# MEASUREMENT OF SUBRESOLUTION TERRAIN DISPLACEMENTS USING SPOT PANCHROMATIC IMAGERY

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**ABSTRACT** Satellite-derived imagery can be used to measure subresolution horizontal terrain displacements associated with present-day earthquakes, sand dune migration, glacial motion, coastal sediment transport, and pre-eruptive volcanic processes. This use of these data allows the detection of change and the determination of rates of many environmental processes worldwide.

**Keywords:** environmental processes, change detection, satellite imagery, subresolution, image matching.

## INTRODUCTION

Satellite image data provide maps of the surface of the earth that are detailed, uniform, and spatially-comprehensive over wide areas. These attributes allow us to use these data to solve significant problems in the earth sciences that are not practical to solve by any other means. We are applying determinations of subresolution spatial differences over time to the detection of change and the measurement of rates of environmental processes worldwide.

The premise of our method is that areally-extensive, subresolution spatial differences in ground patterns between images acquired at differing times can be accurately measured to high-precision and can be distinguished from systematic image differences, such as those due to sensing-system attitude variations. The idea for this approach was conceived while considering tectonic effects of the 17 October 1989 Loma Prieta ('San Francisco') earthquake and their possible effects upon image data.[1] Thus far, we have tested a preliminary algorithm that shows that the approach is reasonable.

The data used are from the French SPOT satellite, which has a "pushbroom" sensor array that provides 10-meter panchromatic imagery. In some cases, the terrain displacements we seek to measure may be as small as a fraction of a meter. In other cases, the displacements may exceed the pixel size, but we may seek subpixel precision. Our general approach is to spatially match the 'after' image to the 'before' image at each point on a grid by iteratively interpolating one and testing its correlation with the other. The statistical sample of each image at each grid point is hundreds to thousands of pixels. Spatial variations in the results correspond to both changes on the ground ("geometric signal") and to image distortions ("geometric noise"). However, most image distortions are attributable to sensor attitude variations that can be identified and removed through recognition and measurement of their distinct spatial characteristics. This allows the possibility of isolating and revealing patterns of environmental change.

Note that we do not need to resolve (nor are we trying to resolve) subresolution objects. Instead, we are *statistically* evaluating radiometric patterns in the data that differ spatially in a consistent direction over many pixels.

## ADVANTAGES OF IMAGEODESY

The name that we have given to this method is "imageodesy", which is a concatenation of "image geodesy" and an acronym for "Image Multitemporal Analysis Geodesy". Imageodesy has several advantages over currently available alternatives.

In studying seismic tectonic deformation, current methods require the establishment of benchmarks at selected locations along a fault, followed by labor intensive surveys. To map out the strain field associated with an earthquake, scientists must wait years, decades, or centuries for an earthquake to occur on that segment of that fault. In contrast, by using satellite image data, an earth scientist need not anticipate the time or location of an earthquake, nor concentrate his effort in any one region in the hope of a data collection opportunity (earthquake) during his lifetime. The 'before' images are available and continue to accumulate in image libraries (collected primarily for other purposes), and the 'after' images can be ordered as needed, for any location in the world. There are no problems of accessibility due to terrain or political factors, and the data are spatially-comprehensive.

Similar advantages of labor savings, spatial uniformity and detail, and global coverage and access are applicable to studies of sand dunes, glaciers, coastal processes, and volcanic processes.

 

## GENERAL APPROACH

### FUNDAMENTAL CONCEPT

Basically, our method relies upon the fundamental statistical concept of a normal distribution. The essence of this concept is that accurate and precise measurements can be obtained statistically from a set of measurements that are individually unreliable and even relatively crude. If measurements have errors that are random, then their probability distribution is symmetrical and bell-shaped, with a peak at the true value. If enough measurements are made, then the shape of the "bell" can be defined sufficiently well to accurately determine the peak. Thus, the probability of accuracy of the statistical determination (at any given level of precision) improves with the number of measurements. Our routine compares hundreds or thousands of pixels in the before image to hundreds or thousands of pixels in the after image in determining each offset vector, and thus may be capable of high accuracy at high levels of precision.

Clearly, the problem we face is not this simple. The measurement errors that we must overcome (radiometric and geometric noise in the image) are not fully random. We discuss these difficulties later.

### BASIC ALGORITHM

The idea for our procedure is an outgrowth of work previously developed and used by one of us to register misaligned bands in a multispectral data set.[2] Our routine calculates a vector at each node on a grid, using, for example, one square kilometer of data (10000 pixels) from each image. We expect to test several improvements, but the basic routine for each vector (as used in our initial tests) is as follows:

(1) The before and after scenes are best-fit matched to the nearest pixel, as determined by visual inspection.

