Assessment of the performance of CosiCorr software in the detection of horizontal displacements using artificial images

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by

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Abstract

The surface displacements at regional scale (e.g. earthquakes) or small scale (e.g. landslides) are always subject of analysis in pursuit of its detection and monitoring. Among some methodologies for horizontal displacement detection, the CosiCorr software is an important recent implementation that automatized the process inherent to the correlation of a pair of images. Although the correlation of optical images by using CosiCorr software was extensively developed and applied in the recent years, it is still present many doubtful situations or inaccuracies in the results that make necessary the discarding and reconsideration of the horizontal displacements detected by the software by using filtration processes.

For this purpose, the present study aims the assessment of the horizontal displacements detected by the software, performing a sensitivity analysis of their more important input parameters: the window size and step size. In order to count with predictable results several artificial images were artificially created, with different spatial resolution, and representing different amount of sub-pixel (less than one pixel) and multi-pixel (more than one pixel) displacements. The use of this artificial input imagery have not any precedent in a study, thus is considered at last as a useful input data for similar future studies.

Using such imagery, it was determined that the resolution of the images used doesn't affect the correlation results; moreover the correlation of different resolution images gives more noisy results. Regarding the software parameters, the step size showed no influence in the results; on the contrary, the window size had a remarkable influence in the results of a correlation. It was found that a displacement, by using artificial images, is accurately detected when the window size that was used is three times higher than the displacement (in pixels) to be detected, considering multi-pixel displacements. Similar relation for sub-pixel displacements was not possible to establish because there were many questionable results obtained.

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So, the long long long trip finally ends…

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1. INTRODUCTION

Change detection analysis in remote sensing is commonly done by using pixel-based methods. This can be done by comparing two optical images taken on different dates. Usual techniques, such as image differencing, rationing, regression, change vector analysis, multi-date principal component analysis, etc., can be applied for two images coming from the same sensor; for images coming from different sensors, the studies are carried out by visual inspection comparing the imageries, or by using unsupervised or supervised classifications. Change detection using pixel-based methods are, for example, applied in forestry (Lin et al., 2005), environment (Lin et al., 2008)., agriculture (Yu et al., 2010), and geology (Yang, 2010)

Alternatively, change detection can also be done by assessing motion; this can be done by using two methods: interferometry for radar data and image correlation for optical data.

The first, the differential synthetic aperture radar interferometry (DInSAR) technique, where a detection and quantification of the surface displacement can be achieved using SAR images. Interferometry applied to SAR images (InSAR) yields at least on three coseismic interferograms. The procedure provides an image, called differential interferograms (DInSAR), representing the surface motion occurring between the acquisitions. The displacements are calculated by differentiating the phase component of the coregistrated SAR images after the removal of the topographic effect. DInSAR technique has been successfully applied for detecting surface displacements caused by phenomena such as earthquake (Goudarzi et al., 2011), ice stream flow (Luckman et al., 2007), and for landslide subsidence (Rajakumar et al., 2007; Singhroy, 2009),

The second method, for motion detection, is the correlation of two optical images obtained at different times. The correlated images have to share a common geometry, which is obtained either by orthorectifying the pair of images (in this case the correlation is performed in the ground geometry) or by resampling a secondary image in the geometry of a reference image (in this case the is correlation performed in the image geometry). In both cases a DEM is necessary; ideally, two different DEMs, contemporary to each correlated image, should be used.

In recent years, one relevant optical correlation method is the one developed by Leprince et al. (2007a). The algorithms that use this method have been implemented in the software called 'Co-Registration of Optically Sensed Images and Correlation' (CosiCorr) (Leprince et al., 2007b). CosiCorr allows an automatic and precise orthorectification and coregistration of satellite or aerial images. The procedure does not require additional information such as GPS measurements of ground control points (GCPs), and is only based on the knowledge of the terrain relief and on the image ancillary data provided by the observing platform (velocities, positions, variations in altitude and pointing directions for space, or calibration reports for aerial platforms.)

CosiCorr correlation capabilities allow mapping of surface changes and measurement of a variety of terrain offsets. Regularly this methodology has been applied to measure large scale displacements generated by earthquakes (Avouac et al., 2006; Van Puymbroeck et al., 2000), seismic ruptures (Leprince et al., 2007b; Leprince et al., 2008), and glacier flow (Berthier et al., 2009; Berthier et al., 2005; Kääb, 2002). However, special uses of this methodology exists for small displacement detection of sand dunes migration (Necsoiu et al., 2009; Vermeesch and Drake, 2008), slow glacier activity (Herman, 2011; Scherler et al., 2011) and land sliding (Delacourt et al., 2004) (Casson et al., 2005)

All these methods have been developed during the last years and successfully applied on sensors either attached to space or aerial platforms, however, these methods often have to deal with constraints in its use, constraints related to the resolution of the input imagery, atmospheric and geometric effects as well as imprecisions of the horizontal displacement detected by the software.

1.1 Research problem statement

Nearly all applications of this technique have been limited to the use of datasets from the same satellite sensor. Change detection with CosiCorr software works preferably with a pair of images that are perfectly co-registered (Leprince et al., 2008), however, some applications explored the use of different image resolution in their respectively research (Delacourt et al., 2004) (Necsoiu et al., 2009).. If using same sensor images, the slightest mismatch leads to less precise or inaccurate horizontal measurements, the use of different resolution add to these difficulties the resolution differences. (Debella-Gilo and Kääb, 2011). When a pair of images has different pixel size, the information in the pixels of either dataset is not directly comparable, thus resampling or resizing of pixel is necessary. This procedure can affect the measurements of displacement of CosiCorr software, thus it is important to assess the effect of the resolution problem for the detection of displacements.

CosiCorr software is efficient at various scales, from small-scale e.g. landslides to regional scale e.g. earthquake. Several results using this technique show an acceptable performance for detection of displacements (Ayoub et al., 2009; Goudarzi et al., 2011; Herman, 2011; Necsoiu et al., 2009; Scherler et al., 2008). However, the efficiency of the software is not always the desired. Often it is necessary to discard and reconsider displacements that are detected by the software using filtering processes. The selection mostly is based in the direction or magnitude expected by the user (Scherler et al., 2008) In some cases, the software overestimated the displacement and can only be used to track slow movements that not result in dramatic changes (Necsoiu et al., 2009). These scenarios require the exploration of the limitations of the software in detecting multi-pixel and sub-pixel displacements in a variety of magnitudes.

1.2 Research objectives

The following main objective has been defined for this research:

Assessing the performance of CosiCorr software in the detection of horizontal displacements using artificial images.

The main objective is met through accomplishing each of the next specific objectives:

- To assess the effect of the correlation of different imagery resolution under controlled conditions

- To determine the capabilities of the software to detect large displacements at multi-pixel level, and small displacement at sub-pixel level

- To develop a sensitivity analysis of the window size and step size parameters as a function of image resolution and amount of displacement

1.3 Research questions

The fulfilment of the objectives is accompanied with the following research questions:

1) How well is the performance of the software using different resolution imagery for detection a specified amount of displacement?

2) What amount of displacement can be detected properly by CosiCorr software at multi-pixel and sub-pixel level?

3) What is the influence of the window size and step size parameters in the achievement of reliable results?

1.3 Research methodology

Many variables influence a proper correlation of pair of images using CosiCorr. Beyond the variables that are inherited to the acquisition of satellite images a correlation also depends on the variables of the correlation itself. In CosiCorr software, the window size, step size and threshold are the main parameters for correlation calculation.

In order to assess the CosiCorr software, it is necessary to work with a controlled condition model, an artificial image that must be free of the well know distortions of real imagery (e.g. atmospheric or geometric distortions) and has to synthesize how a real displacement is represented in a real image.

The use of such artificial assemblies has not antecedents in literature. Thus, the design of such an artificial image and the attempt to control as many variables as possible is considered as an important challenge which will assess the strengths and weaknesses of the detection of horizontal displacements with CosiCorr software.

The study is aimed at assessing CosiCorr performance by using small-scale artificial images. The results of a moving simulation in a controlled experiment are presented.

2. LITERATURE REVIEW

2.1 Methods for the Correlation of optical images

Optical remote sensing uses image processing algorithms to quantify the offset of pixels by correlation of their geographic location in different images from a site. The processing results can be presented in East–West and North–South components detailing the direction and the magnitude of such representation. This information can be used for the delimitation and characterization of any kind of surface displacements.

The next mathematical approaches can be mentioned as examples:

(Van Puymbroeck et al., 2000) used Fourier analysis to correlate satellite images for detection of earth displacement after an earthquake zone in California. This event produced metric displacements in an arid area. The study used a SPOT panchromatic imagery of 10 meters of resolution and a DEM with a resolution of 20 m. This technique provides near-fault measurement with accuracy of 10 cm and low-frequency measurement with accuracy of 1 m. The technique is limited mainly by the decorrelation of the images, the accuracy of the DEM, the aliasing of the images, and uncertainties inherited to the measurements of the satellite sensor.

Another approach is the normalised cross-correlation (Debella-Gilo and Kääb, 2011). These researchers evaluate the achievements of several different approaches to achieve sub-pixel precision of normalised cross-correlation when measuring displacements from optical images. Both approaches are applied to three common mass movement types: rock glacier creep, glacier flow and landslides. By increasing the spatial resolution and decreasing the ground pixel size of the images by 2 to 16 times, 40% to 80% reduction in mean error to the same resolution original image was achieved. The study also quantifies the proportion of mismatches and the proportion of undetected movements increase with increasing pixel size (i.e. decreasing spatial resolution) for all of the displacement examples investigated.

The last method, which is the one used in the present study, is the sub-pixel correlation technique by (Leprince et al., 2007a). The algorithms used for such have been implemented in a software package named CosiCorr, developed with Interactive Data Language (IDL) and available as a plugin to ENVI image processing software. CosiCorr allows to coregister optical images, acquired from satellite or aerial systems.

2.2 Correlation of optical images using CosiCorr software

In principle, the pair of images require a common geometry, that can be obtained by either orthorectifying both images or by resampling a third image in the geometry of a reference image (Leprince et al., 2007a). A DEM is necessary in both cases. The DEM can be obtained by topographic information or satellite platforms (ASTER GDEM or Shuttle Radar Topography Mission SRTM DEM)

At the displaced areas, the visible and recognizable features are shifted by the displacement. In order to identify the surface displacement that occurred between two images, a correlation window of a specified width (about 4 to 256 pixels) is defined. The window is searched on the secondary image by maximizing a correlation function (Leprince et al., 2007b). The starting point of the search is the expected position of the window as if no displacement occurred between the two acquisitions. The measured shift is directly related to the ground displacement by the pixel size. The main parameters of the calculation are the size of the local window and the maximum displacement expected between the acquisitions (Delacourt et al., 2007). The process is repeated for each pixel of the oldest image.

The choice of the size of the correlation window is a compromise between the desired accuracy of the shift and the needed spatial resolution with respect to the velocity field (Delacourt et al., 2007). When the size of the window increases, the noise is reduced as well as the number of independent measurements since each measurement is the average value on the whole window.

CosiCorr software package allows for an automatic orthorectification, coregistration, and subpixel correlation of satellite and aerial images [Leprince et al., 2007]. The procedure does not require external information such as GPS measurements of ground control points, and it is based solely on topographic knowledge and on the ancillary data provided with the observing platform. The software takes advantage of the availability of accurate digital elevation models with global. Subpixel change detection (i.e., correlation) is then applied to the set of ortho images produced. CosiCorr makes it possible to measure local displacements between temporal series of images, possibly acquired by different instruments and at different resolutions, with measurement accuracy of the order of a small fraction of the nominal images' resolution.

2.3 Input imagery resolution

Optical images correlation methods have some considerations regarding the resolution of the images used (e.g., 2.5–10m for SPOT, 15 m for ASTER), seldom insufficient to measure earth ground deformations, especially where displacement is less than 1 m which is typically the case for slow land sliding (Leprince et al., 2007a) . In the same manner, the availability of images suitable for correlation can restrict the use of a pair of images that comes from the same satellite sensor.

The use of different satellite imagery has to consider additional pre-processing steps (e.g. pixel resampling, pixel resizing, geometric and atmospheric corrections, etc) in order to solve the differences in spatial resolution, viewing angles and spectral sensitivities of the images selected. However, these additional processing steps can affect the accuracy of a correlation.

For instance, if it is necessary to adjust the resolution of a pair of images, a resampling operation is required for the different resolution imagery generating an alteration of the image's original radiometry. This alteration can lead to over estimation or under estimation of displacements after a correlation operation (Gomarasca, 2009).

A couple of examples of the use of different resolution data in a correlation exists:

- ✓ In first instance the case of, "La Clapière" landslide in France can be referred. In this area, aerial images and high resolution. To be correlated successfully, the images have to be exactly in the same geometry, so an orthorectification procedure has been applied on both aerial and QuickBird. Digital Elevation Models (DEM) have been processed from the stereoscopic aerial images. The aerial images were resampled at a spatial resolution of 1 m; QuickBird image has been orthorectified and resampled to 1 m in order to have the same spatial resolution as the aerial images. All images have been projected into a Lambert II conic conform projection. Some alterations in the number of areas with low correlation were attributed to the different characteristics of the two sensors (QuickBird and aerial images do not have the same initial spatial resolution, undersampled before the correlation process). Furthermore, radiometric sensitivity and acquisition season and time were different (Delacourt et al., 2004).
- ✓ Other application by using different satellite imaging was performed for monitoring of dunes for the quantification of subtle rates of landscape

evolution (Necsoiu et al., 2009). Here, the analysis included a 2.5 m ground resolution SPOT 5 Panchromatic image (SPOTPAN) with spectral sensitivities of 0.48– 0.71 μm, and 15m ground resolution ASTER VNIR images with spectral sensitivities of ASTERB1 (0.52–0.60 μm), ASTERB2 (0.63–0.69 μm), and ASTERB3N (0.76–0.86 μm). Before the correlation, to correct for the geometric differences, the SPOT L1A Panchromatic image was orthorectified at a resolution matching the ASTER VNIR resolution of 15 m.

2.4 Horizontal measurements

CosiCorr has been applied successfully to measure displacements induced by different factors: ground deformation related to coseismic deformation (Avouac et al., 2006; Konca et al., 2010; Tahayt et al., 2009)ice flow and glacier dynamics (Berthier et al., 2005; Herman, 2011; Quincey and Glasser, 2009) or dunes migration (Necsoiu et al., 2009; Vermeesch and Drake, 2008) and landslides (Delacourt et al., 2004 (Leprince et al., 2008).

Most of the applications of CosiCorr software were used for the detection of displacements at regional scale (measured in kilometres):

- One example is the study of the surface slip after the Kashmir earthquake determined from the correlation of ASTER images, (15 m ground resolution) (Avouac et al., 2006). The correlation image was obtained with a sliding 32×32 pixels correlation window and 8-pixel step in the slide. Surface fault was traced from the discontinuity of the offset field, then horizontal slip vectors at about 2 km spacing along the fault trace, were measured from the discontinuity of E–W and N–S ground displacement measured at the fault on 18-km-long, 6-km-wide profiles perpendicular to the fault. Filtering is applied to points where correlation is lost or where outliers have been filtered out. The correlation is lost mainly due to landslides or variation of the snow cover. It did not specify why the outliers, measured ground displacements higher than 10 m, are filtered, thus, it can be interpreted as a result of the researcher criteria.
- To investigate the surface deformation produced by the 2004 Al Hoceima earthquake, two images with 2.5-meter resolution from the SPOT5 satellite are correlated (Tahayt et al., 2009). The 364-day time separation is exactly equal to 14 orbital cycles for the SPOT5 spacecraft. The one-year time separation ensures a similar solar illumination for the two SPOT5

acquisitions, minimizing the errors due to the changes in length of the shadows. Windows of 32 by 32 pixels were used to correlate the SPOT5 images with a constant step of 16 pixels in each dimension. The correlation of SPOT5 images, with dm-level of uncertainty as used here, confirms that the Al Hoceima rupture did not reach the free surface and the horizontal throw. No registration of rupture is found because any coseismic surface rupture can be no larger than 5 to 10 cm thus. This is estimated affirming that this technique could detect a coherent surface throw as small as 0.2 pixel or 50 cm with the SPOT5 images used here.

- The rupture process of the 1999 Mw 7.1 Duzce earthquake is analysing using three panchromatic 10 m resolution SPOT images (Konca et al., 2010). These three images were orthorectified using topography from the SRTM (90 m) digital elevation model (DEM) and cross correlated following the method of Leprince et al. (2007). Ground deformation measured from the subpixel cross correlation of SPOT images reveals a 55 km long fault trace and smooth surface-slip distribution peaking at 3.5–4 m. The measured surface slip shows a rather smooth distribution enveloping most of the field measurements. The procedure leads to smoothing of any variability of surface slip at length scales less than about 1.5 km. No relation of step size and window size used is given.

Applications that are more challenging (because Cosicorr was not specifically made for them) are related with slow movement or small scale displacements due to a small spatial extent of the phenomena (e.g. mountain glacier variation, landsliding and sand dunes migration):

- Using repeat optical imagery in 2002 and 2006 Coverage of ice velocities in the central part of the Southern Alps, New Zealand, is obtained (Herman, 2011). For this study only nadir-looking ASTER acquisitions were selected. The velocity estimates presented are therefore free from any potential biases, which could be due to elevation model errors or from potential ice-thickness changes between acquisitions. The VNIR (visible/near-infrared) bands 3N at 15m ground resolution were used. Horizontal displacements were measured from sub-pixel correlation using a multi-scale approach where the smallest correlation window size is 32x32 pixels, sliding every pixel. Large displacements are observed (i.ie. up to 80 m), indicating large velocities for mountain glaciers (i.e. up to 5md–1). The norm of displacements and uncertainties were derived in the north–south and east–west directions and then combined. Uncertainties of displacements are specified in 2.6m

- A case related to a slowly moving landslide is the La Valette landslide, located in the Ubaye Valley, French Alps. An area extensively studied for almost nine years using traditional techniques (Squarzoni et al., 2005). Horizontal displacement and displacement vectors as imaged from the correlation of two 2.5-meter SPOT 5. The maximum displacement measured is 9 meters. Apparently the displacement field revealed from the sub-pixel correlation has not been recognized by use of geodetic measurements (Leprince, 2008).
- Finally for quantification of the rates of slowly migrating dunes at the Great Kobuk Sand Dunes (GKSD), Alaska (USA), two satellite imaging systems with different viewing angles and spectral sensitivities are used. ASTER Visible Near Infrared (VNIR) and SPOT Panchromatic images with a 5-year temporal separation were correlated to measure the horizontal velocity of the GKSD. To reduce correlation noise, ASTER VNIR bands were linearly mixed to match the SPOT Panchromatic band, and raw correlation measurements were projected onto a local robust migration direction to estimate unbiased velocity magnitudes. The results show that the most likely migration rate for the GKSD ranges from 0.5 to 1.5 m/year, with peak velocities up to 3.8 m/year, and uncertainty of approximately 0.16 m/year.

