SOME OPERATIONAL APPROACHES TO REAL-TIME GEOREFERENCING WITH STEREO IMAGERY

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One of the **fundamental** requirements of a Geographic Information System (GIS) is the ability to co-register data planes into a common coordinate system. For the U.S. Forest Service and other earth monitoring agencies, co-registration capabilities must also include aircraft and satellite spectral imagery and often in a real-time manner. The two basic problems with registering aircraft imagery with other GIS data planes are: 1) establishing the earth coordinates of the aircraft's nadir, and 2) correcting the imagery for topographic relief displacements. The first problem is being addressed by the Global Positioning System (GPS), which has demonstrated the capability to provide accurate aircraft position (latitude and longitude) from the intersection of multiple GPS satellite telemetry signals. The second problem of topographic relief displacement is fundamentally more difficult.

For several years the U.S. Forest Service sponsored the Jet l'repulsion Laboratory to develop and implement an aircraft-based Forest Fire Advanced System Technology (FFAST, dubbed "FIREFLY") to gather, transmit, and display forest fire information in a near-real-time manner (Nichols and Warrent, 1987). The basic requirement is to image forest fire perimeters and hot spots, and output the information in the form of vector plots registered to a map database within 30 minutes of last data acquisition. The two dimensional accuracy requirement of the plots is 91 meters (300 feet) RMS with a 30 meter **(100** foot) goal throughout the 120 degree! field-of-view of the sensor. Given these constraints and requirements, several approaches were evaluated: 1) Digital Elevation Models; 2) Graphical Matching Stereo Parallax; 3) Ruled Surface Stereo Parallax; and 4) Neural Network Stereo Parallax. The latter two approaches were found to be the most promising for resolving the topographic relief displacement problem.

TOPOGRAPHIC RELIEF DISPLACEMENT

Topographic relief displacement is the shift in position of an object displayed in an image, caused by the elevation (topographic relief) of the object. Displacement is away from nadir for objects whose elevations are above datum. Relief displacement is given by the equation:

$$D = \frac{r\,h}{H} \qquad (1)$$

The DEM approach to georeferencing is expected to be a viable approach when a complete 30 meter library of DEM data becomes available for the forested regions of the United States. In the meantime, use of the coarse resolution three arc-second DEM data would exceed the upward limit of required FIREFLY accuracy in the area between 40 and 60 degrees from nadir, Thus, the FIREFLY requirement for a 120 degree field-of-view would have to be relaxed to 80 degrees in order to use the DEM approach with three arc-second data. In addition, the issues of onboard aircraft storage and retrieval of the required large amounts of digital DEM data would need to be addressed.

Stereo Parallax Approaches

The basic premise common to the three approaches discussed in this section is that elevation data can be calculated from the stereo parallax present in overlapping aircraft imagery produced from different viewing angles. This is the same principle utilized by the USGS for generation of DEM datasets. Once produced, the parallax-generated elevation data can be inserted into the topographic relief equation (1) to determine the correct position of fire event data.

The three evaluated parallax approaches utilize a parallel flight path arrangement, requiring the aircraft to image the fire in an initial pass, then circle around to image the fire a second time from the opposite direction. The three approaches measuring parallax in the overlapping area include the ‘Graphical Matching,’ ‘Ruled Surface,’ and ‘Neural Network’ procedures.

Graphical Matching Stereo Parallax Approach. The Graphical Matching approach attempts to co-register two flight paths using an iterative (pyramid) correlation tiepoint procedure. The basic assumption is that relief distortions are too large to accurately co-register the two flight paths in one operation. Thus, several small steps are used instead, each one removing a small quantity of relief distortion with each iteration. For example, the flight paths might be reduced in size iteratively (e g., to 75°/0, then 50%, 25%, 10%, of original size), correlating the fire graphics together at each scale, and then iteratively geometrical y adjusting one of them (at original scale). With enough steps, the two paths come into registration, and overall displacements (parallax) are determined and corrected. This approach was prototype, and the correlation algorithm was found to be CPU intensive and insufficient for matching common points between the two flight passes except in areas of minimal relief.

The “Graphical Matching” technique represents the serial approach to what is intrinsically a simple pattern recognition problem. The most appropriate technology would be one that mimics the pattern recognition capabilities of the human brain. Such a technology, known as Neural Networks, has been under development for several years in various universities and laboratories around the world. This technology was prototype and found to be extremely CPU intensive. However, when fully developed with hardware implementations, the Neural Network offers the fastest and most accurate solution to the pattern recognition/matching problem of parallel flight paths. The basic Neural Network procedure is described below.