(2) Conceptually, the before image is used as the mapping base and is held "constant". Processing is implemented on a supercomputer.

(3) 100x100 pixels of the before image are statistically compared for maximum correlation to a moving template of 100x100 pixels in the after image, as follows:

(A) Full-pixel steps:

(i) Correlation is determined at the starting (full-scene visual) match position and at the 24 neighboring full-pixel steps, resulting in a 5x5 array of correlation coefficients.

(ii) If the maximum correlation in the array is not at the starting match position, a vector is "drawn" (in effect) to the point of maximum correlation, and a new 5x5 array of correlation coefficients is calculated (without redundancy) at that point.

(iii) Maximum correlation is determined again and the vector is "redrawn", if necessary. (Further iterations are allowed but were not necessary in our initial tests. As verified visually, the best-fit starting position had provided image registration to within a few pixels at all locations within the scene.)

(B) Sub-pixel steps:

(i) Repeated bilinear interpolation of the after image is applied to create a set of half-pixel-step translationally-shifted images for comparison to the before image. These include the peak-correlation full-pixel shift location and its 8 neighbors (a 3x3 array of correlation coefficients). The highest correlation in this array is determined, and the vector is "redrawn" to it, if necessary.

(ii) Quarter-pixel image shifts that include the peak-correlation half-pixel shift location and its 8 neighbors (again a 3x3 array) are calculated, their peak correlation value is determined, and the vector is again "redrawn" if necessary.

(iii) This routine is repeated in seven steps down to shift steps of 1/128 pixel (about 8 cm on the ground). Not surprisingly, 1/128 pixel appears to be well beyond the random noise level of precision, as indicated by separate tests (discussed below).

After the full array of vectors across the image is generated, trends that are clearly attributable to differences in data collection between the before and after images are characterized and removed. If these trends are related to detector array distortions, then they are distinctly constant along the satellite path (and appear as differences among entire columns of pixels). If they are related to attitude variations through time, then they are distinctly constant across the satellite path (and appear as differences among entire rows of pixels). Thus, these trends are spatially distinct and can generally be removed in order to isolate image differences due solely to ground deformations.

## RESULTS OF INITIAL TESTS

We have successfully demonstrated the imageodetic method by measuring the subresolution movement of barchan sand dunes in an area west of the Superstition Hills, Imperial County, California. Figure 1 shows the SPOT Panchromatic imagery. Figure 2 displays the temporal difference vector pattern. The dune movement is detected because the dunes and their shadows (in contrast with the underlying terrain) form the dominant radiometric patterns in this local area. Although further processing is needed to largely zero-out the background pattern, vectors for the dunes are sharply anomalous, point downwind (as verified by regional dune morphology), and measure 6-8 meters. This amount of movement is very reasonable for the time span between the images (15 months) for dunes of this size (about 50-70 meters across). Movements of one nearby dune (in an area likely to have stronger winds) have averaged 15 meters per year over the past several decades.[5]

