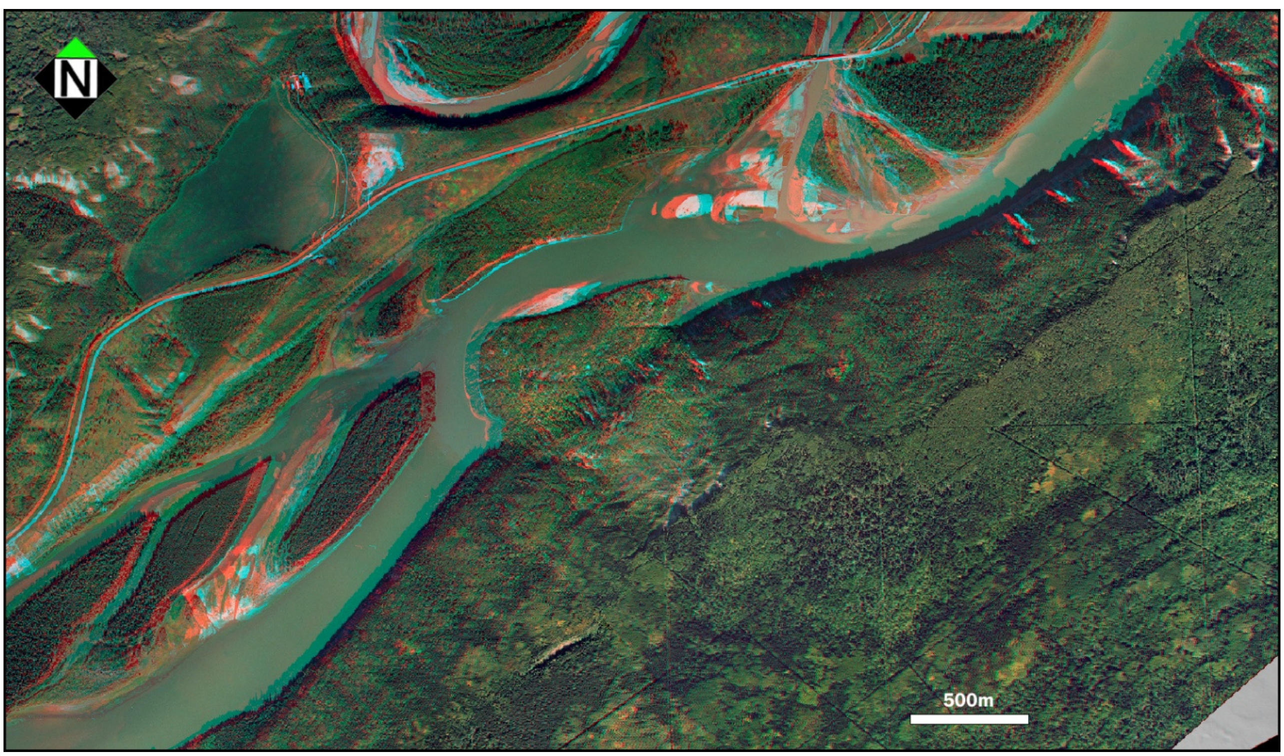

Figure 5a. Red-cyan anaglyph showing the Attachie slide along the Peace River, northeastern BC. 1m colour aerial orthoimagery overlain on sub-metre DEM derived from LiDAR data.