Neural Network Stereo Parallax Approach. The neural network is an artificial intelligence technique that attempts to mimic the cognitive processes of the brain through the collective behavior of simple, human-like "neuron" processors (McClelland, et al., 1986). Massive amounts of parallel input data (e.g., aircraft imagery) are channeled as analog voltages through the neurons via weighted "synaptic" connections. If a particular neuron receives an input voltage greater than a fixed threshold, the neuron fires, sending new signals along the synapses to other neuron fires, sending new signals along the synapses to other neurons in the network. With appropriate "training" imposed upon the synaptic weights, the collective behavior of specific neurons in the network converge to represent a "memory" or a "response," which is output as the product result.

A neural network for co-registering stereo imagery and calculating parallax was prototype using simulation software, Given a left-right stereo image pair, a neural network "forward-feed" approach was used to extract oriented edge features utilizing Sobel operators, and to perform "shift-correlation" on the edge features to construct initial elevation maps. These initial maps indicated the strength of correlation of the right image with the left stereo image. The images were then passed through a "competitive" network, where each pixel-neuron in each image sent stimulation signals to the surrounding pixel-neurons, and sent inhibitory signals to the corresponding pixel-neurons in the other elevation images. This process imposed Marr-Poggio constrains of continuity and uniqueness upon the final elevation maps, eliminating f alse matches. The stereo network was initially designed to operate upon binary random-dot stereo pairs, but has now been shown to exhibit the ability to extract difference information from a satellite-type image dataset such as a Viking Mars-Lander stereo image pair. A successful stereo elevation map resulted from the processing of the Mars-Lander datasets.

The limited neural network georeferencing prototype described above, is a serial computer simulation of what is primarily a parallel computer application. The simulation proved very CPU intensive, but is probably a few years away from operational capability when electro-optical hardware implementations become practical. However, the neural network approach represents one of the best long-term solutions to stereogrammetry, real--time co-registration, and parallax/elevation generation because of its fundamental biological simplicity and potential fast processing speed.

Ruled Surface Stereo Parallax Approach. Within the constraints of the FIREFLY requirements, the most efficient and accurate serial solution to the matching of parallel flight paths is the "Ruled Surface" approach, named for the mathematical surface used in the procedure, In this approach, line-of-sight vectors from both overlapping passes are calculated from the fire target to the aircraft using the look angle, aircraft altitude, heading, and fire coordinates, The three dimensional vectors (representing a ruled surface) are stored in a two-dimensional planimetric view image; one image for the left side of the fire polygons, and one image for the right side (producing four total images when considering both passes). The true position of the fire target occurs along the line-of-sight vector; the intersection of the four planimetric images provides the correct location and elevation of the fire target. The topographic relief displacement equation (1) is then used to correctly place the fire perimeter and hot spot data, and is combined with GPS positional information to determine latitude and longitude. The Rule Surface Stereo Parallax approach requires moderate CPU power and was prototyped to reveal a high level of fire position accuracy. The approach is described below.

PROTOTYPING THE RULED SURFACE APPROACH

In order to evaluate the Rule Surface approach, a 'control' based on Landsat Thematic Mapper satellite imagery co-registered to 30 meter DEM data was prepared. The 'control' consists of a complex series of simulated fire perimeters and hot spots (polygons) drawn at different elevations on the Landsat imagery (Figure 1). Elevation ranges in the Pasadena, California, study area vary from 120 meters to 1443 meters. Topographic roughness varies from level plain to steep mountains, with over 600 meters of relief common in several 1.6 kilometer distances. Latitude and longitude coordinates for each image pixel were provided inherently by the DEM data.

The prototype included simulated left and right aircraft stereo views of the fire perimeter data generated using the relief displacement equation (1) to introduce parallax. A raster-to-vector algorithm was used to convert the 'control' and 'displaced' image raster fire perimeters to vector format (Figures 1 and 2). Simulated GPS information and *maximum* realistic pitch, roll, altitude, and heading avionics errors were introduced. The prototype case flew at an altitude of 4572 meters (15,000 feet) with a 120 meter elevation base. The key calculation is the slope of the aircraft look angle which determines where the line-of-sight vector is to be drawn to form the ruled surface. The slope of the look angle is:

$$((\text{Altitude}) - (\text{Base Elevation})) \;/\; \text{Distance} \qquad (2)$$

where distance is the number of pixel units between a fire coordinate (in lines, FL, and samples, FS) and its closest nadir coordinate (in lines, ND],, and samples, NIX):

$$\text{Distance} = \text{SQR}(((\text{NDL-FL})^{**}2)+((\text{NDS-FS})^{**}2)) \qquad (3)$$

From the previous section, the ruled surface algorithm generates planimetric images of the line-of-sight vectors describing the left and right halves of each fire polygon. Thus, two ruled surfaces (images) are generated for each aircraft pass (for a total of four images). Figures 3 and 4 show two ruled surfaces derived for the prototype test case for one left / right pass. Four additional images are generated for each aircraft pass (for a total of twelve images), with the 'extra' images used in subsequent processing to 1) remove false line-of-sight intersections, and 2) regenerate failed line-of-sight intersections. The actual calculation of line-of-sight intersections occur in two separate image arithmetic operations where 1) the fire polygon's left side in the right flight pass is matched with the fire polygon's left side in the right flight pass, and 2) vice versa

(Figure 5). The arithmetic operation is actually a test, where the two line-of-sight vector values (elevations) must not exceed a user specified 'error' threshold to be considered a - true ~~exceed a~~ user specified 'error' threshold to be considered a true match.