These unprecedented applications conclude the value of the method to reliably detect and monitor subtle ground movements including large-scale processes: coseismic deformation and surface earthquake displacements; and small-scale processes: dune migration, glacier flow, mass movements, and other. However, detection of small horizontal displacement is difficult from coarse resolution images and temporal variation due to changes in vegetation is another important obstacle for optical correlation.

2.5 Some limitations of optical correlation

The method itself has no limit in precision. According to Delacourt et. al., (2007), correlating similar images which are just processed one compared to another and which are sampled, with low noise, can lead to precisions of up to 0.001 pixels. However, in real practice, this accuracy is never reached. As far as sampling is concerned, the data must be accommodated as it is delivered. As far as similarity is concerned, the most similar that the instruments (same spectral sensitivity) are the better is the correlation that will be obtained, this implies the most similarity in terms of geometry (same point of view) and illumination (same season, same time in the day).

The accuracy of the technique using satellite or aerial images mainly depends on the quality of the projection of the two images in a common geometry, which implies a resampling of one image. The orthorectification and coregistration by can lead to some biases in the results if a DEM used for that purpose has not a similar date acquisition to the imagery. The difficulties increased, when different sensor imagery is used, because the geometric distortion of the images induced by the imaging system can be even higher.

Other limitation occurs in the case of images acquired under different atmospheric conditions e.g. sun light or clouds cover. In the first example the different shadow projections could present an apparent displacement in the correlation images because their shadow changed in size and direction or in vegetated areas the signal value of the different trees in the correlation window is redundant. (Berthier, 2005).

Decorrelation can be described as the loss of correlation, characterized by a low or null signal to noise radio (SNR), or by extremely large unphysical measurements. According to Leprince et. al., (2007a), the correlation is lost in three major circumstances. First, temporal decorrelation occurs when windows to correlate contain drastic changes. The second source of decorrelation is the shadowing difference. The third source of decorrelation involves ground features that are, at the correlation window scale, translation invariant

Surface state variation (due to abrupt changes or geometric and atmospheric distortions) can affect the quality of the results producing decorrelated areas. While the geometric and atmospheric aspects are not considered in the present study, because the nature of the artificial images, an attempt to generated a decorrelated area (caused by a surface dramatic change) is part of the analysis.

3. METHODS AND DATA

3.1 Overview of CosiCorr input parameters

In Figure 1, we can see the initial box dialog for the correlation of CosiCorr software where the pre-state image and post-state image is selected.

The CosiCorr software includes two types of correlator engines: frequential and statistical. The frequential correlator is Fourier based and is more accurate than the statistical one. It should be used in priority when correlating optical images. However, this correlator has more sensitivity to noise and is therefore recommended for optical images of good quality (e.g. few atmospheric and geometric distortions, free of clouds) (Ayoub and Leprince, 2007).

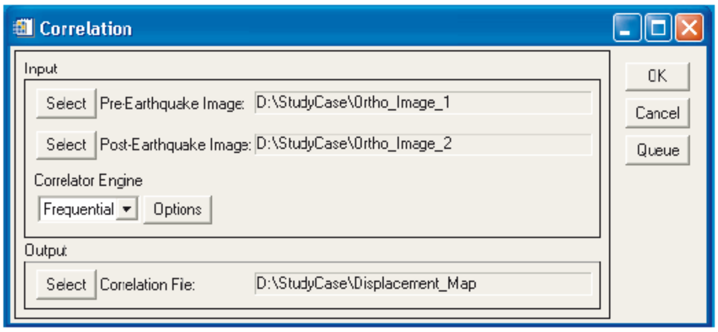

Figure 1: Correlation parameters selection tool

In the present study, because the images are artificially constructed, (pre-established characteristics thus good quality for a correlation, without atmospheric or geometric distortions) the Frequential correlator engine will be used for the different application and study cases. After this box dialog it is necessary to specified the parameters for the frequential correlator, see Figure 2

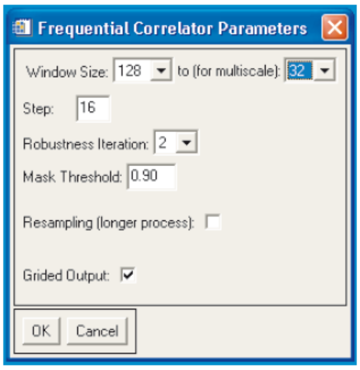

Figure 2: Frequential correlator parameters

The parameters considered in present analysis are described next:

1. “Window Size”: Size in pixels of the sliding window that will correlate the images (see Figure 3). The frequential correlator can be used in two modes: the simple mode where a unique window size is specified and the multi-scale mode where the multi-scale correlator accepts a maximum and a minimum window size. In the present study the simple mode seems more suitable for a sensitivity analysis in order to make the results comparable whit displacements at multipixel and subpixel level.

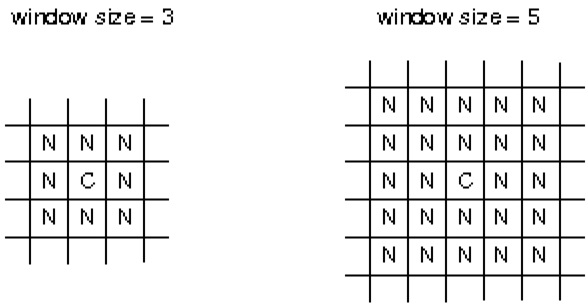

Figure 3: Examples of window size

2. “Step Size”: This parameter determines the step, in pixels, between two sliding windows. If the step is greater or equal to the window size, then all measurements will be independent.

4. “Mask Threshold”: Allows the masking of the frequencies. A value close to unity (e.g. 0.90, 0.95, and 0.99) is appropriate in most cases. See Leprince et al. (2007a) for more details. For the present study a value of 0.90 was considered for all the cases.

3.2 Artificial imagery approach

If changes in earth surface can be tracked by comparing optical images from the same area, there is the possibility to repeat the same exercise by a lab artificial approach. The approach avoids the use of DEM, relief or any effect of rugged terrain affecting the measurement of ground displacements. The same counts for atmospheric or geometric disturbances that can affect the correlation of image in change detection.

3.2.1 Artificial image

This approach begins with a small square image with known dimensions, consisting on a group of pixels whose values are randomly generated, and simulates a displacement in relation with other group of pixels that works as a background. More specifically, the half right part of the inner square is moved up in order to create a controlled displacement (see Figure 4).

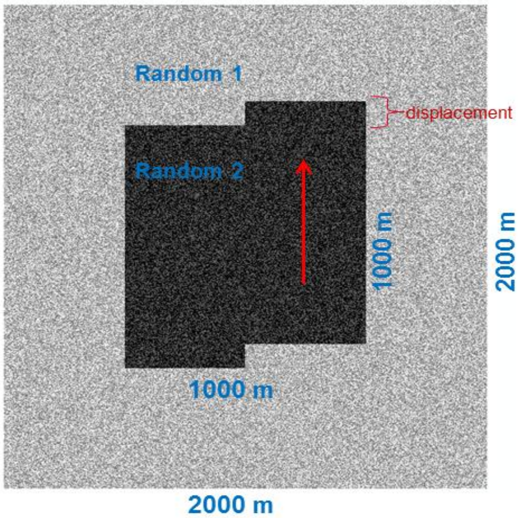

Figure 4: Schema of the artificial approach

The artificial approach will be used for testing the correlation of images using different combinations of parameters. Such montage basically will consider two situations to be tested: one is showing the inner black square intact, *pre-state image*, and the other including a simulated vertical displacement of the half right part, *post-state image*.

For the present analysis, we are interested in the interaction of 2 image parameters (resolution of the images and amount of displacement generated) and 2 software parameters (window size and steps size). Different resolution and amount of displacement are static parameters for each test and varied only between tests. On the other hand, the software parameters that are part of the sensitivity analysis are the Windows Size and Step Size; these are actually the variables of this study and define the result of a correlation of imagery using CosiCorr.

3.2.2 Segment displacement

The displacement establishes the main difference between the pre-state image and the post-state image and has an important role in the analysis in this study.

The simulated northward displacement of the right part of the inner square simulates a real displacement of an object in a real satellite image. Knowing the conditions and of this displacement it will be possible to evaluate the performance of the software at different level of displacement and different parameter's specifications.

In the present study two types of displacement defined: the multi-pixel and sub-pixel displacement. Each of them has its own characteristics and magnitude

The multi-pixel level means that the movement is done at a multi-pixel scale. Multi-pixel displacement can be interpreted as the displacement of a group of pixels, in a quantity equal or higher than 1 pixel. Therefore, the amount of the displacement is measured in pixels. In Figure 5, a group of three pixels moves upward in different amounts:

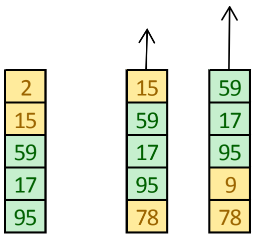

Figure 5: Mutipixel displacement. Left: original image; Middle: 1 pixel of displacement Right; 2 Pixels of displacement

The displacement tested consisted of 1, 2, 4, 5, 10, 20, 40, 50, 100 pixels shift in the synthetic images (see Figure 6 for examples, the rest of the artificial images can be seen in Figure A-1 to A12 in Appendix A).

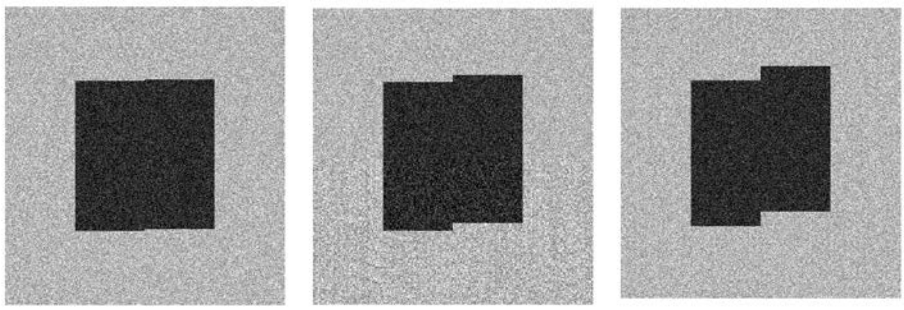

Figure 6: Different multi-pixel displacements

The sub-pixel level refines the measurements at a sub-pixel scale by estimating the displacement difference of the images by proportional changes of the radiometric value of each pixel and the displacement desired.

Sub-pixel displacement can be described as the displacement of a group of pixels, in a quantity lower than 1 pixel. Because the single pixel size cannot be lower than 1, a sub-pixel movement can only be tracked by analysing the relative proportion of the displaced subsequent group of pixel values. In Figure 7, some of the sub-pixel movement examples are presented. I.e. the value 38 of the third column is obtained by displacement of half of a pixel; this means that the values 59 and 17 are multiply by 0.5 and added. As a result, is obtained a value of 38 that represents a displacement of half of a pixel.

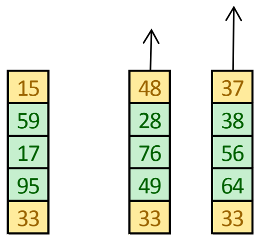

Figure 7: Sub-pixel displacement. Left: original image; Middle: 0.25 pixel of displacement Right; 0.50 pixel of displacement

At sub-pixel level the displacements evaluated were 0.01, 0.05, 0.1, 0.2, 0.5, 0.8 pixels shift (see Figure 8 for examples, the rest of the artificial images can be seen in Figure A-13 in Appendix A).

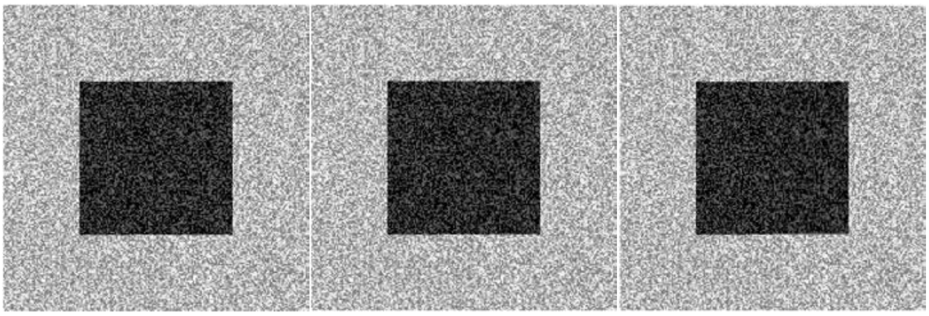

Figure 8: Different sub-pixel displacements

(Note: it is difficult to appreciate the displacement at sub-pixel level because such movement only modifies the pixel values of the area displaced)

The applicability of the software to track a specific unit of longitude (e.g. meter or kilometre) is directly related to the resolution of the imagery. The higher the resolution of the optical image, the better is the precision of movement detection. Thus, the present analyses only consider the displacement of the pixels rather than a real scale distance.

The accuracy of the pattern and magnitude of the movements detected by the software is tested by correlating images, with known amount of displacement, using different combination of window size and step size values. The idea is to determine how accurately the software can detect very small (sub-pixel) and large (multi-pixel) displacements.

3.2.3 Image Resolution

In order to test the capacity of the software to detect displacements using different resolution imagery, two situations can be defined.

The first consist in the analysis of a pair of equal resolution images, under different amount displacement conditions. Because it is the most common situation and no further pre-processing is needed no more explanation is needed.

The second situation works varying the resolution within a pair. This operation allow the evaluation of the procedure that compares two different resolution images with different amount of displacements (e.g. an IKONOS image and an ASTER image

In this case the procedure is as follows. First, a vertical displacement is created, after that, while the pre-state image maintain a fixed resolution the post-state image is resampled to a lower resolution, therefore their pixel values of the displaced part change.

After this operation, this image is resampled to its original resolution, the same of the pre-state image. In this manner a correlation is done between the two images. The same procedure is applied in the inverse sense, resampling the post-state image to the resolution of the pre-state image. The analysis is done decreasing the resolution of the *post-state image* and increasing of the *pre-state image* (see Figure 9).

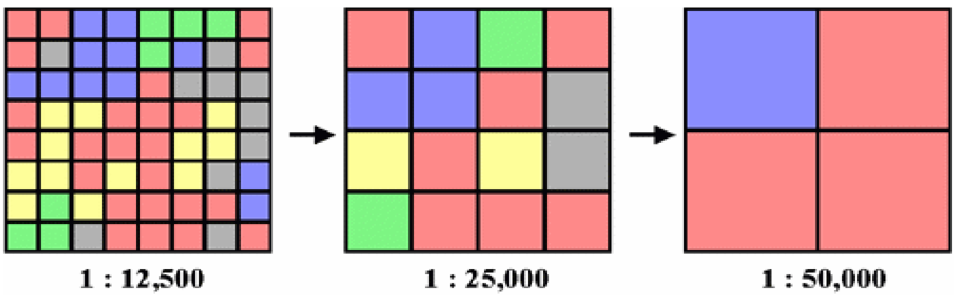

Figure 9: Different resolution images but same kernel size

In the last case, the main disadvantage is the valuable information that is lost because the redefinition of the size and value of each pixel. For the corresponding sensitivity analysis of the two situations, the resolutions employed are 1, 2.5, 5 and 10 pixel/unit; with amount of displacements equal to 1, 2, 4, 5, 10, 20, 40, 50, 100 pixels.

The software parameters are step size 8, window size 16 and threshold 90 and are fixed as constants for all the resolution effect analyses. The selection of this values considered was conditioned by the clearest visualization of the results and was antecedent by the selection of other combinations.

3.2.4 Step Size

This parameter determines the step, in pixels, between two sliding windows. If the step is greater or equal to the window size, then all measurements will be independent (Leprince et al., 2007a)

The step size is evaluated considering a range that includes the next values: 1, 4, 8, 12, and 16 pixels. Its sensitivity is tested maintaining similar conditions in the image. Theoretically the step size only has an influence in the presentation of the results but not in the patterns or in the magnitudes of the displacement detected

3.2.5 Window Size

The Window Size is defined as the area in pixels of the sliding window that will correlate the images (Leprince et al., 2007a). The window size parameter is a value inherited to the CosiCorr Software and is part of the three parameters that mainly influence the correlation of two images (window size, step size, and threshold).

The window size is evaluated exhaustively in all of the analysis in order to check its sensitivity in the different cases proposed. To evaluate the effect of changes of the window size value used in a correlation, different comparisons of window sizes were made. The study includes 4x4, 8x8, 16x16, 32x32, 64x64 pixels (see figure 10)

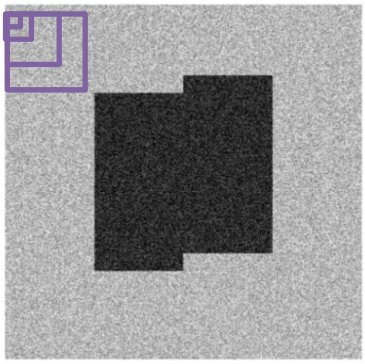

Figure 10: Different Window Size for the Correlation

3.2 Analysis & Interpretation

The methodology adopted for this study explores the different methodological parameters that mainly influence the results of a correlation using the CosiCorr software. By varying these parameters, window size and step size and the two image variables, image resolution and displacement, more than 100 correlation image results with their vector displacement component were obtained.

A correlation image using CosiCorr software gives horizontal displacement values in two bands; band-1 is East-West displacement component while band-2 describes North-South displacements. After a post processing using the same software different correlated images were obtained. Using these correlated images a product is derived in the form of vector displacement graphs for their comparisons and analysis.

A vector displacement figures are obtained from the correlation image using both displacement components. This represents the displacement values in form of vectors. The magnitude of a vector in vector field map is the measurement of displacement and its orientation is the direction of displacement. Vector field images were exported as shape files for comparing different results in order to evaluate the performance of the CosiCorr software.

Based on an image resolution matrix, starting from the high-resolution image, the proportion of mismatches and the proportion of undetected movements will be investigated, increasing and decreasing pixel size (i.e. decreasing spatial resolution) over the model, in order to define the different amount of distortions. At the same time, different values of Step and Window Size are included in the sensitivity analysis.

The vector correlation outputs of the multi-pixel analysis only has two possible results (see Figure 11): the incorrect or noisy result were the resultant vectors show an erratic pattern without possible interpretation; and the correct result were the resultant vector show an accurate direction and magnitude according to the displacement generated in the artificial model.

A third additional ‘result’ for this case is defined as doubtful, and is referred to pattern of vector displacements which show a relative correct pattern but with some level of inaccuracy caused by the wrong deviation of some of their vectors. Such a result can’tbe defined as a correct or incorrect.