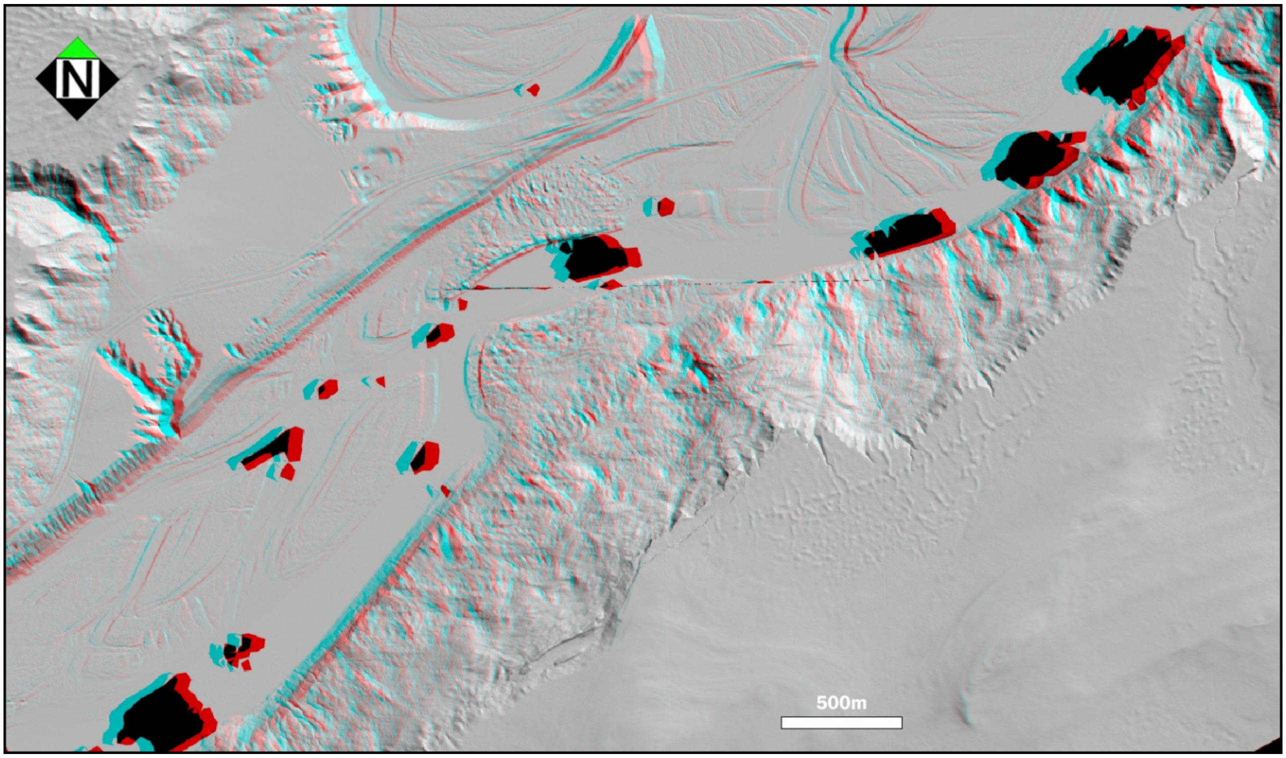

Figure 5b. Same area as shown in Figure 5a, except using a hill-shaded raster derived from the LiDAR DEM as the drape layer.

3.4 Case Study - Big Muddy Valley, Saskatchewan

The Big Muddy Valley in southern Saskatchewan originated as glacial meltwater eroded weakly cemented Cretaceous bedrock strata. Subsequent postglacial erosion due to overland runoff created a network of branching coulees and gullies on the Big Muddy valley walls. Where soil conditions are suitable, north facing slopes of the main valley and adjoining coulees are treed while drier south facing slopes support mainly grasses and shrubs. Steep bedrock slopes are mostly unvegetated regardless of slope aspect, revealing horizontally layered bedrock stratigraphy.

Figure 6 is a red-cyan anaglyph showing part of the Big Muddy Valley north of the town of Coronach, Saskatchewan. The anaglyph was created by draping 0.6m colour digital orthoimagery over a 30m DEM derived from photogrammetrical analysis, and then tilting the view angle to produce an oblique image. The GIS software then used the 3D structure of the DEM to calculate the amount of parallax needed for each portion of the image in order to produce a correct anaglyph. To the software, view angle is simply a component of the anaglyph calculations, and so oblique anaglyphs are rendered in the same manner as vertical ones.

Such techniques can even be extended to the production of oblique anaglyph 'flythoughs' and simulations. Since the software would have to calculate the parallax for every conceivable angle in every frame of the animation the main limitation for many users may be the amount of memory required and the time to render such anaglyph views. Such stereo oblique views, however, can provide a very effective means of terrain visualization for a range of studies.

4 SUMMARY

Stereoscopic (3D) viewing of contact air photo prints has for decades been an important tool for engineers and geoscientists working on a wide range of engineering, geoscience and resource development projects. The development of techniques to produce 3D views on a computer screen is simply a natural progression in the ongoing requirements of engineers and geoscientists for more innovative and effective means of 3D terrain visualization and integration with other spatial datasets (in particular, integration of such 3D views into a GIS).