Numerous false line-of-sight intersections and missing line-of-sight intersections are a functional by-product of the ruled surface approach. To remove them, an optimization technique is used utilizing the 'extra' images co-produced with the ruled surfaces. The 'extra' images provide information as to which fire polygon was involved in the intersection match and the line (coordinate) number of the intersecting/matching polygons. Given this information and the original file of fire polygon coordinates, the number of matching points between left and right polygons relative to the total number of points in the polygon of interest are calculated. The optimization technique selects the matching points that best represent the true fire polygon and marks the remaining points for deletion from the file.

The result of the optimization technique is a file of original fire polygon coordinates (the left pass was chosen arbitrarily) with associated ruled surface produced match elevation values. Missing intersection values (i.e., elevations) are interpolated between existing intersection matches. The elevation values associated with the fire polygon coordinates are then submitted to the relief displacement equation (1) to move the fire perimeter and hot spot coordinates to their correct geographic location. A post transformation converts the line and sample coordinates to latitude and longitude coordinates.

RULED SURFACE ACCURACY ASSESSMENT/CONCLUSION

The Rule Surface approach was evaluated based upon the ability of the prototype to restore the fire perimeter data to its original location. Figure 6 displays the 'Control' and ruled surface 'Product,' and can be compared to qualitatively assess accuracy. Quantitative accuracy was assessed using maximum avionics errors (pitch 0.2 degrees, roll 0.2 degrees, heading 0.4 degrees, altitude 25 meters) applied oppositely to maximum effect. Table 2 displays the resultant average RMS errors for two different look angles and four different aircraft altitudes. At an aircraft altitude of 4572 meters (15,000 feet), the Rule Surface georeferencing approach easily meets the required FIREFLY accuracy requirements (91 meters RMS). With reduced avionics errors, the approach probably satisfies FIREFLY requirements at an aircraft altitude of 6096 meters (20,000 feet). The USFS desired goal of 30 meters RMS error is easily obtained with maximum avionics errors when the aircraft is flying at an altitude of 1524 meters (5,000 feet). Thus, the 'Ruled Surface Stereo Parallax' approach to real-time georeferencing is the most attractive procedure given today's technology. This approach represents an important enhancement in the ability of Geographic Information Systems technology to perform real-time co-registration and elevation generation. Given sufficient time however, the "Neural Network" approach is probably the best next generation solution, and should be of great interest to all agencies charged with earth monitoring activities.

ACKNOWLEDGEMENTS

The research and development described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The authors would like to acknowledge the significant contributions of Gary S. Parks, J. David Nichols, and **Nevin** A. Bryant to the completion of this paper.

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Nichols J. D., Warren J. R., 1987. "Forest Fire Advanced System Technology (FFAST): A Conceptual Design For Fire Detection and Mapping," *Proceedings of the Symposium on Wildland Fire 2000,* April 27-30, Pacific Southwest Forest and Range Experiment Station, pp. 85-91.

TABLE AND FIGURE CAPTIONS

Table 1: I Horizontal relief displacement due to topography from an aircraft at 4572 meters (15,000 ft) above ground base. From the table, an object 3000 meters from aircraft nadir and 600 meters in elevation would suffer a 394 meter displacement from true location.

Table '2': Average RMS accuracy assessment (in meters) of the Ruled Surface Stereo Parallax approach applied to the Pasadena, California prototype test case, for two look angle cases at four separate aircraft altitudes. The two look angles in each case represent the northward then southward flight passes. Each pass includes avionics errors of pitch (0.2 degrees), roll (0.2 degrees), heading (0.4 degrees), and altitude (25 meters), applied oppositely to compound their effect. The Ruled Surface approach easily meets the FIREFLY accuracy requirement of 91 meters RMS at altitudes of 4572 meters and below, and probably satisfies the requirements at 6096 meters altitude with reduced avionics errors. At altitudes below 1524 meters, the FIREFLY goal of 30 meters RMS is achieved, but with considerable reduced field-of-view.

Figure 1: Landsat TM satellite 'Control' image of the I'asadena, California, prototype study area showing simulated fire areas. (The vector version of the 'Control' image is shown as Figure 6.) Elevation ranges in the study area vary from 120 to 1443 meters (4734 ft), with terrain roughness varying from level plain to steep mountains. Image was co-registered with 30 meter DEM data to geometrically associate latitude and longitude coordinates with pixel values.