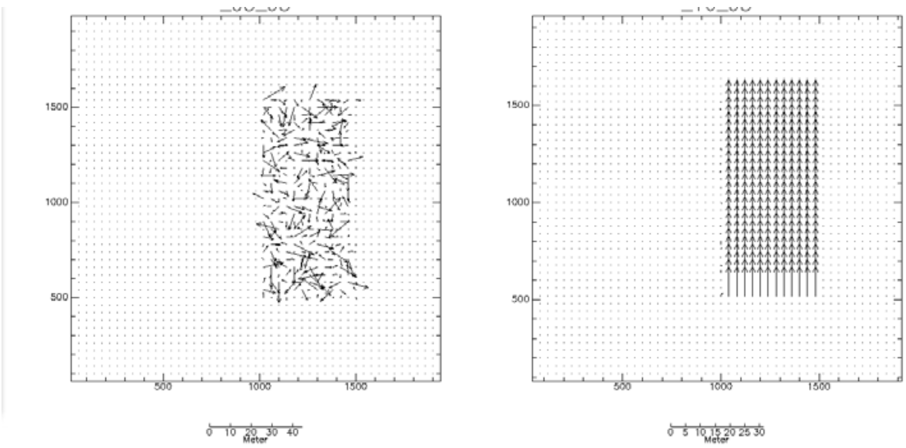

Figure 11 Left: incorrect result; Right: correct result

3.3 Simulation cases

Three cases simulate real conditions of landslides in order to test the effectiveness of the correlation of images. The cases imply mainly a sensitivity analysis of the window size among simulation of movements of landslide that often happen using real imagery.

For this purpose, a segment of 2x3 pixels is moved 1 pixel upward in the *post-state* image for the first and second case, while for the third is replaced.

3.3.1 Case 1: High contrasted displacement

The present case is an attempt to simulate a real situation where a small area of 2x3 pixels, that show a high contrast with its background, is moved up 1 pixel. The pre-state image consist in a square with pixels randomly generated, range of 0 to 127 value. Then a small area 2x3 random pixel in a range of 128 to 256 is moved upward.

This belongs to the post state image, see Figure 12. (see Figure A-14 in Appendix A for all the images).

This case can be equivalent to a situation where a bare landslide moves in some direction; the surrounding area of this landslide can be a vegetated area or rock materials that show remarkable different reflection properties.

For the simulation of the situation described above the artificial model was modified. In this case, a group of randomly generated pixels function as a background. A grid of 2x3 pixels is created over the previous background. Then, their values are also randomly generated but with enough contrast to be differentiated from the first one. Then, this 2x3 grid is displaced 1 pixel upward. The correlation is performed using different window size: 4, 8,16,32,64

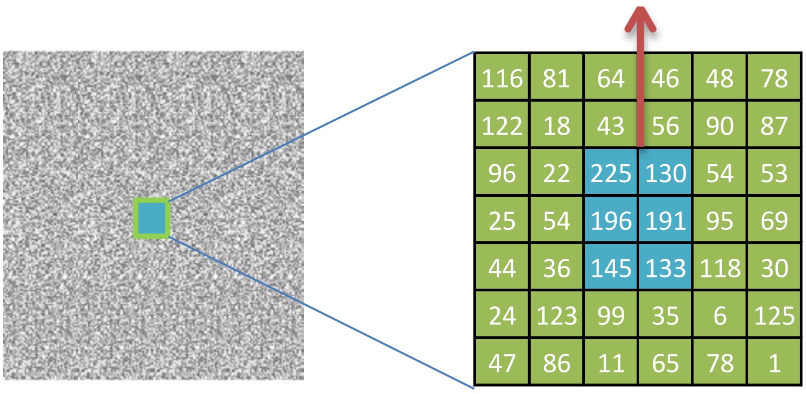

Figure 12 Schema of the model, image post state. Case 1

3.3.2 Case 2: Low contrasted displacement

The present case is an attempt to simulate a real situation where a small area of 2x3 pixels, that show a low contrast with its background, is moved up 1 pixel. The pre-state image consist in a square with pixels randomly generated, range of 128 to 256 value. Then a small area 2x3 random pixel in a range of 128 to 256 is moved upward. This belongs to the post state image, see Figure 13 (see Figure A-15 in Appendix A for all the images)..

This case can be equivalent to a situation where a landslide with a vegetated cover; moves in some direction while its surrounding area of this landslide are vegetated as well. It can also be equivalent to a case where we have a glacier displacement. In both examples the reflection properties of the active and passive area are very similar.

For the simulation of this model the artificial model is the same that the one used in the earlier analyses. The main difference for the correlation of the images is that only a grid of a 2x3 pixels are selected from the existing pixels in the inner square. In this case the 2x3 pixel area selected has a very low contrast. Then, this area of 2x3 pixels is displaced 1 pixel upward. The correlation is performed using different window size: 4, 8,16,32,64

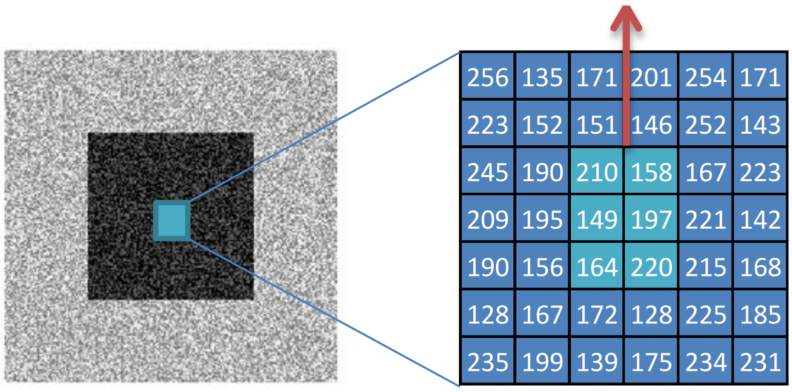

Figure 13 Schema of the model, image post state. Case 2

3.3.3 Case 3: Decorrelation area

The present case is an attempt to simulate a decorrelation situation where and area of 2x3 pixels change dramatically. The pre-state image consist in a square with pixel randomly generated, range of 0 to 127 value. This area changes dramatically by replacing a group of random pixels in a range of 128 to 256, this belongs to the post state image, see Figure 14 (see Figure A-16 in Appendix A for all the images).

For the simulation of this model, the artificial model is the same as the one used in the earlier analyses. The main difference is that an area of 2x3 pixels is removed from the existing pixels in the inner square; consequently back ground pixel values taking their place. In this case, the 2x3 pixel area selected has a very high contrast however it maintains a relation with the area surrounded. This area of 2x3 pixels is not displaced. The correlation is performed using different window size: 4, 8,16,32,64

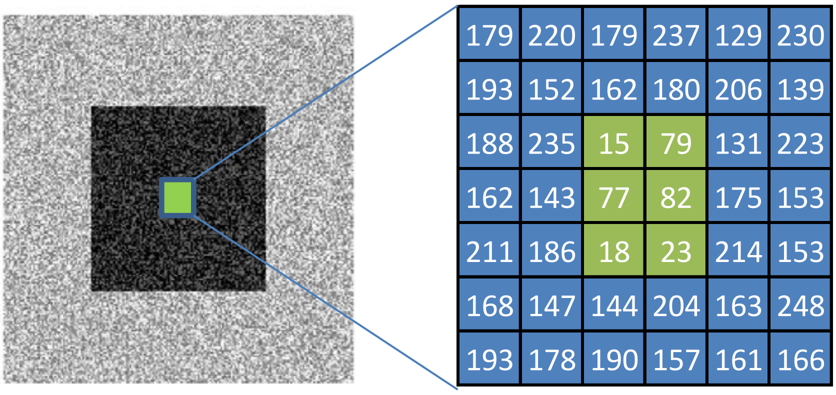

Figure 14 Schema of the model, image post state. Case 3

4. RESULTS AND INTERPRETATION

Correlation of artificial images through the described methodology using variation of image variables and software parameters given in the CosiCorr software is presented next. The summary of the behaviour of these parameters solo and in combination are in the present chapter.

4.1 Resolution effect

The effect of the resolution of the images can have different effect over the correlation results. The first results are referred to the capability of the software to detect a certain amount of displacement at different resolutions. A second scenario is are related to the combination of different resolution imagery in order to detect a same amount of displacement.

4.1.1 Different resolution images capability

For the present assessment of the resolution on a correlation, comparisons of correlation results using pair of images at different resolution (1, 5, 10 pixels/unit) were made using a frequential correlator and the parameters step size 8, window size 16 and threshold 90 as constant. The displacement artificially created had a magnitude of 10 pixels. Below are presented the results of this analysis:

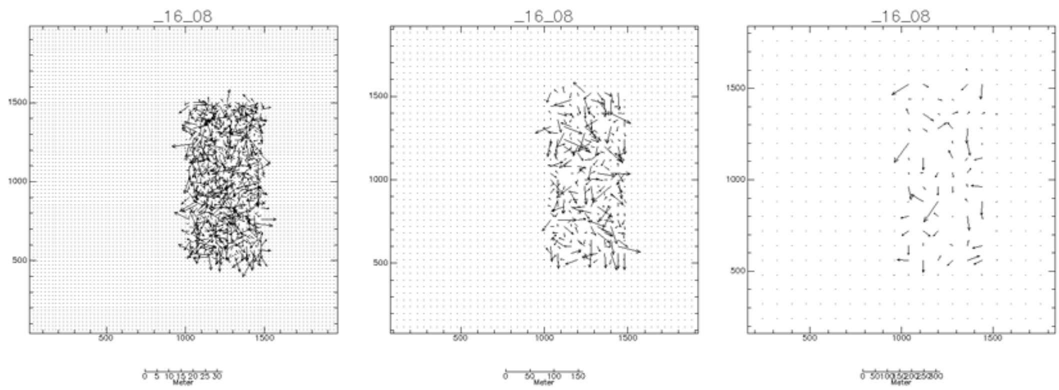

Figure 15 Correlation results Left: 1 m/pix; Middle: 5m/pix; Right: 10 m/pix

Apparently the image resolution only affects the resolution of the correlation result. In Figure 15, we obtained in all the cases a noisy result. The only variation lies in the resolution of the results, the spreading of the movement vectors are higher at higher resolution. The area that contains the displacement vectors match the area displaced in the original images but their magnitude and direction show no distinct pattern.

4.1.2 Resampling and Resizing

The results of the first scenario (resampling the higher resolution to match the lower resolution image) using artificial images, is comparable to the results and interpretation that were described in the previous point 4.1.1 and showed in Figure 15. It was not possible to test the other way around, resampling the higher the resolution image to match the lower resolution one, because the nature of the artificial images. It is not possible to simulate the different acquisition sensitivities of different sensor images to test the result of a resampling operation, because the artificial models were created using the same root of pixels randomly generated. Thus, if we resampled one of the images in order to match the other, the resultant image will have the same pixel values of the image that we want to compare, thus the correlation results are similar to the case presented in first instance.

For the testing of the second scenario (resizing the pixels of the lower resolution image in order to match the high resolution image), 5 and 10 pixels/unit resolution images were resize to match a 1 pixel/unit resolution image. Thus, the resolutions effects were analysing using 10, 20 and 100 pixel of displacement, and combinations of 1 to 5, 1 to 10, 5 to 1 and 10 to 1 pixels were analyse (see Figure B-1 in Appendix B). In Figure 16, the results of the correlation of 1 to 5 pixels/unit (resampled to 1/pixel/unit) and 1 to 10 pixels/unit (resampled to 1/pixel/unit) are presented.

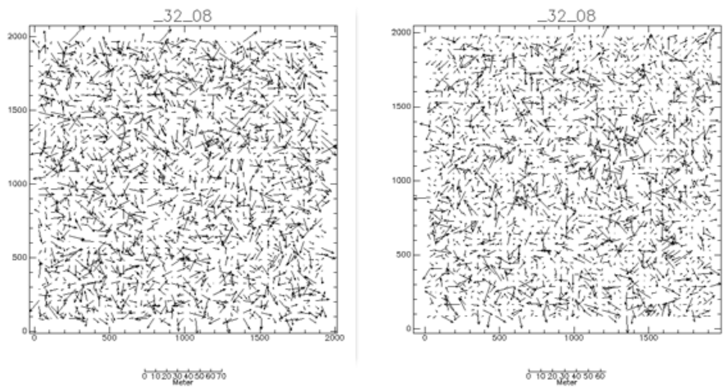

Figure 16 Correlation results Left: 1 to 10 unit/pix; Right: 1 to 5 units/pix

All the results in their different combination (1 to 10, 1 to 5, 10 to 1 and 5 to 1) show fully noisy results. Not only the area that has a controlled displaced show erratic displacement vectors but also all the area that is part of the correlation. Consequently, it can be confirmed that the resize of the pixel of an image for a correlation leads to a totally noisy result were it is impossible to infer any interpretation. This conclusion is valid using artificial images and CosiCorr software.

4.2 Displacements detection

As it was said in the Chapter 3, CosiCorr was developed for various change detection applications. The evaluation of its applicability for detecting ground displacements can be divided regarding two different types of pixel displacements: multi-pixel and sub-pixel displacements.

4.2.1 Multi-pixel level

To check the effectiveness of CosiCorr to detect displacement at multi-pixel level comparisons of different grade of displacement (1, 5, 10 pixel) were made using, a frequential correlator and the parameters window size 16, step size 8 and threshold 90 as constant. The resolution used was 10 units per pixel.

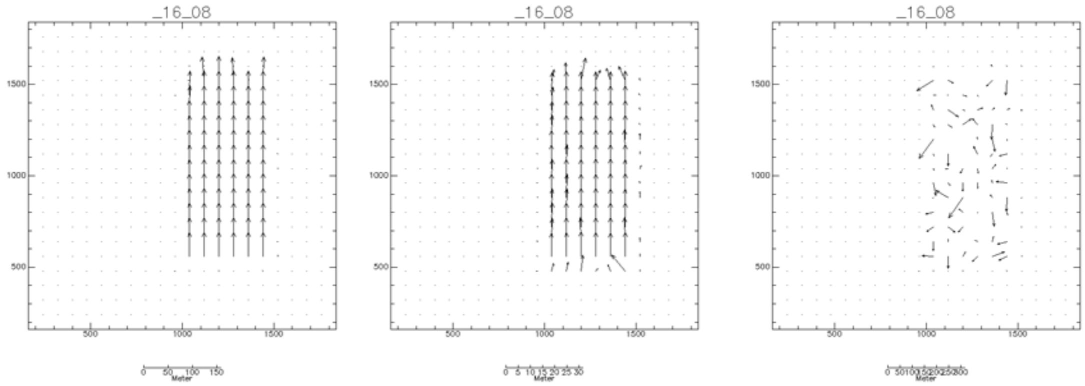

Figure 17 Correlation Results. Left: 1 pixel of displacement; Middle: 5 pixels of displacement Right; 10 pixels of displacement

According to the result showed in Figure 17 it can be said that CosiCorr software loses sensitivity at some amount of displacement. In Figure 13 the displacements of 1 and 5 pixels were properly detected in magnitude and direction, on the contrary the correlation applying 10 pixels of displacement showed a noisy result. Thus, it can be concluded that the software lose movement detection capacity under some combination of parameters and some amount of displacement.

Because the software loses movement detection capacity under some combination of parameters the amount of displacement can be considered as a critical variable. When the software detects properly the displacements the vector displacements figure show a clear pattern in terms of magnitude and direction of the area affected. An extensive analysis of the combination of the amount of displacements and correlation parameters is presented in point 4.2.5, where the multi-pixel analysis is further extended in combination with other variables

4.2.2 Sub-pixel Level

To check the effectiveness of CosiCorr to detect displacement at sub-pixel level comparisons of different grade of displacement (0.1, 0.2, 0.8 pixel) were made using, a frequential correlator and the parameters window size 16, step size 8 and threshold 90 as constant. The resolution used was 1 unit per pixel.

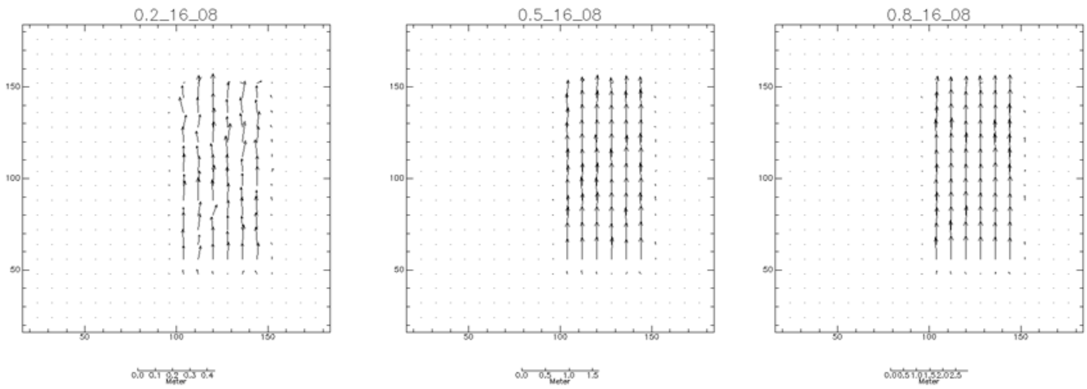

Figure 18 Correlation Results. Left: 0.2 pixel of displacement; Middle: 0.5 pixels of displacement Right; 0.8 pixels of displacement

At sub-pixel level, the correlation performance of CosiCorr works with good precision. In Figure 18, the vector displacements outputs showed a precise detection of the magnitude and direction of the movement. However, in the lowest displacement correlation, many vectors look a bit erratic, they maintain the main direction but with some deviation.

Because the software loses movement detection capacity under some combination of parameters the amount of displacement can be considered as a critical variable. Contrary to the multi-pixel case analyses, the correlation results obtained doesn't show a sharp boundary between the displacements correctly and incorrectly. There are doubtful results between the correct and incorrect representation, where some characteristics are erratic and indefinable. When the software detects properly a displacement the vector displacements figure show a clear pattern in terms of magnitude and direction of the area affected.

An extensive analysis of the combination of the amount of displacements and correlation parameters is presented in point 4.2.5, where the sub-pixel analysis is further extended in combination with other variables.

4.3 Step Size

Step size defines how many pixels will shift between the two sliding windows for measuring correlation. To check the effect of step size on correlation, comparisons of different step sizes (1, 4, 8, 12 and 16) were made using, a frequential correlator and the parameters window size 32 and threshold 90 as constant. The resolution used was 10 units per pixel and the effects were analysing at 1, 5 and 10 pixel of displacement (see Figure B-2 in Appendix B).

The use of different step size only defines the number of pixels (resolution) in the correlated image. For example, a step size of 4 (Figure 19) has more frequency of pixels (resolution 60 m in this case) as compared to others e.g. step size 12 (Figure 19) gives 180 m resolution (less number of pixels).