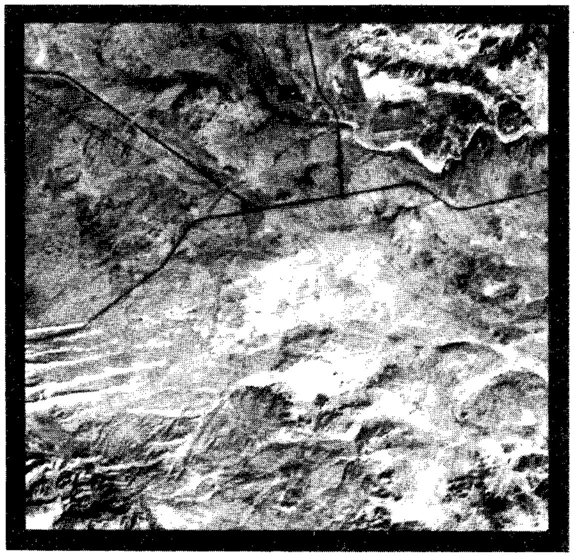

**Figure 1.** SPOT Panchromatic image. © CNES

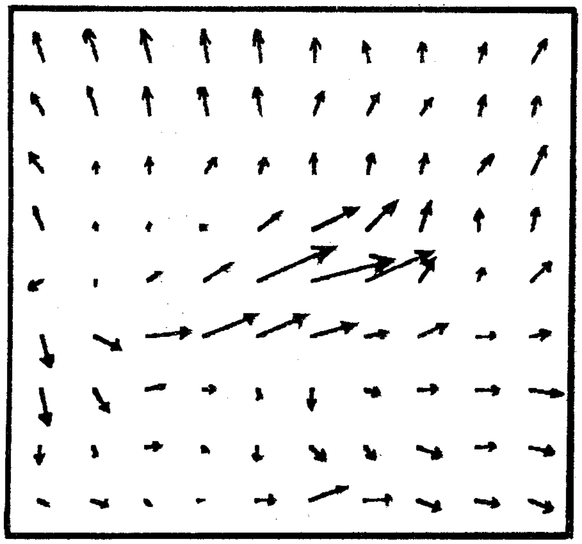

**Figure 2.** Displacement vector map. Largest vector represents about 8 meters displacement.

## ERROR TYPES AND LIMITATIONS

### SOURCES OF ERROR

The primary challenge in this work is to overcome measurement errors of a wide variety such that an adequate level precision can be attained in the image comparisons. Sources of error are of two primary types: radiometric and geometric.

Errors due to radiometric problems result primarily from (A) inhomogeneities in the detector array, (B) general signal-to-noise inadequacies, and (C) radiometric changes in scene content between the dates of image acquisition. We have found SPOT image data to be of very high radiometric quality. However, our requirements are unusually high.

Minor differences across the detector array (which may be significant for our purposes) are evident as vertical striping in both filtered data and difference imagery. A time-variable error that results in horizontal striping is also evident. We may be able to adjust for both of these error types by characterizing and correcting them on a column-by-column and row-by-row basis (we are using unrectified, unresampled 'level 1A' SPOT data).

An inherent limitation of our method is that we require patterns in the image data in order to conduct image comparisons. In some cases terrain will be flat and featureless and very difficult to match between images (signal variance will be inadequate). A map of correlation coefficients can be used to identify such problem areas, but it is unlikely that this problem can be fully solved.

Radiometric differences *between* the scenes can also be problematic. Natural vegetation can grow or die, drainage channels across alluvial terrains can migrate, and roads can be modified. In some cases, entirely new features will not be problematic because they will not spatially match anything in the older scene and will therefore not *spatially* bias the correlation patterns. In general, however, radiometric feature differences should be identified via image differencing and removed from the correlation procedures via image masking. In areas where radiometric change is pervasive (e.g. agricultural fields) image matching of edges (e.g. field boundaries) may be possible.

The problems of 'geometric noise' are also critical, but we believe that they are not insurmountable. Sun angle and view angle differences between scenes should be avoided. Shadows will not match between scenes having differing sun positions. Likewise, radial distortion of topographic features in images will differ between images of differing view angles. In many cases, we must therefore compare scenes taken from the same orbit path (SPOT is a pointable sensor) on approximately the same day of year. (SPOT is in a sun-synchronous orbit, so matches of time of day are not problematic.) (Our Superstition Hills images were not taken on the same day of year, but instead on days that are nearly 'symmetrical' around the winter solstice.)

The other major source of 'geometric noise' is sensor attitude *differences* during the two periods of image acquisition. Variations in yaw, pitch, and roll are all possible. Ancillary data on these variations are provided on SPOT digital data tapes and are described in the SPOT User's Handbook.[6] However, our best way of dealing with these problems is to identify, measure, and remove their fairly distinct spatial patterns in our results, as discussed previously. In our initial tests, we found the primary differences to be a constant (static) difference in yaw and a constantly changing (dynamic) difference in roll.

### INDICATIONS OF THE PRECISION LIMIT

The precision of image matching varies as a function of the image signal-to-noise ratio, the number of pixels involved, image pattern textures, and the interpolation method.[7-8] However, a general statement on precision *may* be possible.

Tests were used to map out broad arrays of correlation coefficients at each level of precision for a few sites. The resultant maps showed correlation increasing smoothly to a peak at the coarser levels of precision, but irregularly at the finer levels of precision, with a transition at about 1/16 to 1/32 pixel. This may indicate the limit of precision for an accurate single-vector result, exclusive of the problems of broader image distortions (discussed above) and exclusive of image pre-processing steps or image-matching algorithm changes which could possibly improve these results.