Figure 2: Vector /graphics fire perimeter and hot spot information showing the effects of simulated topographic relief displacement. The left picture simulates the flight pass with nadir on the *left* edge and with displacement towards the *right*. The right picture simulates the flight pass with nadir on the *right* edge and with displacement towards the *left*.

Figure 3: The 'ruled surface' image corresponding to view "B" in Figure 5, used to reconstruct the *left* side of a fire polygon. The "smear" in the picture represents the valid range for which the fire polygon exists. The intersection of two ruled surfaces indicates the true (relief corrected) position of the fire polygon.

Figure 4: The 'ruled surface' image corresponding to view "D" in Figure 5, used to reconstruct the right side of a fire polygon.

Figure 5: Diagram shows the calculation of line-of-sight intersections from 'ruled surfaces' marked A, B, C, and D. Actual ' ruled surfaces' A and D are shown in Figures 3 and 4, respectively.

Figure 6: Resultant product of the 'Ruled Surface' approach's ability to recreate the original Pasadena prototype study area by removing topographic relief displacement.

The left picture shows the 'Control,' and the right picture shows the resultant 'Product.' Both pictures were converted to latitude/longitude coordinates and arc shown with 2.5 minute reseau marks.

KEYWORDS

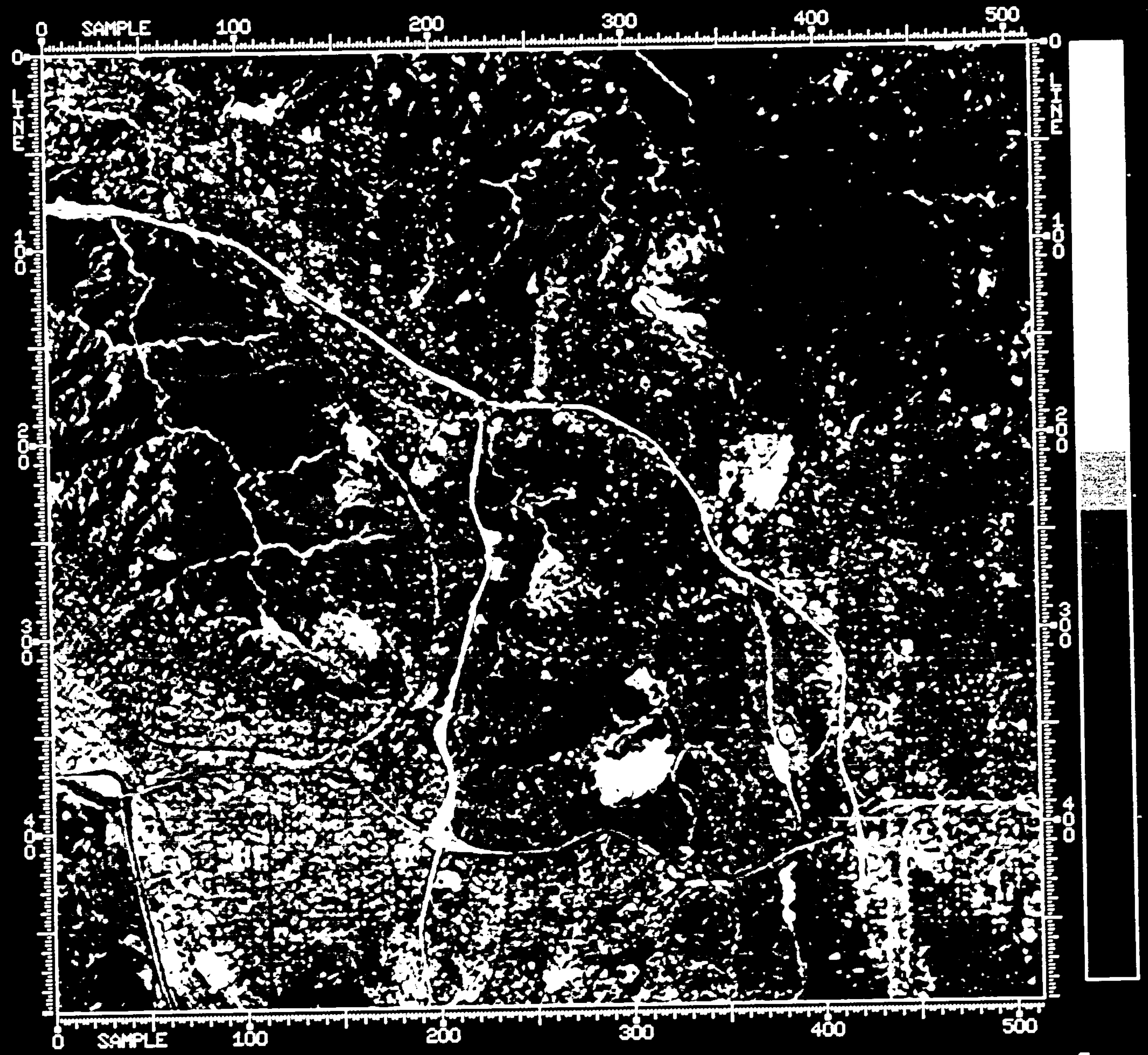
Georeferencing, GIS, GPS, FIREFLY, Neural Network, DEM, parallax, stereo, satellite imagery, aircraft photography, ruled surface.

