Spectral and polarimetric analysis of hyperspectral data collected by an acousto-optic tunable filter system

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ABSTRACT

Analysis of data collected during a ground-based experiment of an acousto-optic tunable filter (AOTF) hyperspectral imaging system shows potential for utilizing this technology for feature identification. The unique capability of an AOTF system to simultaneously acquire two orthogonally polarized images allows both spectral and polarimetric characterization of ground features. The AOTF sensor used in the experiment operated over a wavelength range from 0.51 to 0.77 microns, collecting two differently polarized images for each of 33 bands. The experiment data images selected for analysis contain camouflaged military equipment deployed in a desert background. The Spectral Image Processing System (SIPS) software package was used for data correction and spectral analysis. Processing the AOTF data required geometric correction in addition to removing the solar and atmospheric effects. Two methods of spectral analysis are addressed in this research. The first method assesses the spectral analysis accomplished using the Spectral Angle Mapper utility in SIPS. The other method illustrates the spectral information gained through band ratioing a combination of carefully selected bands which highlights a particular target within a scene. Comparison of images created by the difference between polarizations for each band provides the basis for polarimetric analysis of the data. Finally, an algorithm developed to combine the information provided by spectral and polarimetric analysis shows how features within a scene can be distinguished from the background. Results show that AOTF hyperspectral technology has potential to enhance current military intelligence collection capability.

1. INTRODUCTION

Hyperspectral imagery has tremendous potential to enhance military capabilities in a variety of areas by measuring the spectral reflectance characteristics of selected targets. This unique technology could provide immense support to strategic intelligence requirements in the areas of threat definition, treaty monitoring, arms control, counternarcotics, and counterterrorism. On a tactical level, hyperspectral sensors could accomplish missions not possible with any other system, such as camouflage and concealment detection nuclear biological and chemical detection terrain and trafficability analysis mapping broad area search mobile missile and weapons systems location and identification friend or foe. Imaging spectroscopy could make significant contributions to military operations in many different scenarios. The capability exists for a hyperspectral sensor to operate in space, either on the space shuttle or as a light satellite; as an airborne system, on a reconnaissance airplane or an unmanned aerial vehicle (UAV); and as a ground-based long range surveillance system.

The organization in the Army tasked to develop intelligence systems that correct identified deficiencies in current systems is the Intelligence Center's Directorate of Combat Developments (DCD) at Fort Huachuca, Arizona. In an effort to provide tactical commanders with more timely imagery intelligence, DCD initiated a project called TERRA SCOUT. The concept of TERRA SCOUT was to determine if a trained imagery analyst could identify and locate targets more quickly and accurately with high resolution optics from space, than could be accomplished using existing systems and procedures. The normal imagery cycle begins with data collection at the sensor. The data is then transmitted to a ground station, processed, and analyzed. Finally, the image with its corresponding analysis is sent to the user. TERRA SCOUT was successful in that a payload specialist aboard the space shuttle was able to downlink accurate analyzed imagery more rapidly than the current procedures allow.

As an improvement to the original TERRA SCOUT project, DCD incorporated hyperspectral imaging technology into the concept of providing better imagery support to commanders. The follow-on project is called TERRA SCOUT II. The Army

Space Technology Research Office (ASTRO) supplied initial funding for the effort and is the program sponsor. Jet Propulsion Laboratory (JPL) and Massachusetts Institute of Technology's Lincoln Laboratory (MIT/LL) are the contractors responsible for designing and building the system. Development of the TERRA SCOUT II system involves a phased approach, requiring proof of concept demonstrations to achieve rapid prototyping of the hyperspectral imaging system. A prototype of the sensor subsystem was delivered by JPL in March 1993 and used in a ground-based proof of concept experiment conducted in April 1993. The next step in the TERRA SCOUT II development process requires analysis of the data collected during this experiment to validate the sensor's capabilities and determine its utility for military applications.

2. SENSOR

The sensor design selected for TERRA SCOUT II uses an acousto-optic tunable filter (AOTF). The operational technique of the AOTF is different than existing hyperspectral imaging systems. The AOTF sensor creates an image by measuring the energy intensity over an entire scene at one time for a particular wavelength. The other type of imaging spectrometer scans a scene by picture element (pixel). It measures the energy intensity for every wavelength over the range of the sensor one pixel at a time. The result is an entire spectrum for each pixel in the scene. The spectra from every pixel are then used to form an image when the data is analyzed.