We are also encouraged by the work of other researchers who have used image matching and analyses in different contexts. Although they have used a variety of data types and processing routines, several have indicated a limit of precision at about 1/20 of a pixel.[9-15] A precision of 1/20 of a pixel corresponds to 50 centimeters on the ground. This precision would be extremely useful for many purposes.

## FUTURE WORK

We hope to refine the method in order to assure high precision and optimum accounting for systematic spatial noise. The former may require filtering of the data, selective masking of temporal differences in land cover, and/or utilization of alternative interpolation and image-matching schemes. The latter will require refined models of the possible results of attitude variations and other factors. Much experimentation will be undertaken.

We believe that this method will ultimately (1) produce spatially-comprehensive maps of horizontal terrain displacements associated with large earthquakes, (2) provide a means of measuring sand dune migration rates worldwide with high-precision, (3) provide input to models of the dynamics of glacial systems, (4) measure sediment transport rates in some coastal areas, and (5) provide a means of detecting topographic changes associated with magmatic migration prior to volcanic eruptions, such as those that occurred at Mount St. Helens in 1980. Other uses are likely to be found also.

## ACKNOWLEDGMENTS

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

## REFERENCES

[1] R.E. Crippen, "Concept for the measurement of horizontal terrain displacements associated with the Loma Prieta earthquake of 17 October 1989 using SPOT panchromatic imagery," *Geological Society of America, Abstracts with Programs,* vol. 22, no. 3, p. 16, 1989.

[2] R.E. Crippen, "The regression intersection method of adjusting image data for band ratioing," *International Journal of Remote Sensing,* vol. 8, pp. 137-155, 1987.

[3] S.F. McGill, C.R. Allen, K.W. Hudnut, D.C. Johnson, W.F. Miller, and K.E. Sieh, "Slip on the Superstition Hills fault and on nearby faults associated with the 24 November 1987 Elmore Ranch and Superstition Hills earthquakes, Southern California," *Bulletin of the Seismological Society of America,* vol. 79, pp. 362-375, 1989.

[4] R. Burgmann, G. Behr, and R. Bilham, "Creep events and interevent slip on the Superstition Hills fault, California," *EOS,* vol. 70, no. 43, pp. 1348, 1989.

[5] J.S. Shelton, *Geology Illustrated,* W.H. Freeman and Company, San Francisco, 434 pp, 1966.

[6] Centre National d'Etudes Spatiales, *SPOT User's Handbook,* SPOT Image Corporation, Reston, Virginia (two volumes), 1988.

[7] W. Forstner, "On the geometric precision of digital correlation," *Mathematical Models, Accuracy Aspects and Quality Control, Proceedings of the Symposium,* edited by J. Hakkarainen, E. Kilpela, and A. Savolainen, International Achieves of Photogrammetry, vol. 24, pp.176-189, 1982.

[8] M.A. Sutton, S.R. McNeill, J. Jang, and M. Babai, "Effects of subpixel image restoration on digital correlation error estimates," *Optical Engineering,* vol. 27, no. 10, pp. 870-877, 1988.

[9] Qi Tian and M.N. Huhns, "Algorithms for subpixel registration," *Computer Vision, Graphics, and Image Processing,* vol. 35, pp. 220-233, 1986.

[10] C.A. Berenstein, L.N. Kanal, D. Lavine, and E.C. Olson, "A geometric approach to subpixel registration accuracy," *Computer Vision, Graphics, and Image Processing,* vol. 40, pp. 334-360, 1987.

[11] M.S. Mort and M.D. Srinath, "Maximum likelihood image registration with subpixel accuracy," *Applications of Digital Image Processing XI, Proceedings of SPIE,* vol. 974, pp. 38-45, 1988.

[12] J.S. Morgan, D.C. Slater, J.G. Timothy, and E.B. Jenkins, "Centroid position measurements and subpixel sensitivity variations with the MAMA detector," *Applied Optics,* vol. 28, pp. 1178-1192, 1989.

[13] D.I. Havelock, "Geometric precision in noise-free digital images," *IEEE Transactions on Pattern Analysis and Machine Intelligence,* vol. 11, pp. 1065-1075, 1989.

[14] E.P. Lyvers, O.R. Mitchell, M.L. Akey, and A.P. Reeves, "Subpixel measurements using a moment-based edge operator," *IEEE Transactions on Pattern Analysis and Machine Intelligence,* vol. 11, no. 12, pp. 1293-1309, 1989.

[15] M. Li, "High-precision relative orientation using feature-based matching techniques," *ISPRS Journal of Photogrammetry and Remote Sensing,* vol. 44, pp. 311-324, 1990.