TERRAIN HEIGHT		SCAN ANGLE (DEG) AND DISTANCE FROM NADIR (M)									
M.	Ft	6.2 500	12.3 1000	23.6 2000	33.3 3000	41.2 4000	47.6 Sooo	51.6 6000	60.2 8000	65.4 10000	Deg M
100	328	11	22	44	66	87	109	131	175	219	
200	656	22	44	87	131	175	219	262	350	437	
300	984	33	66	131	197	262	328	394	525	656	
400	1312	44	87	175	262	350	437	525	700	875	
500	1640	55	109	219	328	437	547	656	875	1095	
600	1968	66	131	262	394	52.5	656	787	1050	1312	
800	2625	87	175	350	525	700	875	10s0	1400	1750	
1000	3281	109	219	437	656	875	1094	1312	1750	2187	

Table 1

		Look **Angles** (Deg)	
		40 / 42	55 / 17
Altitude (Meters)	6096	60.1	99.9
	4572	43.4	72.7
	3048	29.1	45.0
	1524	14.8	21.8

Table 2



MIPL PIC ID 87/11/11/125719 TLL/FFASTPIX

JPL IMAGE PROCESSING LABORATORY

FIGURE 1

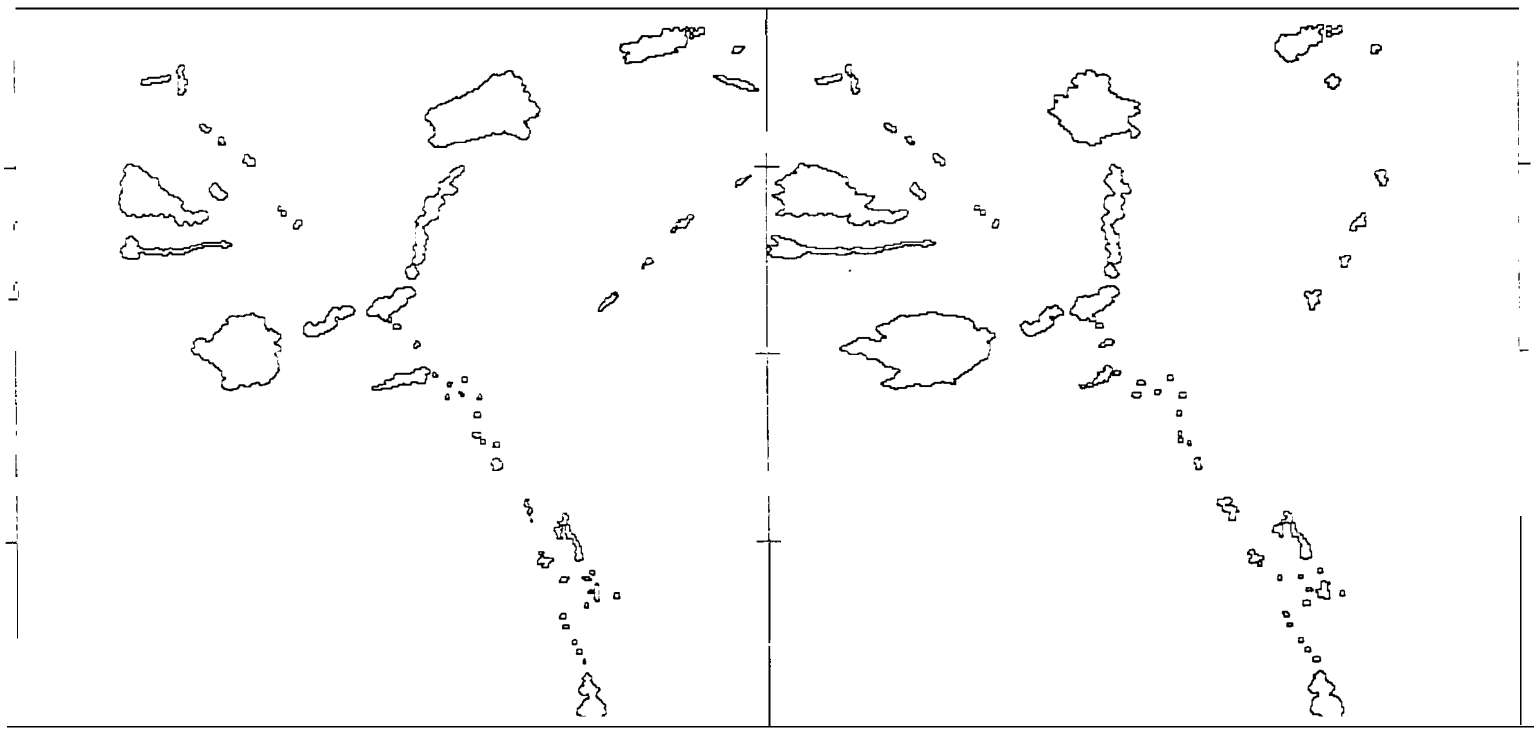
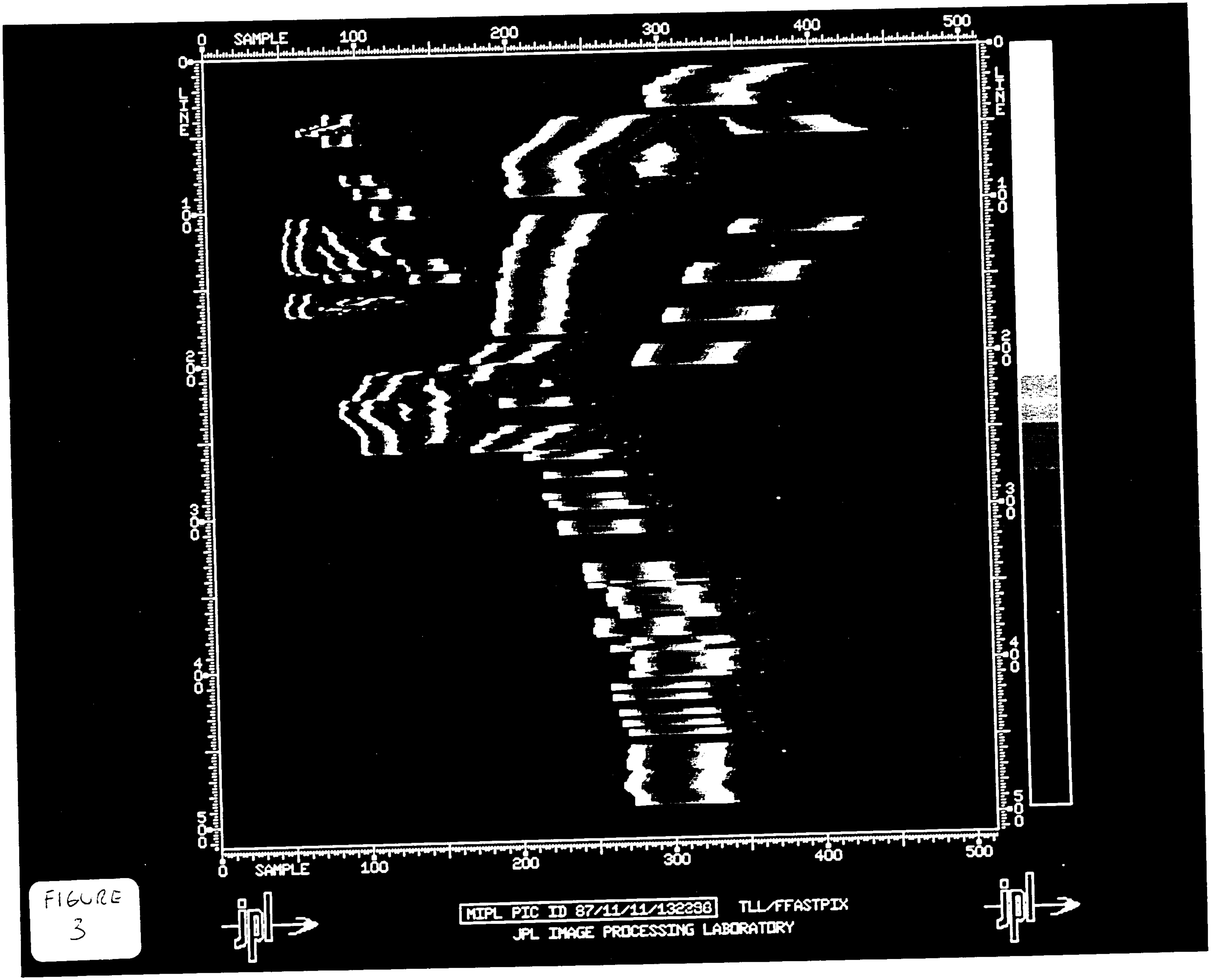
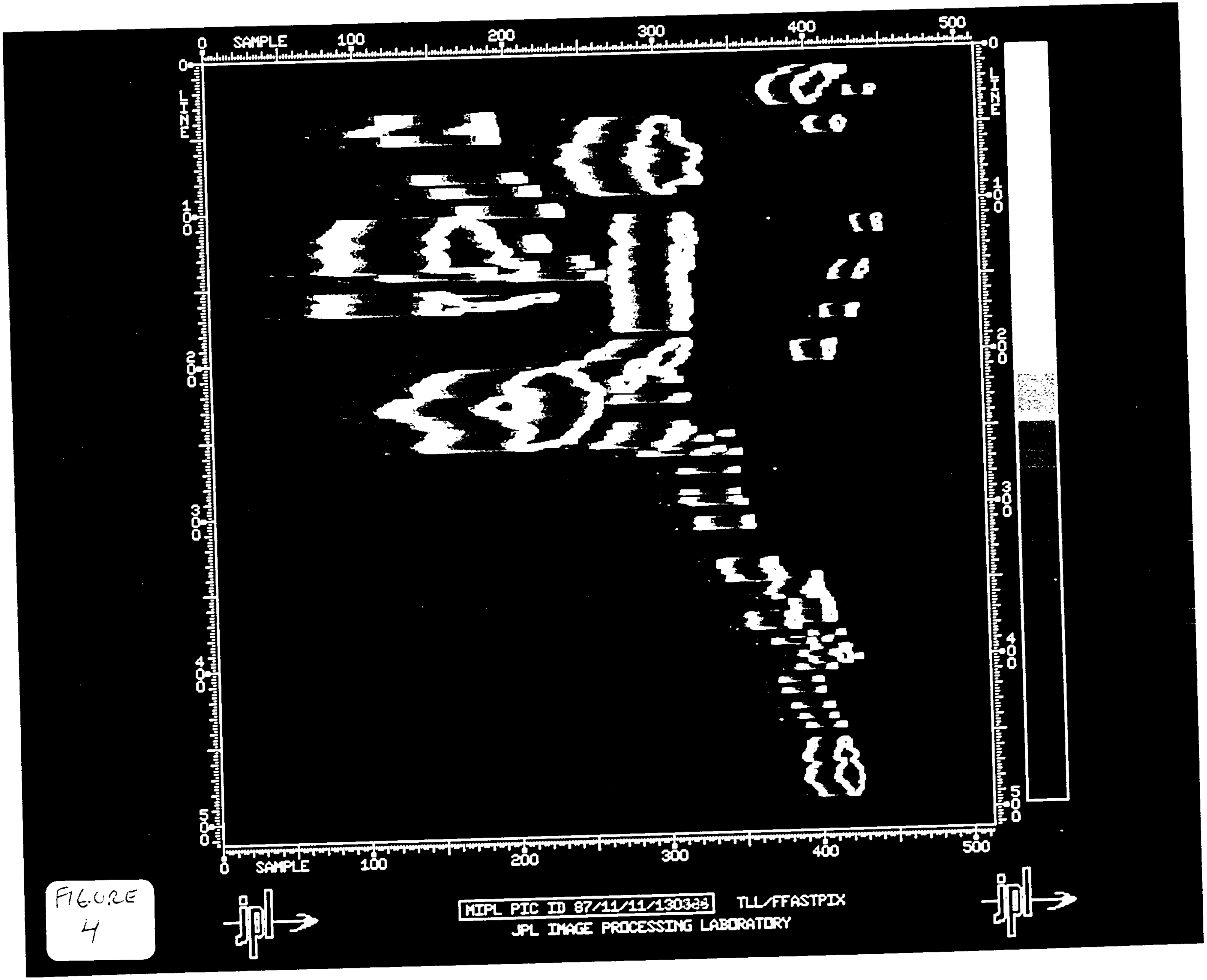