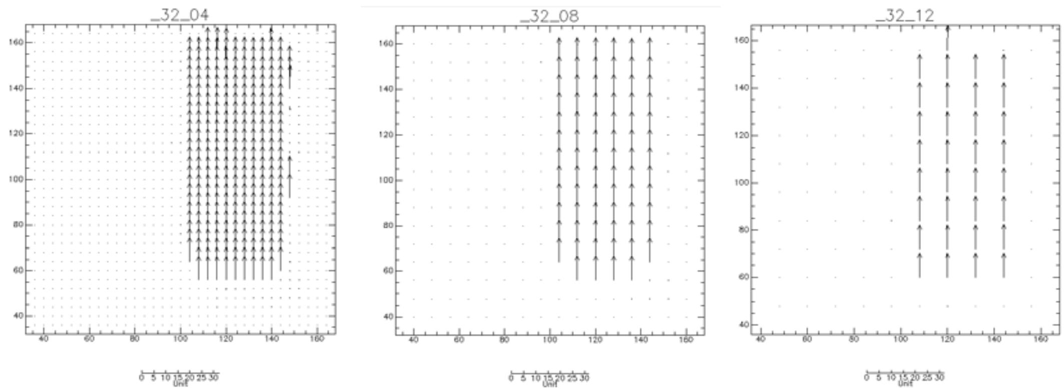

Figure 19 Correlation Results Left: step size 4; Middle: step size 8 Right: step size 12

From Figure 19, we had a clear perception about the performance of different step sizes used in the correlation method. According to figures, average and variability of the displacement distances is almost the same in S-N direction in both results. Step size 4 shows the highest frequency of pixels displaced at 180 degrees (S-N direction), while step size of 12 shows the same characteristics of displacement but with lower frequency.

The use of different step size only defines the number of pixels (resolution) in the correlated image. Step size has not an influence in the correlation results using the artificial images, only affects the vectors resolution of the correlation result. In the cases where the software detects properly a displacement the vector displacements figure show a clear pattern in terms of magnitude and direction of the area affected

4.4 Window Size

Correlation window defines the area (in pixels) of a couple of images to check the correlation. To assess the effect of window size on correlation, different comparisons of window sizes were made using a frequential correlator and correlation parameters (step size 8, threshold 90) as constant. The resolution of the images was 5 unit/pixel and the displacement created is 10 pixels. The different window sizes selected for the purpose of comparison are 4, 8, 16, 32 & 64.

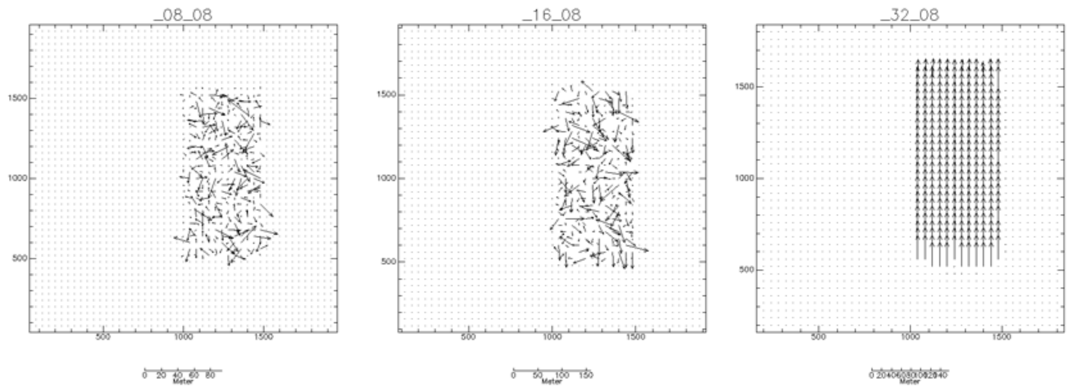

Figure 20 Correlation Results Left: step size of 4; Right: step size of 12

Figure 20 show the results using window sizes 8, 16 & 32. It can be observed that window size of 32 provide excellent direction of displacement in S-N direction, on the contrary window size of 8 and 16 show a noisy result. According to all the results obtained, considering the parameters of this case, the window sizes of 4,8,16 give a noisy result, from that window size in ahead the correlation results correct.

The window size for correlation of two artificial images is sensitive in giving the displacement results. Lower window size does not give correct results; results are too noisy and unreliable. Higher window size showed better accuracy in terms of magnitude and direction. When the software detects properly a displacement the vector displacements figure show a clear pattern in terms of magnitude and direction of the area affected

From the present analysis we can see that results of window sizes 4, 8 & 16 give mostly noisy correlation images. There is not any specific correlation pattern for these three window sizes as compared to the window size 32 and 64.

4.5 Sensitivity Analysis

In point 4.2.1 in was observed that the effect of the resolution is more related with the resolution of vectors displacement result, however different resolution imagery can affect the result of displacement higher that 1 pixel, because the correlation is performed without modification of the pixel values.

In point 4.2.2, the examination of the capability of CosiCorr to track different amount of displacements let us know that the software lose its movement detection capability when we had some amount of multi-pixel displacement. On the contrary at sub-pixel level the correlation loose precision with the lowest displacements.

The software parameters Step Size and Window Size show us in point 4.2.3 and 4.2.4 respectively, that the step size only affects the pixel size in the output correlated image, consequently its inclusion in a sensitivity analysis is not critical. Opposite to this the window size is clearly sensitive in giving the displacement results consequently further analysis of this parameter is needed.

As a result, a sensitivity analysis that combines the parameters: resolution, amount of displacement and window size at multi-pixel and sub-pixel level is presented next.

4.5.1 Multi-pixel level

The sensitivity analysis for the evaluation of CosiCorr software gives an overview of how the change in different methodological parameters affects the change in correlation results with multi-pixel displacements. The combination of the resolution of the images (1, 2.5, 5, & 10 unit/pixel), the displacement of the pixels (1, 2, 4, 5, 10, 20, 40, 50 & 100 pixels) and the window size (4, 8, 16, 32 & 64 pixel-pixel), are part of the analysis showed below. Because the step size is not considered a critical parameter for this evaluation it was fixed in 8 pixels as that gives a relative good resolution of the vectors displacement result, considering the kernel size of the artificial figures (see also Figures B- 3 4, 5, 6 in Appendix B).

As it was said in the previous chapter, the vector correlation outputs of the multi-pixel analysis only have two possible results: the incorrect or noisy result and the correct result were the resultant (see Figure 11).

The summary in Figure 21 presents all the results:

Test	Pixel resolution (m/pixel)	Displacement (in pixels)	Window size 4	8	16	32	64
Test 1	1	10	✗	✗	✗	✓	✓
		50	✗	✗	✗	✗	✗
		100	✗	✗	✗	✗	✗
Test 2	2.5	4	✗	✗	✓	✓	✓
		20	✗	✗	✗	✗	✓
		40	✗	✗	✗	✗	✗
Test 3	5	2	✗	✓	✓	✓	✓
		10	✗	✗	✗	✓	✓
		20	✗	✗	✗	✗	✓
Test 4	10	1	✗	✓	✓	✓	✓
		5	✗	✗	✓	✓	✓
		10	✗	✗	✗	✓	✓

✗ incorrect ✓ correct

Figure 21 Summary of the correlation results considering different image resolution

In Figure 21, comparing the result considering 10 pixels of displacement with 1, 5 and 10 pixel resolution we observe that they are equivalent. Same situation we observe with 20 pixels of displacement with 2.5 and 5 of pixel resolution. In conclusion we can confirm that the resolution of the correlated images only affects the resolution of the vectors displacement output. Therefore, we can synthetize the previous table without considering the resolution variable (see figure 22)

Displacement (in pixels)	Window size 4	8	16	32	64
1	✗	✓	✓	✓	✓
2	✗	✓	✓	✓	✓
4	✗	✗	✓	✓	✓
5	✗	✗	✓	✓	✓
10	✗	✗	✗	✓	✓
20	✗	✗	✗	✗	✓
40	✗	✗	✗	✗	✗
50	✗	✗	✗	✗	✗
100	✗	✗	✗	✗	✗

✗ incorrect
✓ correct

Figure 22 Summary of the correlation result at multi-pixel level

Visual inspection of the above Figure 22 shows that there is a direct relationship, a sharp transition, between the types of result (correct or incorrect) obtained from the combination of the pixel displacement and the windows size in a correlation. In order to obtain a numerical value of such relation a graph was created, see Figure 23. This graph plots the lower window size that detect property its corresponding displacement (e.g. for a displacement of 5 a window size of 16)

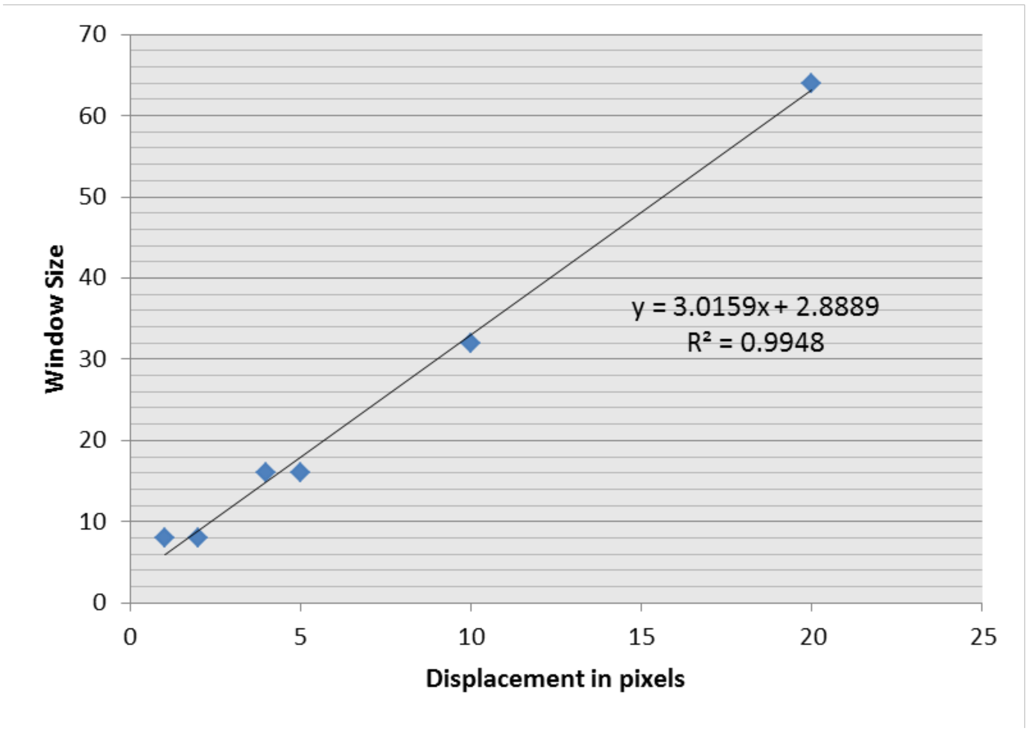

Figure 23: Graph of window size and mutipixel displacement

From the previous graph it can be concluded that there is direct relation, a sharp proportion, between the window size used in the CosiCorr software and the displacement that we want to detect. The higher the displacement is the higher that the windows size must be in order to obtain a good correlation result. From the equation of Figure 19, the relationship appears to be 3 to 1. This means that the software detects accurately a displacement with a window size value 3 times higher than the displacement measured in pixels.

4.5.2 Sub-pixel level

The sensitivity analysis for the evaluation of CosiCorr software gives an overview of how the change in different methodological parameters affects the change in correlation results with sub-pixel displacements. The combination of, the displacement of the pixels (0.01, 0.05, 0.1, 0.2, 0.5, 0.8 pixels) and the window size (4, 8, 16, 32 & 64 pixel-pixel), are part of the results showed below. At sub-pixel level, the resolution considered is 1 pixel per unit, ant the step size 8 for all the analysis (see also Figures B- 7 and 8 in Appendix B).

As it was said in the previous chapter, the vector correlation results of the sub-pixel analysis have three possibilities: the incorrect, the correct result, (see Figure 11), and the third defined as doubtful. Thus the next figure presents a summary of the results:

		WINDOW SIZE				
		4	8	16	32	64
DISPLACEMENT (in p	0.01	✗	✗	O	O	O
	0.05	✗	✗	O	O	✓
	0.1	✗	✗	O	O	✓
	0.2	✗	O	O	✓	✓
	0.5	✗	O	✓	✓	✓
	0.8	✗	O	✓	✓	✓

✗	incorrect
O	doubtful
✓	correct

Figure 24 Summary of the correlation result at sub-pixel level

Figure 24 shows that there is not a linear relationship, a clear proportion, between the types of results obtained (correct, incorrect and doubtful) obtained from the combination of the pixel displacement and window size in a correlation. In order to obtain a numerical value of such relation, a graph was created that plots the lower window size that detect property its corresponding displacement (e.g. for a displacement of 0.2 a window size of 32) (see Figure 25).

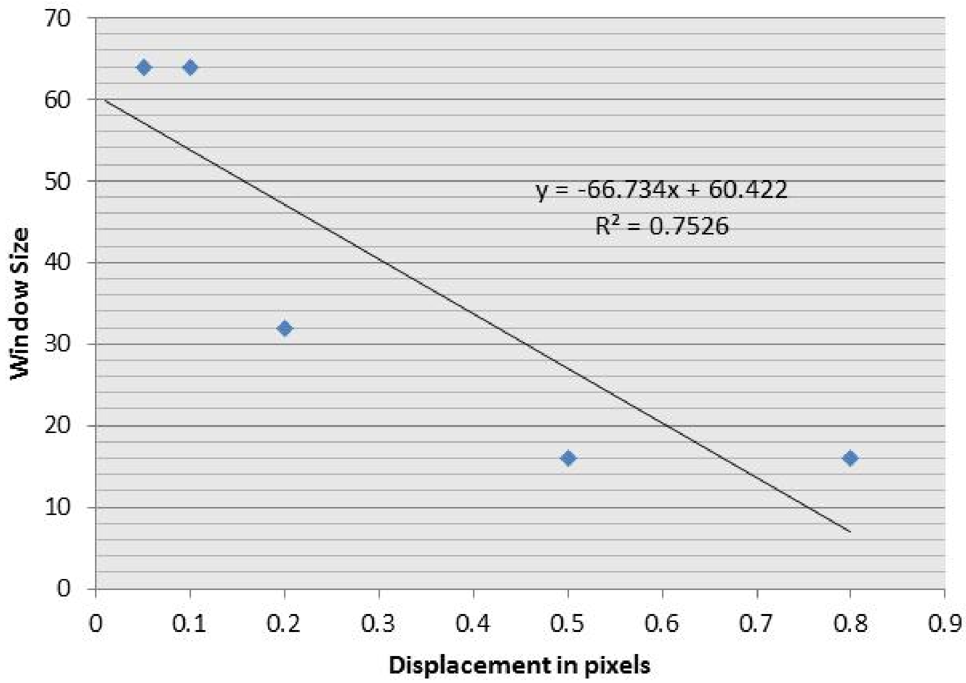

Figure 25 Graph of window size and sub-pixel displacement

In the sub-pixel analysis the graph is not conclusive, comparing it with the multi-pixel case. In the previous graph the relation is poor between the window size used in the CosiCorr software and the displacement that we want to detect. Thus, there is not a relative relationship, a blunt proportion, between the types of result obtained (correct, incorrect and doubtful) obtained from the combination of the pixel displacement and the windows size in the correlation

In general, it can be interpreted from the previous analyses that at multi-pixel level, the higher the displacement the higher that the windows size must be in order to obtain a good correlation result. Opposite to this, at sub-pixel level, the higher the displacement the lower that the windows size must be in order to obtain a good correlation result.

4.6 Simulation cases

As a corollary of the present study it was considered important to apply the artificial approach to simulate real cases that often occur for the correlation using optical images, airborne or spaceborne. An area of 2x3 pixels is subject of analysis considering an average situation considering the existing resolution imagery.

4.6.1 Case 1: High contrasted displacement

In this case, that reflects a displacement of a landslide in a context with a high contrast of pixel values, a small grid of 2x3 grid is generated in a contrasted background, and then is moved upward 1 pixel. Resolution fixed in 1 pixel/unit and step size in 8 pixels. This case can be interpreted as a simulation of a vegetated area where a bare landslide only can be detected considering the alteration in the pixel value.

The correlation is performed using different window size: 4, 8,16,32,64. This results in the visualization of the vectors image of the correlation result. Next the results using 4, 16 and 64 of window size (see also Figure B-9, appendix B) :

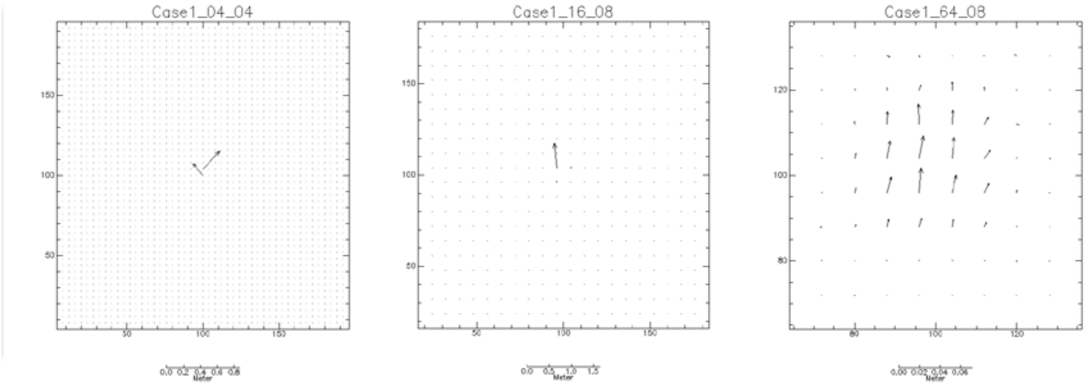

Figure 26 Results of the correlations. Case 1

In Figure 26, we observe a good performance when intermediate values of window size e.g. 8, 16 is used. At lower window size values the accuracy of the direction is lost, so we can say that is a doubtful situation. Using alarger window size, an area larger than the area effectively displaced (2x3 pixels) reflects a non-existent displacement totally incorrect.

4.6.2 Case 2: Low contrasted displacement

Remembering, this case keeps the background and the inner square of the artificial model intact. In this case a grid of 2x3 is selected from the inner square of the model. Thus, the area selected is moved upward 1 pixel. Resolution fixed in 1 pixel/unit and step size in 8 pixels. The main difference of this case is that there is no more high contrast between the portion moved and the background.