The AOTF type of sensor possesses unique properties which make it well-suited for intelligence collection. It simultaneously collects both spectral and polarimetric information. This polarization capability, not available on other existing systems, provides an added dimension to imagery analysis which could enhance target detection. The AOTF technique allows real time collection of only the data required for a specific purpose. For example, an AOTF system is not limited to collecting images for every wavelength within its range. It can be programmed to collect only the images for selected bands that will provide the most information about the target. This feature, combined with the ability to easily tune the sensor, enables operational flexibility in tailoring observation parameters. Additionally, the AOTF is compact and has no moving parts, making it versatile and reliable.

The prototype AOTF hyperspectral imaging system used in the proof of concept experiment was designed and built by JPL engineers. It operates in the wavelength range between 0.48 and 0.76 microns with a field of view of 10.4 by 14.1 meters. At a power of 12 dBm the AOTF sensor has an integration time of one second. The AOTF system is composed of an AOTF, foreoptics, imaging optics and two silicon charge coupled device (CCD) cameras. The optics equipment and cameras planned for eventual airborne and space experiments are being developed at MIT/LL and were not used in the ground-based experiment.

During the experiment, the foreoptics consisted of an ordinary camera zoom lens and a field lens was used for imaging optics. A 386 IBM-PC compatible computer was necessary for control and data acquisition. The prototype system also included an image grabber and a generator as an independent power supply.

The AOTF uses a tellurium dioxide (TeO_2) crystal which splits a beam of light entering the sensor into a set of two narrow band, orthogonally polarized images for each wavelength determined by the acoustic frequency input to the crystal. The field lens is placed behind the AOTF and in combination with the zoom lens, generates the diffracted images, one directed at each focal plane array. The CCD cameras then detect the images and convert the measured analog information to digital data by assigning a digital number to the corresponding intensity for every pixel in the arrays. Thus, the arrays of pixel values create digital images for both polarizations at each of 33 different wavelengths.

3. EXPERIMENT

In order to determine the capabilities of the prototype AOTF system, analysis of data collected during its proof of concept experiment is necessary. The experiment was conducted at Fort Huachuca, Arizona, where convenient sensor locations were identified which allowed the AOTF system to easily image military targets with different types of backgrounds. Hilltops were selected for sensor locations to simulate, as closely as possible, the geometry of sun and viewing angles such as an airborne sensor would detect a scene. During the AOTF experiment, spectral measurements of various targets and background features were made with a portable field spectrometer. The field spectrometer data is used to validate the hyperspectral imagery collected by the prototype AOTF system. The portion of the AOTF experiment data that contains camouflaged military equipment deployed in the desert is the focus of the spectral and polarimetric analysis accomplished in this thesis.

4. METHODOLOGY

4.1 Data processing

Prior to analysis, it is necessary to correct the data for both the geometry of the sensor design and the atmospheric effects. First, the misalignment between the images of each band, caused by changing wavelengths, must be adjusted to insure accurate spectra for each picture element (pixel) in the scene. Next, the effects of the atmosphere and the sun are removed to properly characterize the spectral signatures of features. The raw AOTF data, which is a measure of radiance, is converted to reflectance by dividing the entire array of pixels by the solar spectrum and atmospheric correction is accomplished in the same process using the flat-fielding technique. Then, to allow comparison of the two different polarizations for each band, the alignment between the two polarized images must be corrected for the entire data set. Finally, the validity of the data set is established by comparing graphs of targets and background spectra produced from field spectrometer measurements taken during the experiment to spectrographs of the same features made with the AOTF data.

4.2 Spectral analysis

Spectral analysis of the hyperspectral data is accomplished using a band ratioing technique. In this method, an image is created by combining ratios of carefully selected bands which displays a target distinguished from its background. The spectra of the surface features within a scene are used to determine the bands which provide the largest spectral differences between a target and its background. By adding or subtracting the images resulting from ratios of particular bands, a target of interest is highlighted, while the background features are subdued.

However, other features with similar spectral curves may also show up as brightly as the target. In order to subdue these bright features yet highlight the target, another ratio of bands is subtracted from the band ratio image. A comparison of the target spectrum and the spectral curves for the features is necessary to determine the bands for the second ratio. The two bands with the largest difference in reflectance recorded for the background features but the smallest difference in reflectance for the target are chosen for the second ratio. By subtracting this ratio from the first ratio, an image is created in which the target remains bright while the previously highlighted background features are subdued. Ratios of selected bands are combined in this manner until the target is distinguished from all its background features.