3D views can be generated from either existing stereo pairs of vertical air photos imported into the computer environment or by 'draping' aerial or satellite imagery over three-dimensional terrain models generated from digital elevation data. Both techniques have their advantages and disadvantages that need to be considered when choosing a method for 3D terrain visualization. Using existing stereo pairs of vertical air photos normally provides the most accurate reproduction of the actual terrain, and provides for 3D views of additional features such as buildings, vehicles, vegetation and fence lines. However, only a small area can be depicted in stereo at any one time, which limits the ease of viewing large, regional areas in 3D. Stereo images developed from

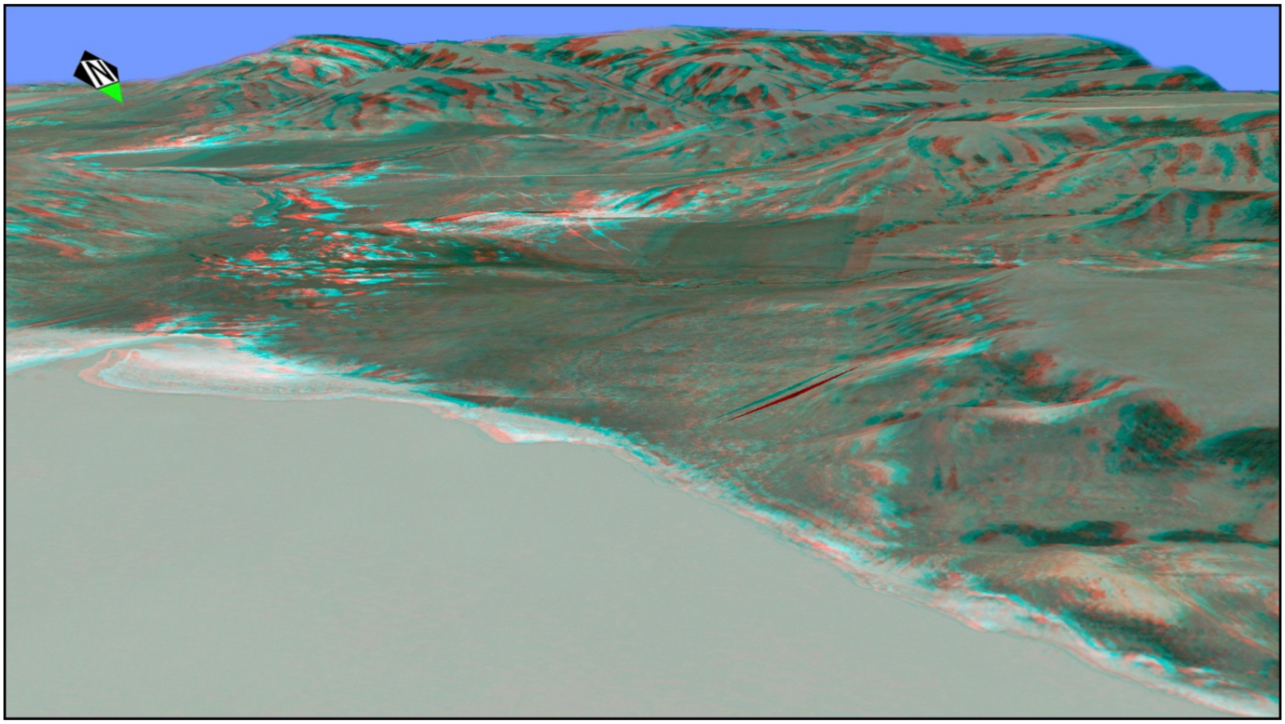

Figure 6. Oblique anaglyph rendering of part of the south wall of the Big Muddy Valley, southern Saskatchewan.

draped imagery of DEMs allows the viewer to zoom in and out of a 3D scene and potentially view very large areas in stereo. Draped imagery need not even be aerial photography or satellite imagery but can be any raster image, such as a hill-shaded image or a scanned topographic map. The 3D views can even be oblique views of terrain, either fixed or as part of an animated fly through. Such unique views can provide a different and potentially very useful perspective for terrain analysts and planners trying to visualize a particular study area.

A number of techniques have been developed over the years to force the stereo separation necessary for 3D views on a computer screen. Such techniques include the use of red-cyan anaglyphs, polarization images, and the use of physical mechanisms such as LCD shutter glasses. The authors have found that simple red-cyan anaglyphs often work just as well as other more sophisticated techniques for 3D viewing of stereo air photos or draped satellite imagery. Although red-cyan anaglyphs are subject to ghosting and slight colour-shifts, they have several advantages including ease of creation, low cost for the necessary red-cyan filter glasses, and the fact that the anaglyphs can be produced on paper as well as on the computer screen.

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REFERENCES

Christiansen, E.A. 1979. Geology of the Saskatoon Region. Part A Regional Studies Program. Saskatchewan Municipal Affairs. 62p.

Fletcher, L., Hungr., O. and Evans, S.G. 2002. Contrasting failure behavior of two large landslides in clay and silt. *Canadian Geotechnical Journal*. 39: 46-62.

Schreiner, B.T. 1984. Quaternary Geology of the Geikie River Area (74-H) Saskatchewan.Saskatchewan Energy and Mines Open File Report 84-11.