The correlation is performed using different window size: 4, 8, 16, 32, 64. This case corresponds to the movement of a landslide in vegetated area, but in this situation the landslide is still covered by the vegetation of the area surrounded. Next the results using 4, 16 and 64 of window size (see also Figure B-10, appendix B) :

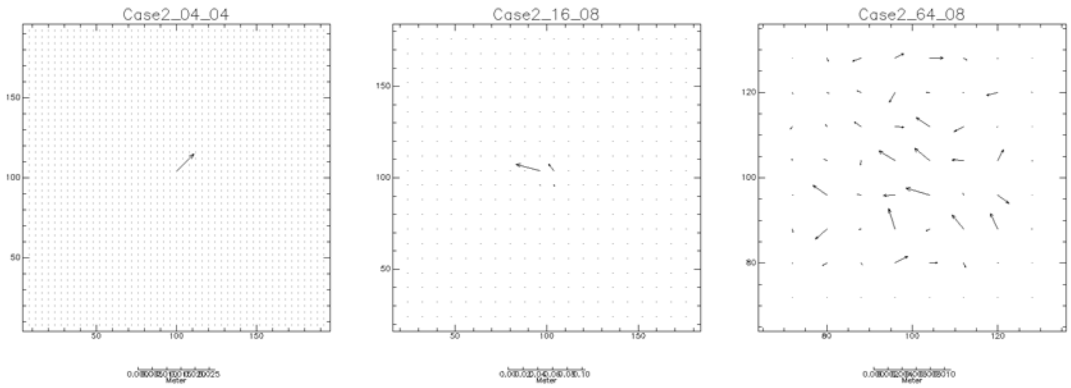

Figure 27 Results of the correlations. Case 2

In Figure 27 we observe a performance with a bad accuracy in terms of magnitude and direction considering all the window size evaluated. The results at 4 and 8 of window size can be defined as doubtful. At 16, 32, 64 of window size value the accuracy of the direction is incorrect same as the magnitude. At higher window size an area higher that the selected area, 2x3 pixels, reflects an inexistent displacement in the area that surrounds it.

4.6.3 Case 3: Decorrelation area

Case 3 explores the behaviour of the algorithm when a possible decorrelation area occurs. Therefore a grid of 2x3 is selected in the intact inner square, and then the selected pixels are removed. This operation exposed the second background. The main difference of this operation relies in the in-existence of a displacement operation. It only consists in a replacement of the pixel values selected.

This case represents a situation of a potential decorrelation area of a small portion of an image. For example, a decorrelation can happen when we try to correlate an image that show no clouds with other that is cloudy. Resolution fixed in 1 pixel/unit and step size in 8 pixels. Next the results using 4, 16 and 64 of window size (see also Figure B-11, appendix B):

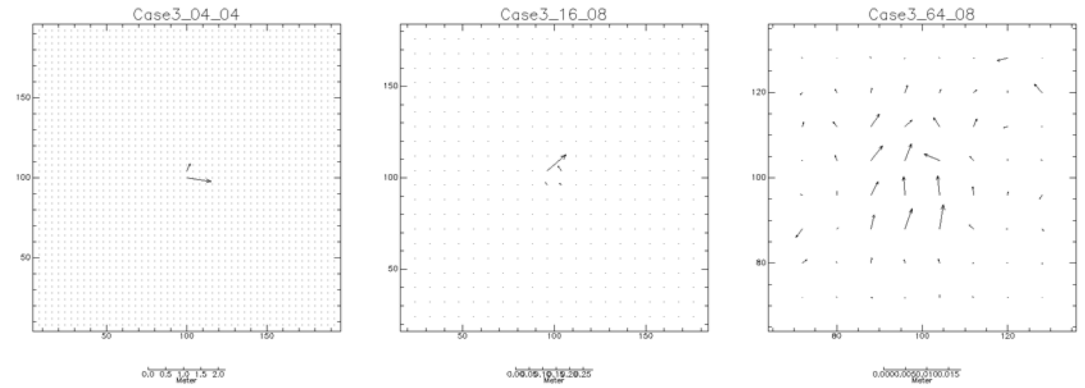

Figure 28: Results of the correlations. Case 3

Unexpectedly, in Figure 28 we observe a performance with a bad accuracy in terms of magnitude and direction similar to the previous case. At any window size values the accuracy of the direction is incorrect same as the magnitude. At higher window size an area higher that the selected area, 2x3 pixels, reflects a non-existent displacement in the area that surrounds it.

4.6.4. Summary of Simulation Cases

The simulation cases were an attempt to apply the artificial experimental approach to real case situation. Three situations were emulated considering the artificial approach used in the main analysis.

In the first case a high contrasted group of pixel values (grid of 2x3) was displaced upward 1 pixel. This can be interpreted as a simulation of a vegetated area where a bare landslide only can be detected considering the alteration in the pixel value.

In the second case a low contrasted group of pixel values (grid of 2x3) was displaced upward 1 pixel. The main difference of this case is that there is no more high contrast between the portion moved and the background.

The third case explores the behaviour of the algorithm when a possible decorrelation area occurs. A grid of 2x3 is selected in the intact inner square, and then the selected pixels are removed

From the results it can be interpreted that:

- ✓ The first case was a high contrasted displacement of a group of pixels. In this case we observe a best performance and accuracy when intermediate values of window size: 8, 16 are used. At lower window size values the accuracy of the direction is lost. At higher window size an area higher that the selected area, 2x3 pixels, reflects an inexistent displacement in the area that surround its but it show a good direction and magnitude of the vectors displacements

- ✓ The second case was a low contrasted displacement of a group of pixels. In this case we observe a performance with a bad accuracy in terms of magnitude and direction considering all the window sizes evaluated. At any window size values the accuracy of the direction is incorrect same as the magnitude. At higher window size an area higher that the selected area, 2x3 pixels, reflects an inexistent displacement in the area that surrounds it.
- ✓ The third case was a potential decorrelated area. In this case we observe a performance with a bad accuracy in terms of magnitude and direction similar to the previous case. At any window size values the accuracy of the direction is incorrect same as the magnitude. At higher window size an area higher that the selected area, 2x3 pixels, reflects an inexistent displacement in the area that surrounds it. Anyway, some vectors displacement was observed, contrary to what was expected as a decorrelated area.

In Figure 29 it is specified a summary of the correlation results of the three precedent cases:

		WINDOW SIZE				
		4	8	16	32	64
CASE	I	O	✓	✓	O	✗
	II	O	O	✗	✗	✗
	III	✗	✗	✗	✗	✗

✗	incorrect
O	doubtful
✓	correct

Figure 29: Summary of the results of simulation cases

5. DISCUSSION & CONCLUSIONS

5.1 Answers to research questions

The results from the experiments as shown in chapter 4 are discussed with respect to the originally stated research questions..

1) *How well is the performance of the software by using different resolution imagery for detection of a specified amount of displacement?*

   The precision of the software, when a pair of images at different resolutions is correlated, is insufficient because the vector displacements graph show no relation with the displacement artificially created. The software loses precision in magnitude and direction of the vectors, thus its performance can be considered as poor. Moreover, the application of pixel resizing techniques, if we want to fit one image on the other, causes a lot of noise in the area that surrounds the area where the displacement had been created.

2) *What amount of displacement can be detected properly by the software at multi-pixel and sub-pixel level*

   According to the results, in using artificial images, two points are critical: the displacement that is desired to be detected and the window size used for the correlation. The software detects accurately a multi-pixel displacement with a window size value 3 times higher than the value of displacement. At sub-pixel level (less than 1 pixel of displacement) the results are not conclusive. It is only possible to confirm a tendency of a better performance if a high window size is used when we want to detect a high displacement.

3) *What is the influence of the step size and window size in the achievement of reliable results?*

   Step size has not an influence in the correlation results using artificial images, only affects its presentation, the resolution of the vector displacement graph. On the other hand, the window size is quite sensitive in giving the displacement results, thus it has a critical influence in the correlation of two artificial images.

5.2 The use of artificial images

The artificial images have met the requirements of the present study, because it was possible to know what results expect according to the displacement generated. In this way it was possible to assess the accuracy of CosiCorr software for the detection of horizontal displacements. Because of this, the artificial images can be used in any other research that requires know previously the conditions and results of a correlation.

Even though, the correlation of artificial images does not consider the use of DEM or relief images that are necessary for the correlation of real images, it shouldn't affect the precision of the correlation because the DEM is only necessary for their coregistration. Thus if both images are correctly coregistered the situation must be quite equivalent to the analyses done in this research. In the same way, the artificial figures do not deal with geometric & atmospheric effects that are found in real images, because these distortions only affect the coregistration of a pair of images but not the result of a correlation.

The software ArcGIS, used for the construction of the artificial images, was not friendly for the manipulation of pixel values and displacement of pixels, for that reason a simplification like an square moving up, was considered for the present assessment. It was the simplest and most effective way to represent a simple controlled displacement.

The evaluation of different resolution imagery was not complete because it was not possible to simulate the different pixel resolution of a pair of images from a same location but obtained by a different satellite sensor. This means that, if an area of 2x2 pixels is detected by one sensor, those values would be different than a single pixel value that can be the representation of the same portion but at lower resolution. Thus, this property can be considered more related with the sensitivity of the sensor and the spatial resolution of the image obtained. As a result, this is an important limitation of the use of artificial images.

5.3 Considerations regarding the assessment

The displacement values created were pre-established and selected under the criteria of the researcher. Because there are no researches similar to the present this values were selected in the widest range possible, according to the difficulties of the construction of the images and according to the sequence of the values that we wanted to evaluate.

The size of the area that is effectively displaced is certainly an important subject to study. It is not the same to evaluated a large area of hundreds of pixels moving upward compared to a small grid of 2x3 moving also upwards. Thus, the results obtained with the present research, and the derived conclusions must be taking this in consideration.

Some analysis of the present research required the resampling of an image in order to compare the detection of a same amount of displacement tested at different resolutions. For this purpose the nearest neighbourhood technique was used for the resampling of images. The nearest neighbourhood was used because it is the most common and practical resampling technique, however, different techniques can also be tested for further investigation.

The research explored the correlator engine of CosiCorr software. It doesn't consider the other options of the software. The correlator engines was tested without considering effects of other parameters more related with the coregistration of images. This was done because the main interest of the research was focussed in the assessment of the correlation algorithms that CosiCorr uses rather than its tools for the equalization of the images

A limitation of the program is referred to the window size that is selected. CosiCorr software only allow the selection of window since that is power of two (4, 8, 16, 32, 64, etc.). For the purposes of a sensitivity analysis these values are very limitative because it is not possible to evaluate the intermediate values in combination with other parameters.

The qualification of a single correlation was defined using a visual evaluation of the result, observing the pattern, direction and magnitude of the vector displacements. Three possible results were considered for the definition of a result; the incorrect, correct and the doubtful. For the incorrect and correct options no more characteristic were needed for a proper assessment, however the "doubtful" was add because it was not possible to say if it was correct or incorrect. Maybe the use of the numerical resultant values of the displacements that can be obtained form the ASCII (American Standard Code for Information Interchange) files would help to establish such definition.

Using the ASCII values, numerical resultants can be obtained from the different analyses. In this way the qualitative analyses of the results could become quantitate.

The grid considered for the analysis of the simulation cases had an area of 2x3 pixels, selected by criteria of the researcher. Because the present assessment relies on the objective to detect small displacement the resolution of the image is an important image variable. The selection of such size of grid was done considering in general a small portion of terrain (like a landslide) that is moving in some direction. An SPOT or an ASTER images, could reflect such phenomena in an extension like the extension selected for this analysis.

5.4 Recommendations

As this study was done experimentally, most of the results provided more opportunities of research that could be explored in a longer period of time. Some recommendations are presented here to give direction to future research:

The following items are recommended for improving the artificial model:

- To explore more options in terms of artificial figures, directions and magnitudes of the displacements created
- To use of pixel values more related with real objects, not randomly generated
- To look options of simulations for the incorporation of DEM relief effect
- To look options of simulations of the geometric and atmospheric effects
- To study the suitability to use different software option rather than ArcGIS for the construction of the images

The following items are recommended for improving the manipulation of image variables and software parameters:

- To test the analyses of the resolution effect by using additional operators e.g., cubic convolution or support vector machine
- To generate sub-pixel displacements by using other operators, rather than the proportional one

The following items are recommended for improving the sensitivity analysis

- To export the vector field images as text (ASCII) files containing East-West and North-South displacement components.

- To calculate the resultant displacements using ASCII values and work statistically with those values
- To add the variable: area displaced in the sensitive analyses in order to observe of it affects the correlator

For the simulation cases, the following recommendation can be done:

- To include the analysis of different grid size, rather than 2x3 grid. The grid selected will depend on the resolution of the satellite sensor selected.
- To repeat the test including images with displacements with different magnitude, multi-pixel and sub-pixel level.

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APPENDIX A

Appendix-A contains the artificial image figures used for the correlations

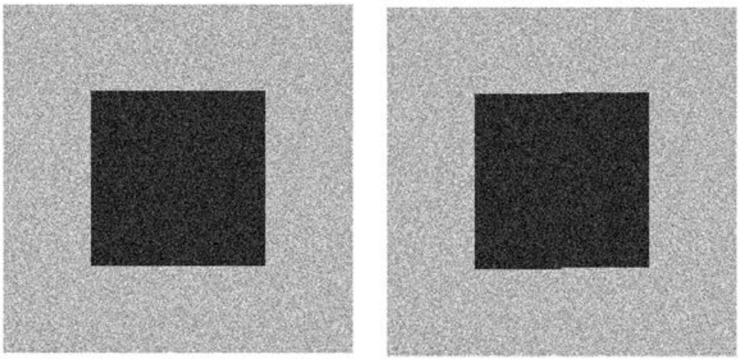


Figure A-1. Artificial models used for Test 1 (multi-pixel level); pre and post state image; resolution of 1 pixel per unit; displacement created of 10 pixels upwards

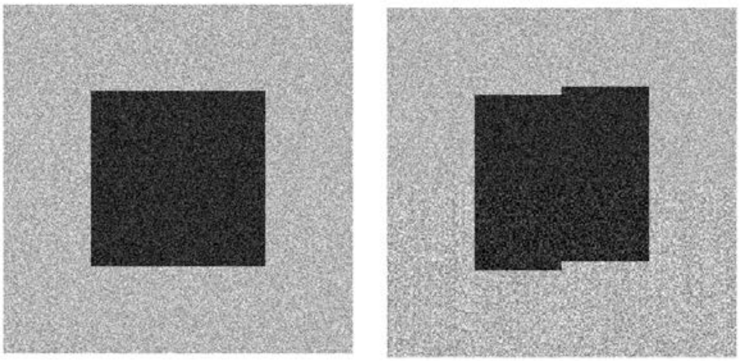


Figure A-2. Artificial models used for Test 1 (multi-pixel level); pre and post state image; resolution of 1 pixel per unit; displacement created of 50 pixels upwards

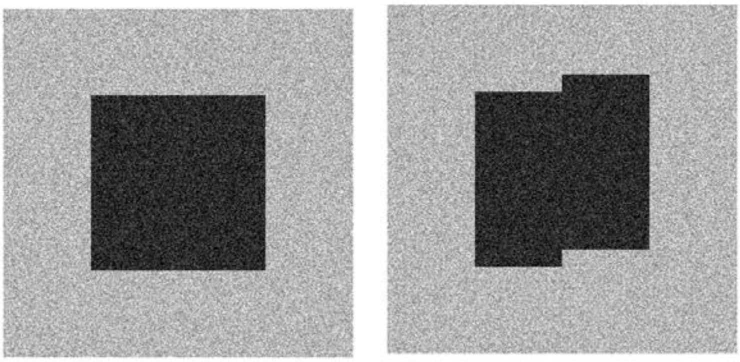


Figure A-3. Artificial models used for Test 1 (multi-pixel level); pre and post state image; resolution of 1 pixel per unit; displacement created of 100 pixels upwards

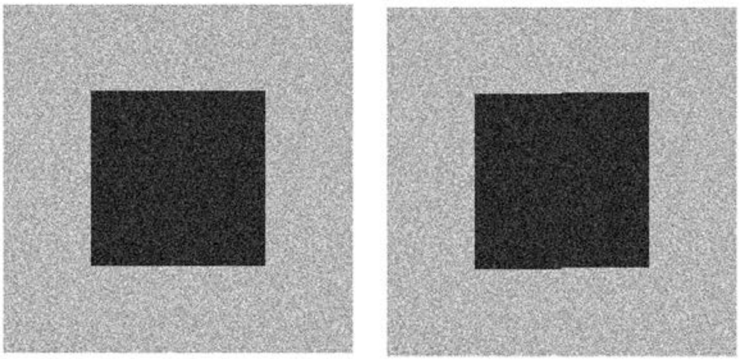


Figure A-4. Artificial models used for Test 2 (multi-pixel level); pre and post state image; resolution of 2.5 pixels per unit; displacement created of 4 pixels upwards

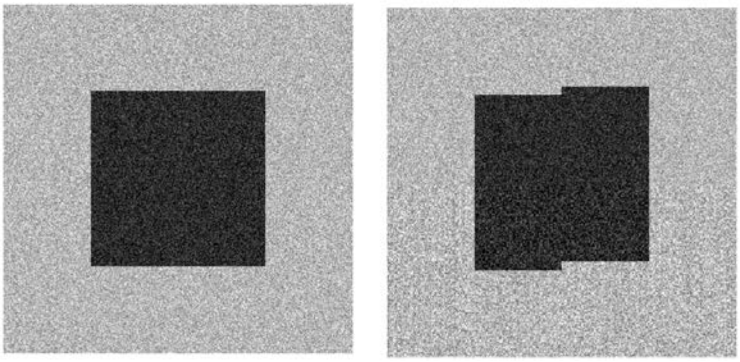


Figure A-5. Artificial models used for Test 2 (multi-pixel level); pre and post state image; resolution of 2.5 pixels per unit; displacement created of 20 pixels upwards

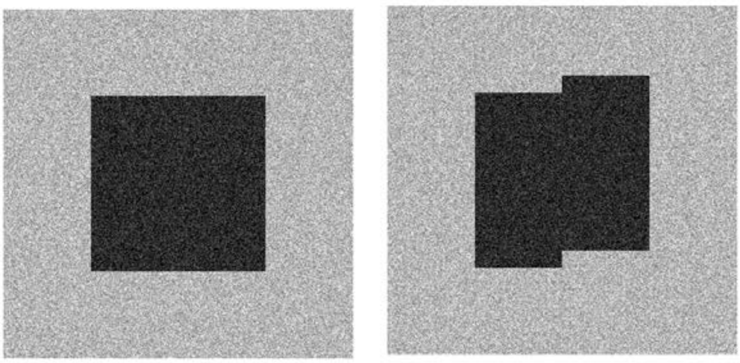


Figure A-6. Artificial models used for Test 2 (multi-pixel level); pre and post state image; resolution of 2.5 pixels per unit; displacement created of 40 pixels upwards