As a result of dividing one band by another, the numbers in the image array are very small. There is little difference between the maximum and minimum pixel values. Thus there is a loss of contrast and clarity in the band ratio images. However, these images can be enhanced by applying a logarithmic scale to the ratios. The band ratio image arrays are replaced with the base ten logarithm for each pixel value. This increases the total range of pixel values and the ability to detect features in the band ratio images. Applying the base ten logarithm to the band ratio images enhances the quality of their display and improves the results achieved by the band ratio technique.

4.3 Polarimetric analysis

A polarimetric analysis of the AOTF experiment data is necessary to determine the utility of a scene's polarimetric characteristics in distinguishing between targets and background features. Theoretically, man-made targets polarize differently than natural ones. Therefore, a comparison of the polarization differences for each wavelength is the method for polarimetric analysis used in this paper.

4.4 Convolution algorithm

The information provided by separate spectral and polarimetric analysis of the experiment data indicates that combining these results to better distinguish targets from the background features is desirable for assessing the AOTF system's utility. A simple algorithm that accomplishes this convolution of the spectral and polarimetric results was developed. By adding the band ratio image to a filtered polarization difference image, a new image is created which should highlight the camouflaged military equipment in the scene. Images can be enhanced using techniques to smooth and sharpen them. Filtering is an example of one image processing technique that outlines of the shapes of features within the image. The filtering process requires converting the image data into the frequency domain using a fast Fourier transform. Then, applying a bandpass filter to the image data removes the very high and low values that clutter the image. After converting the filtered data back into the spatial domain, the resulting image is added to the band ratio image.

5. RESULTS

5.1 Scene 1

The first AOTF data set to be analyzed is the scene called TNT. It contains a communications site with four separate camouflaged pieces of equipment. Figures 1 and 2 show the two different corrected polarization images for Band 14. A dark green camouflage net conceals the smaller piece of equipment in the middle of the scene. The other equipment is concealed under woodland camouflage nets that are patterned shades of browns and greens. There are yucca cactus in the foreground and different types of grass, dirt, plants and bushes in the background.

5.1.1 Spectral analysis

By carefully selecting bands to ratio and combine, an image can be created that highlights a particular feature based on its spectral characteristics. An image illustrating this technique applied to the TNT data is shown in Figure 3. The bands selected for the first ratio are Band 25 and Band 9. They represent images at wavelengths of 0.68 and 0.55 microns respectively. These two bands were chosen to create an image that makes the camouflaged equipment appear bright relative to the background features. The second ratio is Band 23 divided by Band 32, while the third is the ratio of Band 30 to Band 3. These bands were determined by comparing the mean spectrum for the camouflage nets to the mean spectral curves for the dominant background features in the same scene. Bands which result in a large difference between reflectance values for grass and plants, but a small difference in reflectance values for the camouflage nets are chosen for these ratios. The second and third ratios are subtracted from the first ratio in order to subdue background features in the image that appear as bright as the camouflage nets.

The image of the combination of band ratios clearly highlights the camouflaged equipment compared to the background. The entire surface area of the camouflaged equipment is represented by brighter pixels than the background such that the shapes of the targets are distinguishable.

5.1.2 Polarimetric analysis

The ability of the AOTF hyperspectral imaging system to collect both spectral and polarimetric data allows the performance of another type of analysis to derive information about surface features from remotely sensed imagery. To analyze the polarimetric characteristics of surface features, given data from two orthogonally polarized images, the difference between the polarizations can provide information. An effective way to visualize the difference between the parallel and perpendicular polarized data collected by the AOTF system is to create an image by subtracting the polarization view for one band from the other for the same band. Figure 4 shows the image resulting from the polarization difference image for the TNT data set at Band 14. A comparison of the spectral curves for the camouflage nets in this scene at each polarization shows that the polarization difference s relatively large in Band 14 or at 0.58 microns.

The difference in polarization provides information about certain features within the scene. The halon panels register quite well in the polarization difference image. The panels were placed at 90 degree angles to one another. One was placed flat on the ground while the other was propped up to face the sensor directly. The very dark pixels in the right center of the image represent the large negative difference between polarizations as a result of the panels perpendicular to the AOTF lens. Similarly, the very bright pixels immediately below the dark ones represent the large positive difference between polarizations as a result of the reflectance off of the halon panel parallel to the AOTF sensor. The smooth surface of the panels caused the reflected sunlight to polarize more significantly than that reflected off of the other features in the scene.