FIGURE 2



SAMPLE
LINE
MIPL PIC ID 87/11/11/132298
TLL/FFASTPIX
JPL IMAGE PROCESSING LABORATORY

FIGURE 3


SAMPLE
LINE
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TLL/FFASTPIX
JPL IMAGE PROCESSING LABORATORY

FIGURE 4

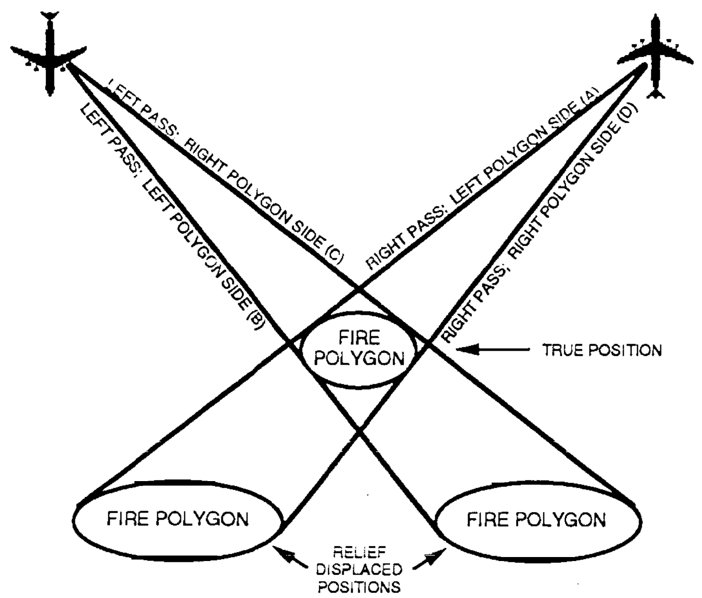
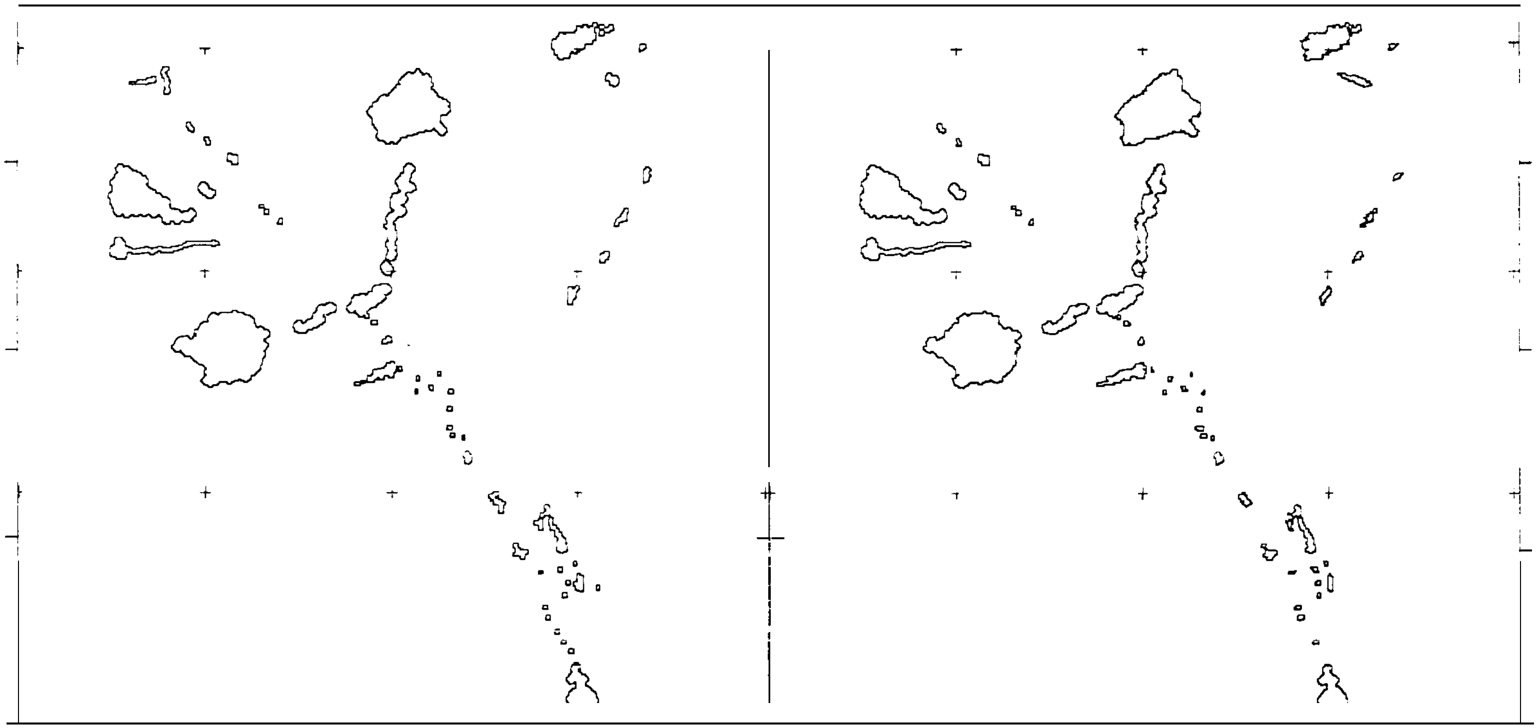

LEFT PASS: RIGHT POLYGON SIDE (C)
LEFT PASS: LEFT POLYGON SIDE (B)
RIGHT PASS: LEFT POLYGON SIDE (A)
RIGHT PASS; RIGHT POLYGON SIDE (D)
FIRE POLYGON
TRUE POSITION
FIRE POLYGON
FIRE POLYGON
RELIEF DISPLACED POSITIONS

FIGURE 5



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