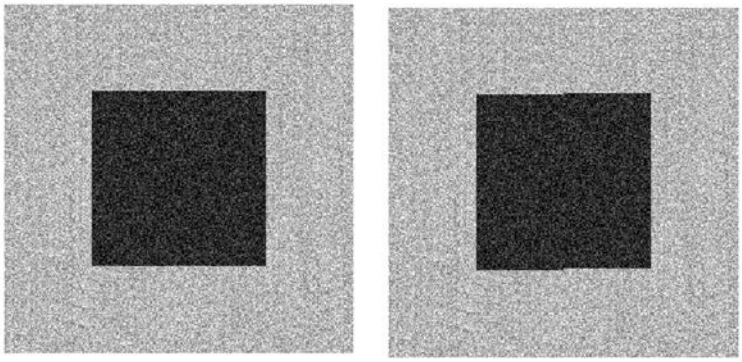


Figure A-7. Artificial models used for Test 3 (multi-pixel level); pre and post state image; resolution of 5 pixels per unit; displacement created of 2 pixels upwards

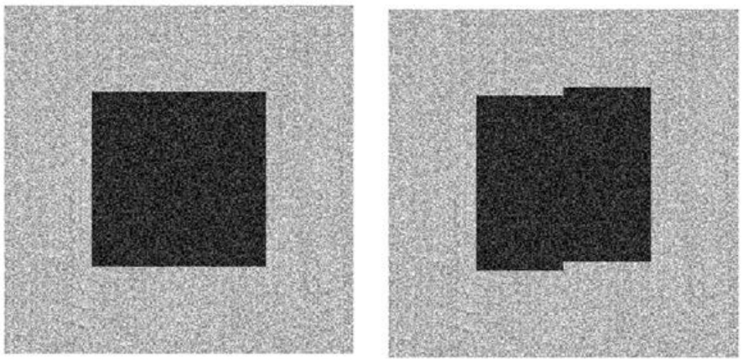


Figure A-8. Artificial models used for Test 3 (multi-pixel level); pre and post state image; resolution of 5 pixels per unit; displacement created of 10 pixels upwards

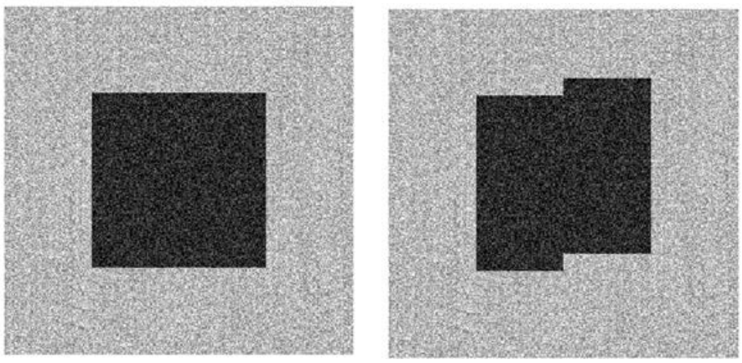


Figure A-9. Artificial models used for Test 3 (multi-pixel level); pre and post state image; resolution of 5 pixels per unit; displacement created of 20 pixels upwards

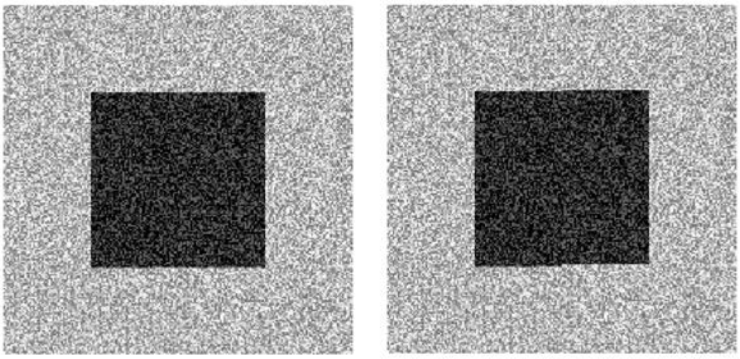


Figure A-10. Artificial models used for Test 4 (multi-pixel level); pre and post state image; resolution of 10 pixels per unit; displacement created of 1 pixel upwards

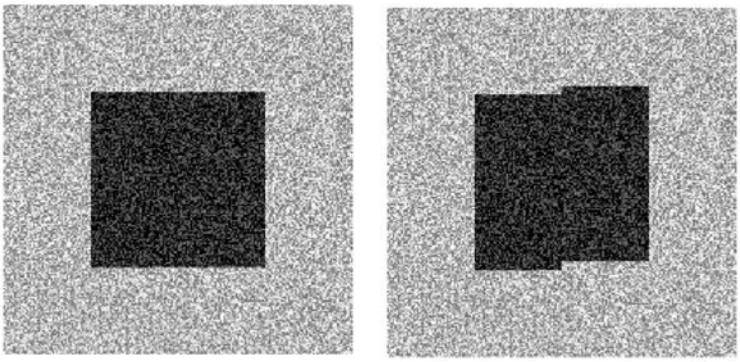


Figure A-11. Artificial models used for Test 4 (multi-pixel level); pre and post state image; resolution of 10 pixels per unit; displacement created of 5 pixels upwards

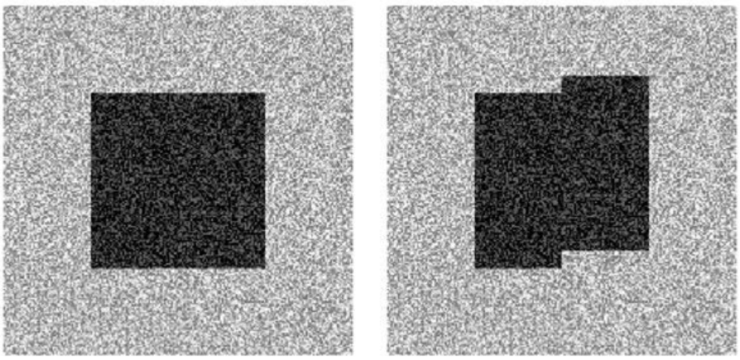
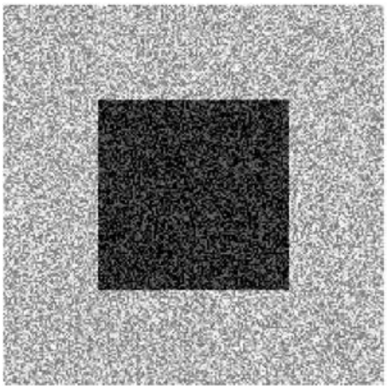
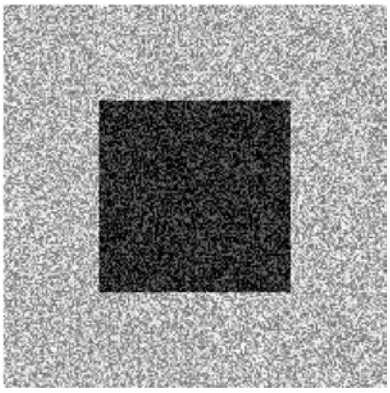


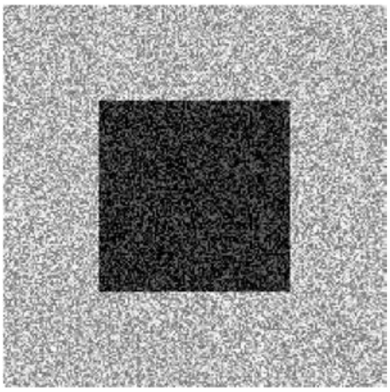
Figure A-12. Artificial models used for Test 4 (multi-pixel level); pre and post state image; resolution of 10 pixels per unit; displacement created of 10 pixels upwards



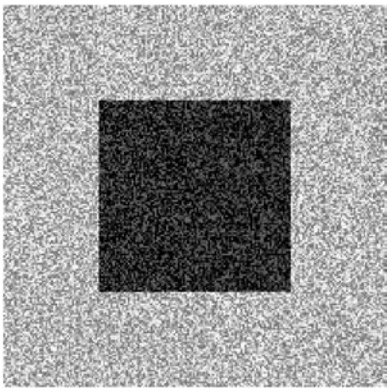
pre state image



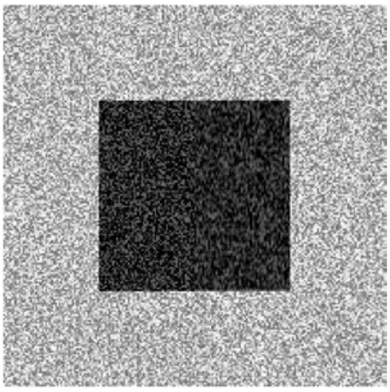
post state image (0.05 pixel upwards)



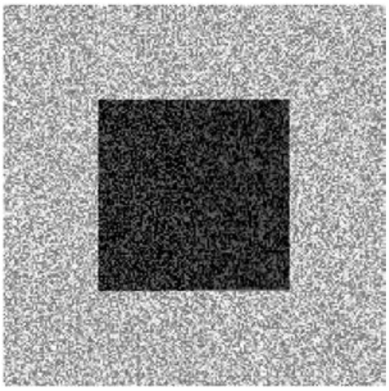
post state image (0.1 pixel upwards)



post state image (0.2 pixel upwards)



post state image (0.5 pixel upwards)



post state image (0.8 pixel upwards)

Figure A-13. Artificial models used for displacement at sub pixel level; pre and post state image at 0.05, 0.1, 0.2, 0.5, 0.8 pixels of displacement; Resolution of 1 pixel per unit. (it is difficult to appreciate the displacement at sub-pixel level because such movement only modifies the pixel values of the area displaced)

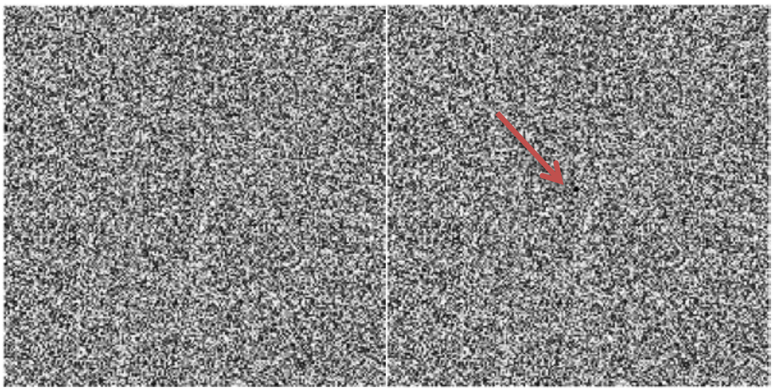


Figure A-14. Artificial models for Simulation Case 1; pre and post state image; displacement of 1 pixel upwards of a 2x3 grid in the area marked

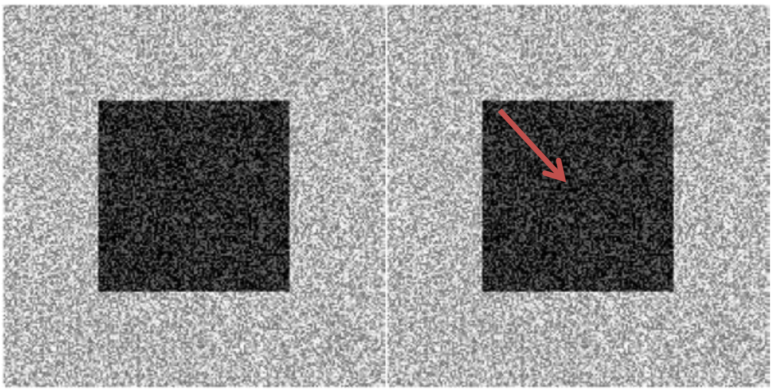


Figure A-15. Artificial models for Simulation Case 2; pre and post state image; displacement of 1 pixel upwards of a 2x3 grid in the area marked

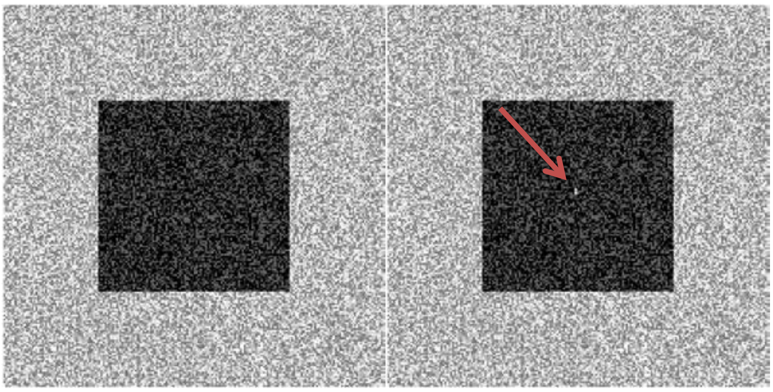


Figure A-16. Artificial models for Simulation Case 3; pre and post state image; no displacement but replacement of a 2x3 grid in the area marked

APPENDIX B

Appendix-B contains the total of vectors displacement results of the correlations

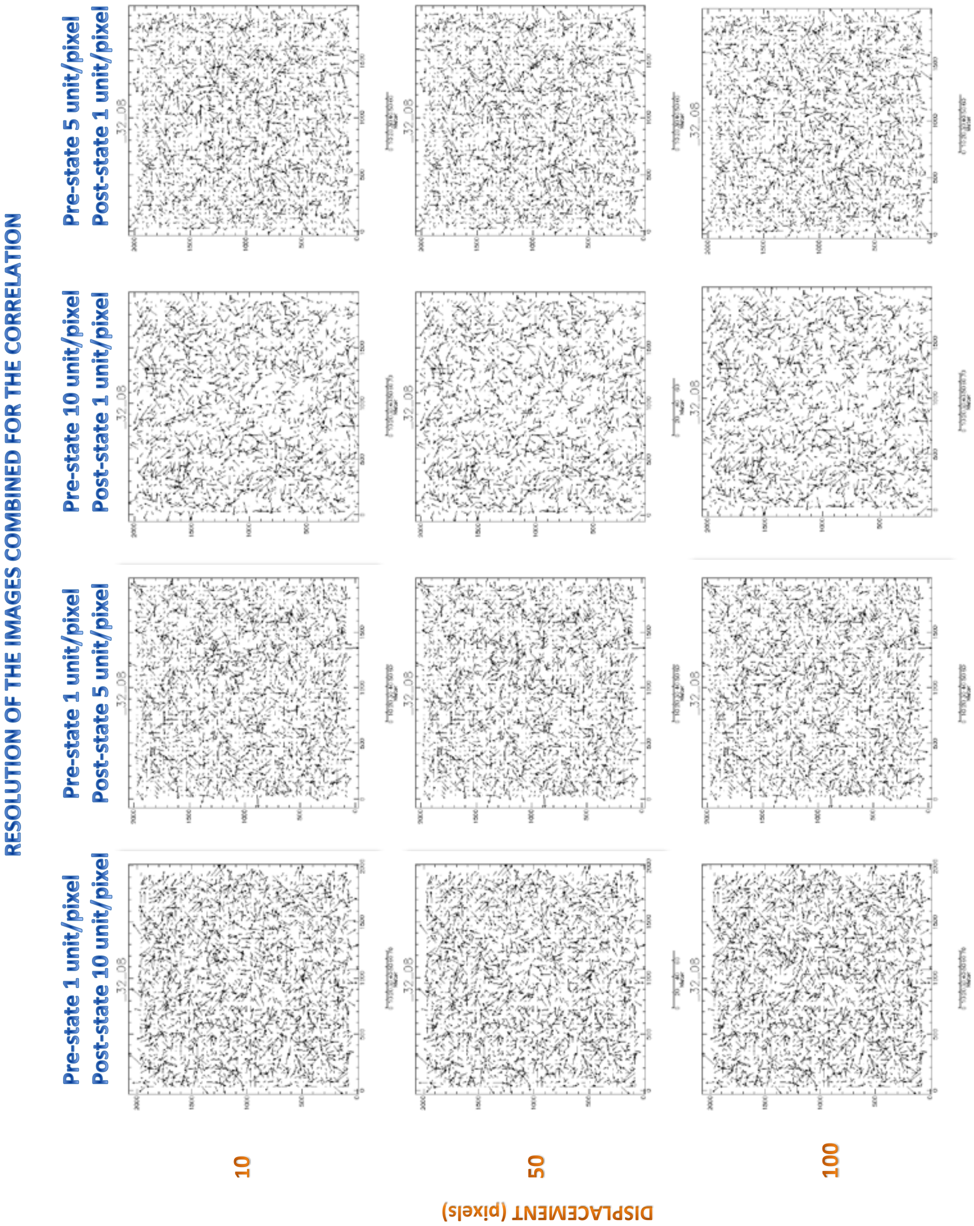


Figure B-1. Correlation results by using different resolution images that were resampled to 1 pixel/unit; different levels of pixel displacement was evaluated

STEP SIZE (pixels)
Correlation results of different Pixel Sizes

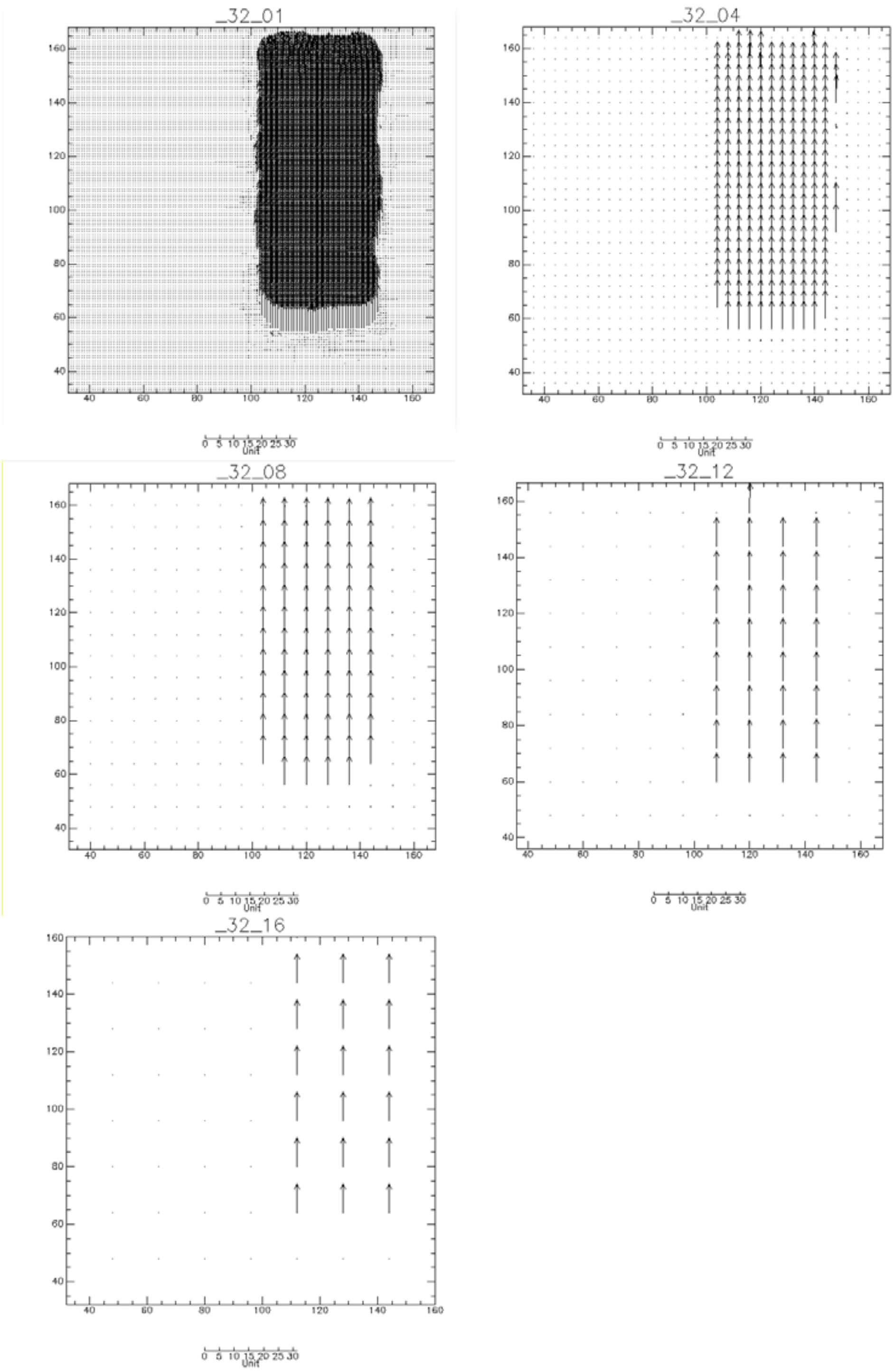


Figure B-2. Correlation results by using different step size value, other variables constant. Up left 4; upright 4; middle left 8; middle right; down left 16.

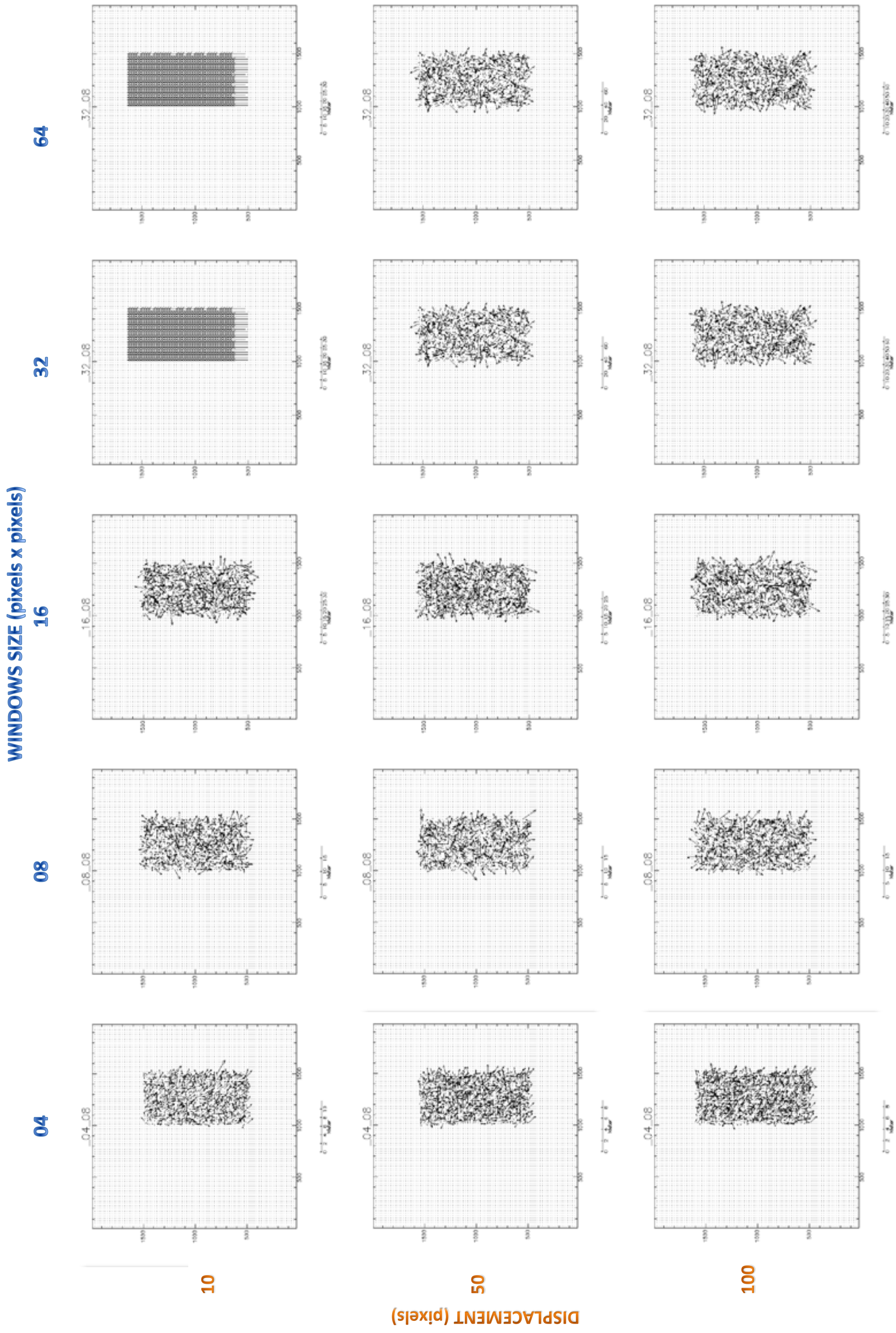


Figure B-3. Multi-pixel Sensitivity Analysis. In figure: Displacement vs. Window Size. Constant values, Step Size: 8; Resolution of the image: 1 pixel per unit

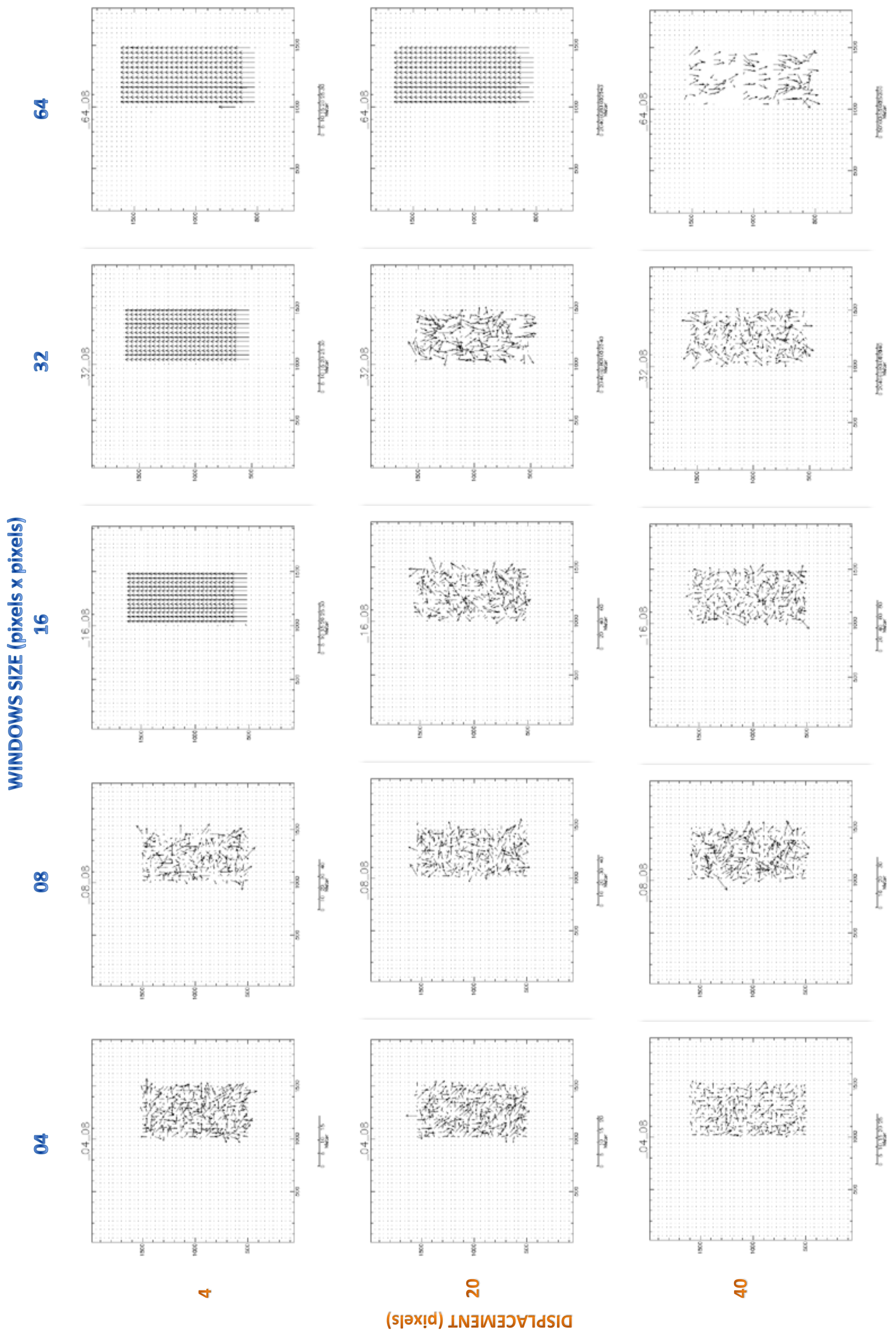


Figure B-4. Multi-pixel Sensitivity Analysis. In figure Displacement vs. Window Size. Constant values, Step Size: 8; Resolution of the image: 2.5 pixels per unit

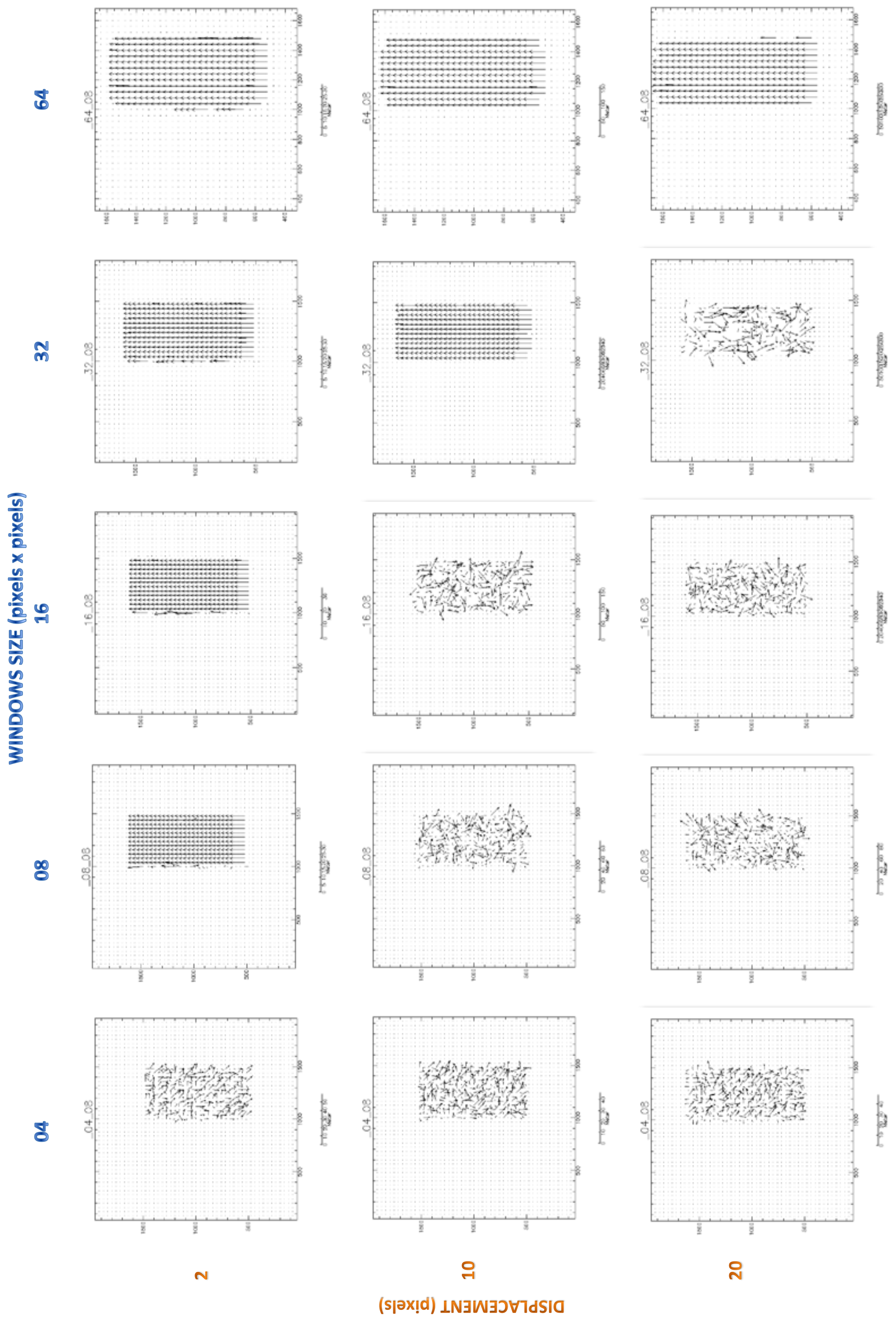


Figure B-5. Multi-pixel Sensitivity Analysis. In figure Displacement vs. Window Size. Constant values, Step Size: 8; Resolution of the image: 5 pixels per unit

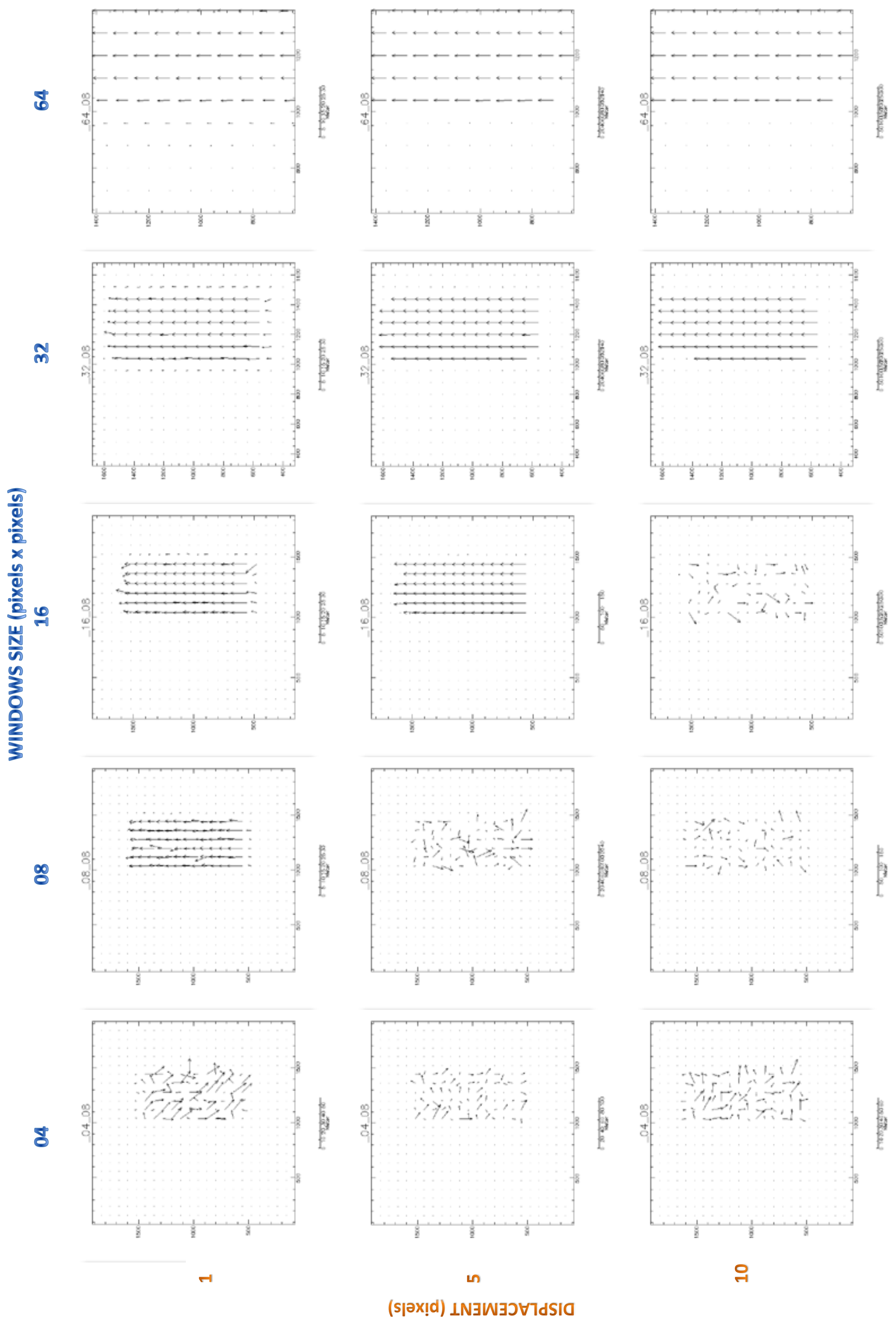


Figure B-6. Multi-pixel Sensitivity Analysis. In figure Displacement vs. Window Size. Constant values, Step Size: 8; Resolution of the image: 10 pixels per unit

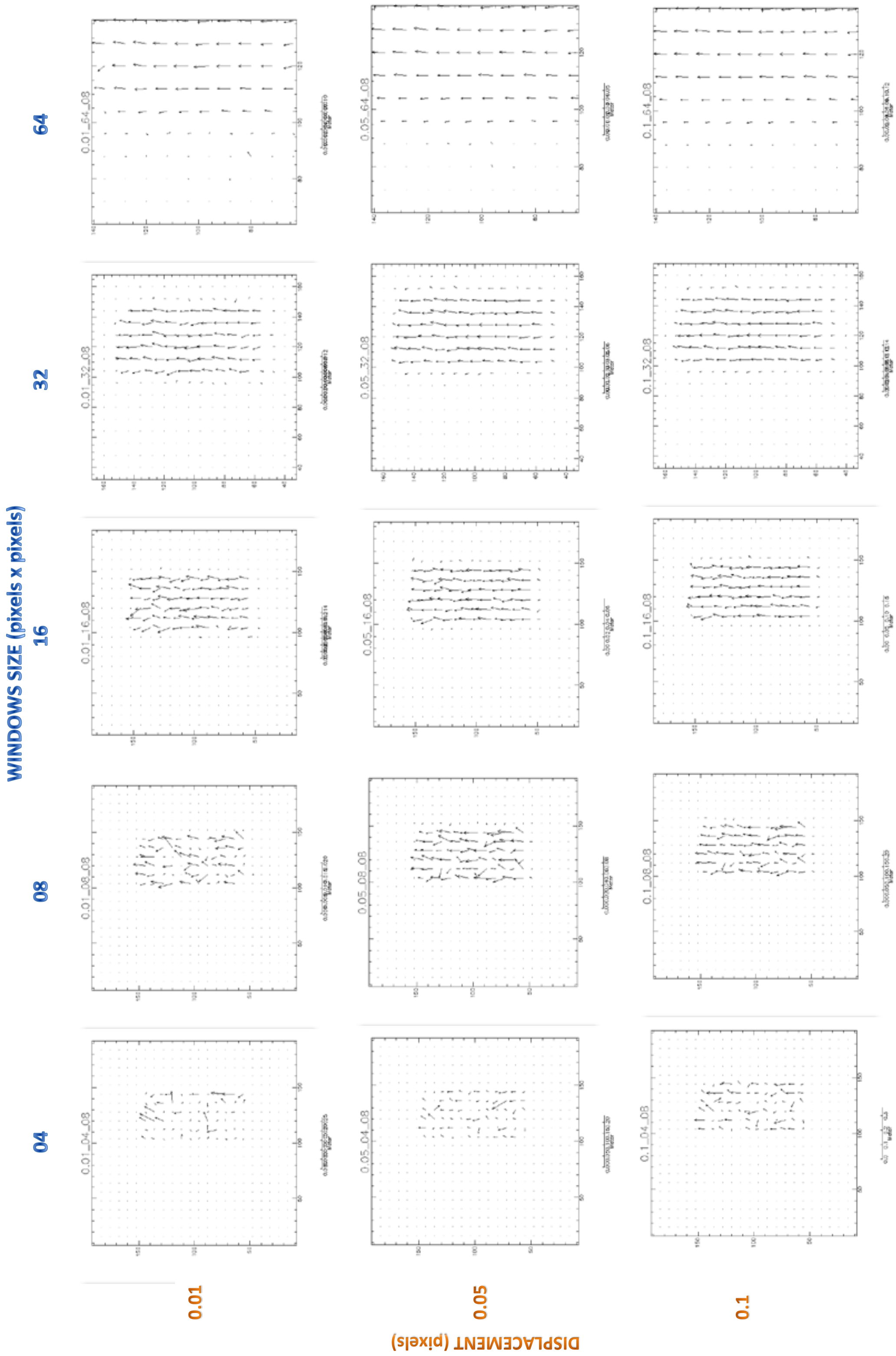


Figure B-7. Sub-pixel Sensitivity Analysis. In figure Displacement vs. Window Size. Constant values, Step Size: 8; Resolution of the image: 1 pixel per unit

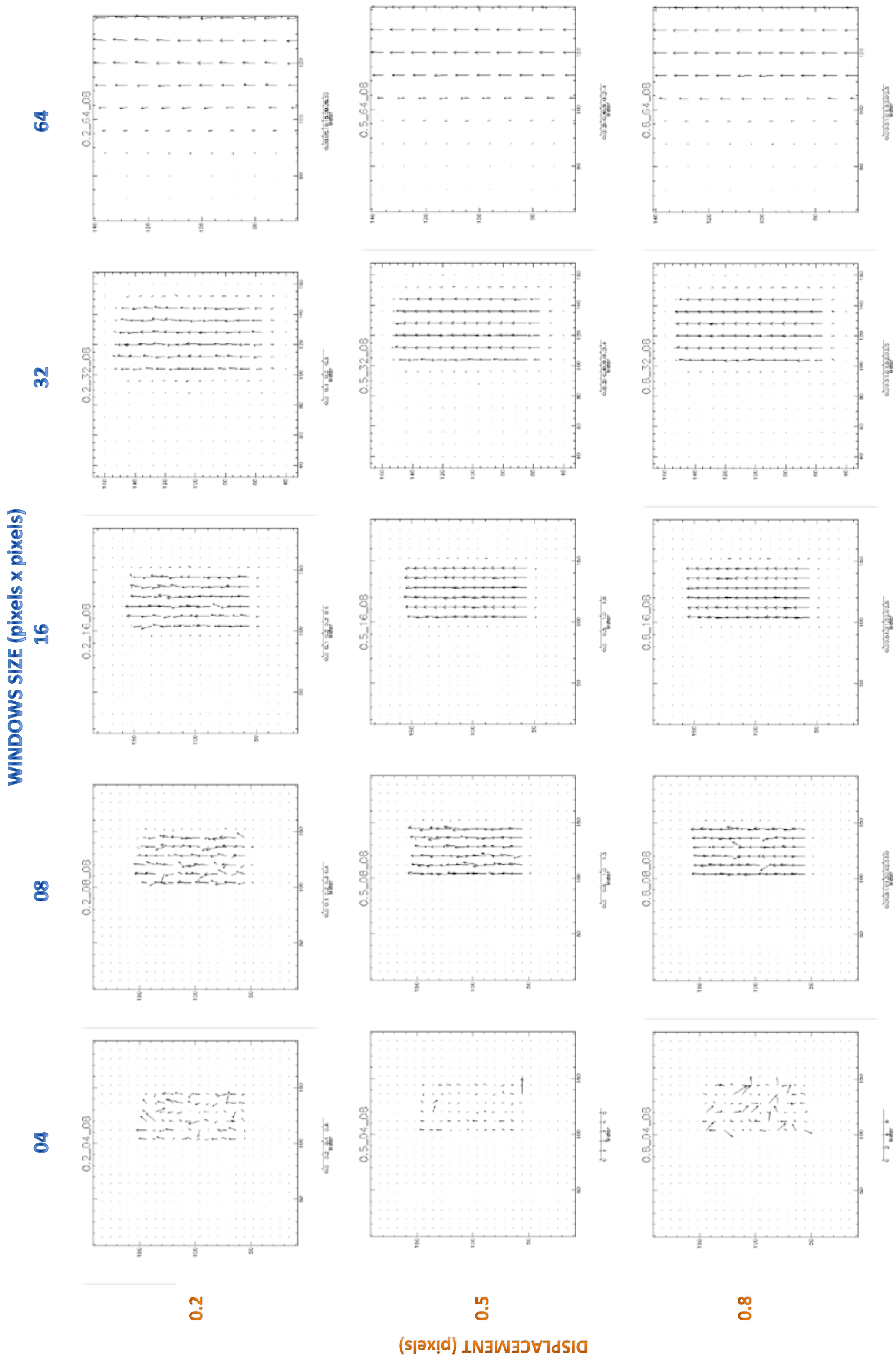


Figure B-8. Sub-pixel Sensitivity Analysis. In figure Displacement vs. Window Size. Constant values, Step Size: 8; Resolution of the image: 1 pixel per unit

CASE 1: CORRELATIONS RESULTS
High Contrasted Displacement

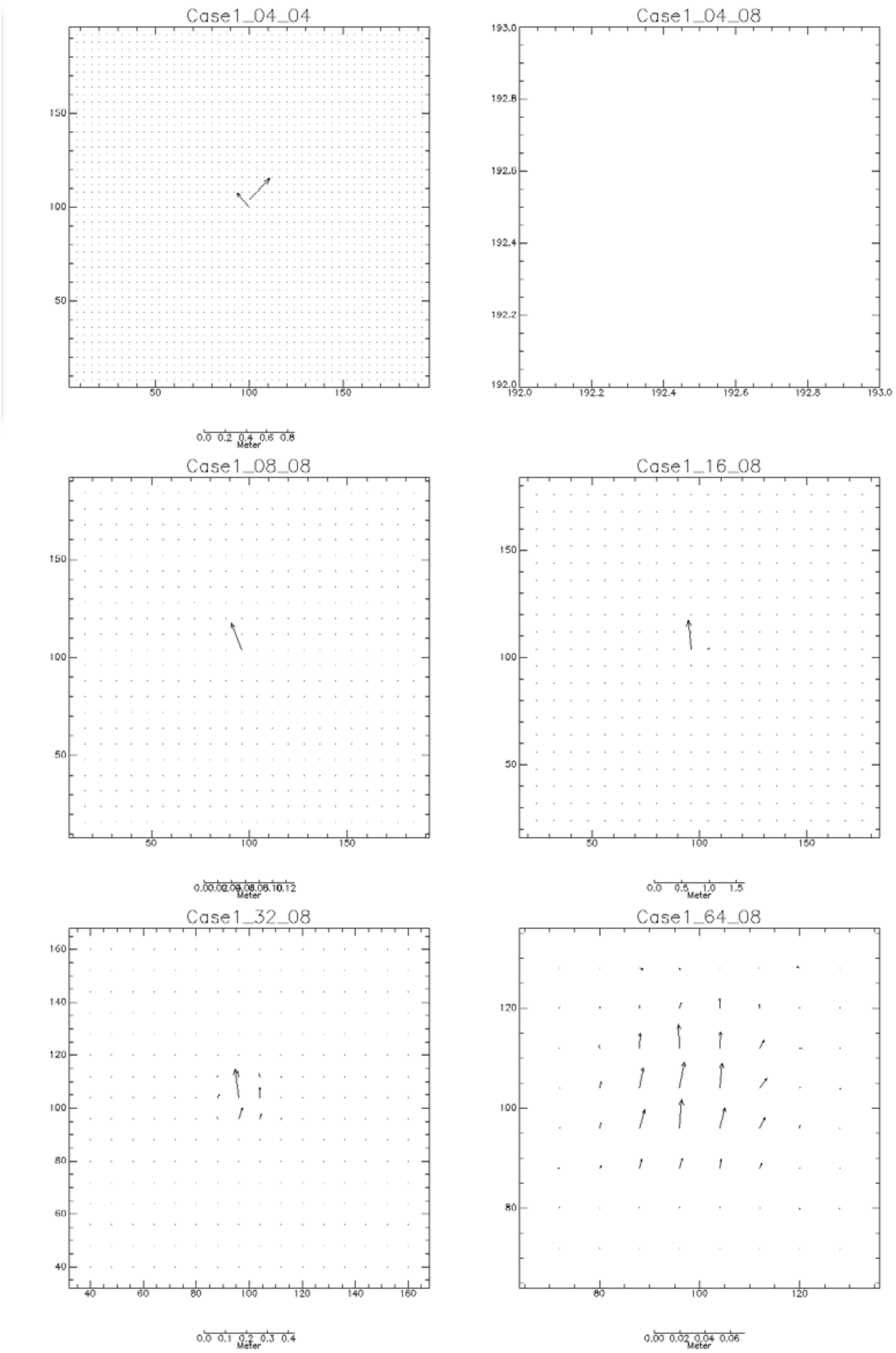


Figure B-9. Vector displacement results for Case 1. Up left: WS4, SZ4; Up right; WS4, SZ8; Middle left: WS8, SZ8 Middle right: WS16, SZ8; Down left: WS32, SZ8; Down Right: WS64, SZ8

CASE 2: CORRELATIONS RESULTS
Low Contrasted Displacement

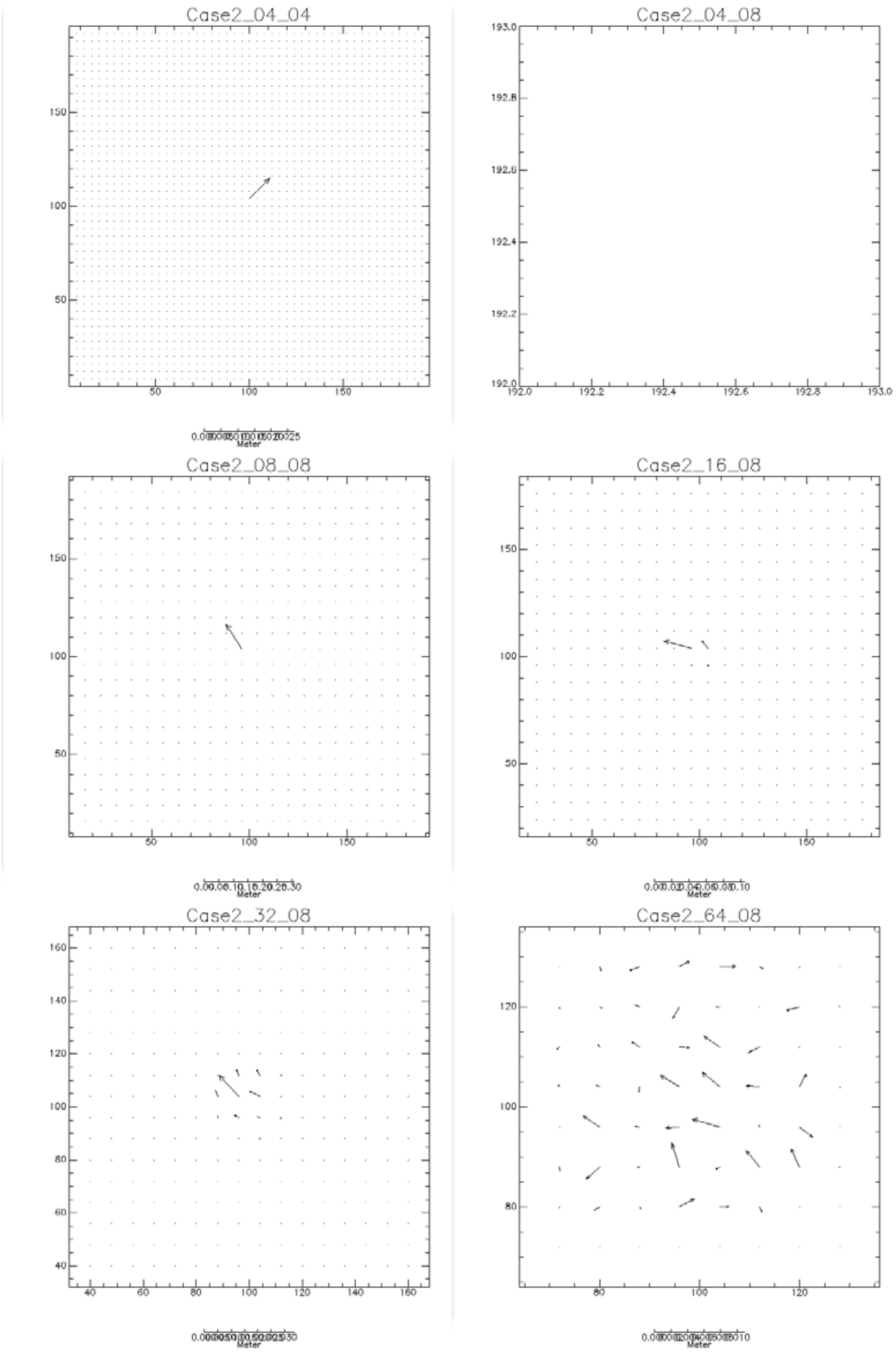


Figure B-10. Vector displacement results for Case 2. Up left: WS4, SZ4; Up right; WS4, SZ8; Middle left: WS8, SZ8 Middle right: WS16, SZ8; Down left: WS32, SZ8; Down Right: WS64, SZ8

CASE 3: CORRELATIONS RESULTS
Decorrelation Area

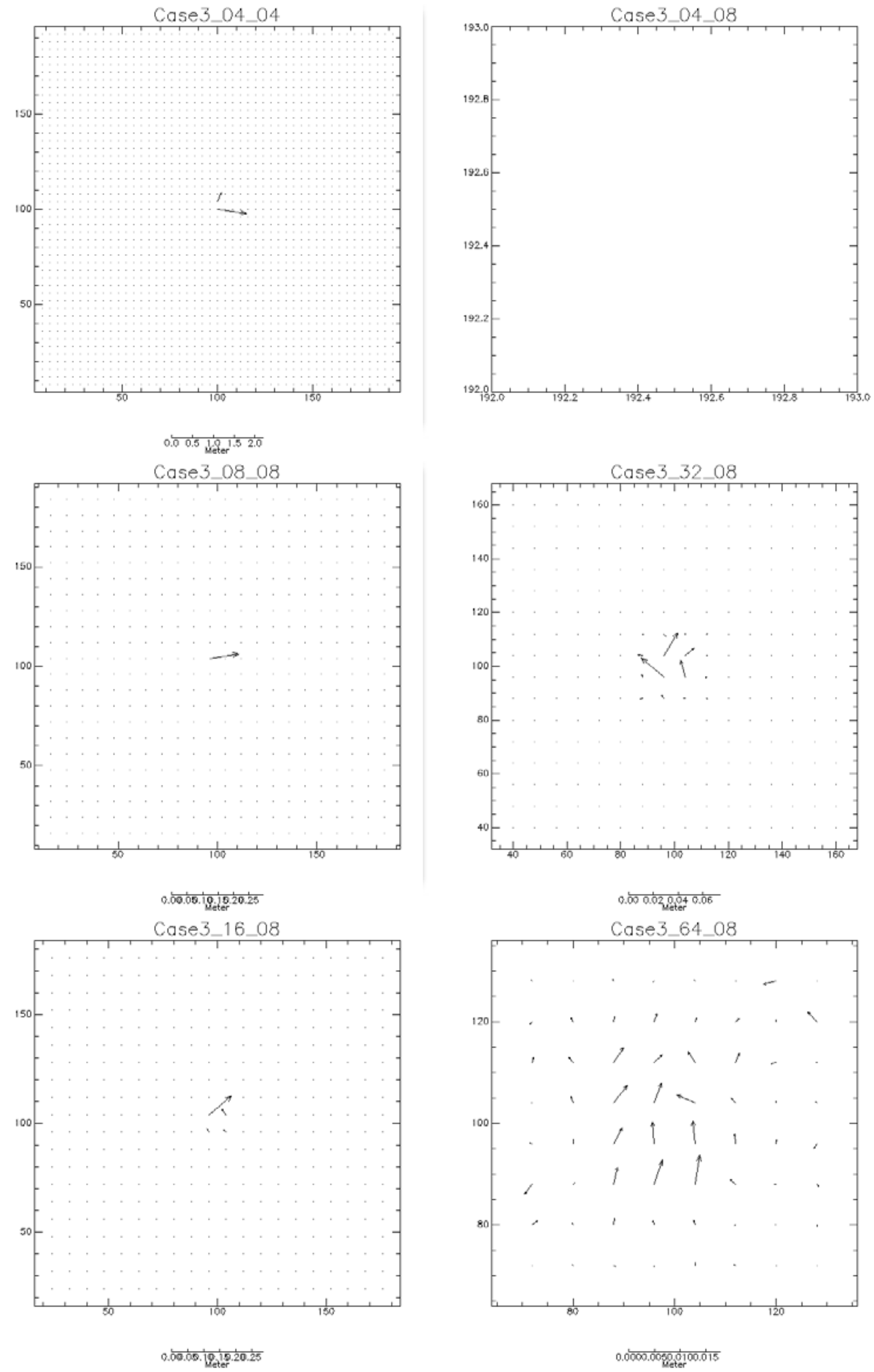


Figure B-11. Vector displacement results for Case 3. Up left: WS4, SZ4; Up right; WS4, SZ8; Middle left: WS8, SZ8 Middle right: WS16, SZ8; Down left: WS32, SZ8; Down Right: WS64, SZ8