The polarization difference image also highlights the shapes of the camouflaged equipment. The top edges of the nets are represented by bright pixels and the bottom edges where the camouflage nets meet the ground are darker. Features like plants, bushes, and the contour of the land have surfaces that reflect light in a way which causes it to polarize. Significant features within a scene can be detected in this manner.

An interesting result is the clarity with which the periscoping antenna protruding from the far left camouflage net in the scene is detected. Its distinct shape and smooth surface polarize the reflected light, allowing it to be easily distinguished from its background in the polarization difference image.

5.1.3 Convolved image

The image resulting from the convolution algorithm applied to the TNT data set is shown in Figure 5. This image is an improvement over both the band ratio image and the polarization difference image shown in Figures 3 and 4. It displays the camouflaged equipment with pixels brighter than the background features and also sharpens the appearance of the target shapes. For the TNT scene, the algorithm is successful in combining the information derived from spectral and polarimetric analysis to create an image where the targets are easily distinguished from the background features.

5.2 Scene 2

The AOTF data set called BRT contains another communications site deployed in the desert. However, the equipment in this scene is concealed under desert or tan colored camouflage nets. There are three separate camouflaged pieces of equipment on the left side of the image and three more camouflage nets concealing equipment further away on the right side of the image. The scene contains grass, plants and shrubs in the foreground with buildings and trees in the distant background. A satellite dish antenna painted dark green is barely discernible in the image between the two sets of camouflaged equipment. Figures 6 and 7 show the corrected images for each polarization in Band 13.

5.2.1 Spectral analysis

Due to the spectral similarity between the tan camouflage nets and the desert grass that dominates the BRT scene, it is difficult to sharply contrast these features even by combining the ratios of bands. Finding bands that highlight the differences between the reflectance values for the tan camouflage relative to the grass is the problem. The best combination of band ratios is:

$$BandRatio = \log\left(\frac{Band24}{Band2}\right) - \log\left(\frac{Band32}{Band13}\right) - \log\left(\frac{Band31}{Band25}\right)$$

The image resulting from this combination of band ratios is shown in Figure 8.

The camouflaged equipment in the band ratio image appears slightly brighter than most of the background features. The shapes of the targets on the left side of the image are well-defined and the tops of the nets on the right side of the image are even discernible.

5.2.2 Polarimetric analysis

An image created by subtracting the BRT Band 13 perpendicularly polarized image from the parallel image is shown in Figure 9. Like the polarization difference image for the TNT data set, the visualization of the difference between the parallel and perpendicular polarizations provides information about the features within the scene. It shows the outlines of the features with surfaces that reflect light such that the difference in polarization is detected. The same polarimetric characteristics of the halon panels are evident in the BRT scene as in the TNT polarization difference image. Also, the camouflaged equipment on the right side of the image is distinctly outlined. The top edges of the camouflaged netting appear dark while the place where the level of the surface meets the netting is shown with very bright pixel values. Places in the scene where the contour of the land causes features to appear closer to the sensor than they actually are have a very strong difference in polarization as illustrated in the BRT polarization difference image.

5.2.3 Convolved image

Figure 10 shows the convolution algorithm applied to the BRT data set. Again, the image combining the spectral and polarimetric information provides a better display of the targets within the scene compared to the band ratio and polarization difference images in Figures 8 and 9. The camouflaged equipment appears brighter than the background features and their shapes are relatively well-defined.

6. CONCLUSIONS

Spectral analysis of the AOTF experiment data shows that targets like camouflaged military equipment can be distinguished from the background features of a scene exists using the band ratioing technique. The ability to derive information about surface features through spectral analysis is limited only by the sensor's spatial resolution and wavelength range.

Polarimetric analysis of this data show that a feature's shape and surface characteristics influence the polarity of the light it reflects. Its contribution to detecting camouflage nets is not necessarily significant because they display polarimetric characteristics very similar to the trees in which these targets are normally concealed. Factors like sun angle, viewing geometry and sensor to target distance influence the polarimetric measurements and more research is necessary before this aspect of analysis can be properly exploited.

The capability to collect digital imagery that allows the contribution of information derived from both spectral and polarimetric analysis provides a new dimension to imagery interpretation. Analysis conducted in this paper shows that the potential exists to utilize this technology in military applications.

Figure 1. TNT Parallel Polarization - Band 14.

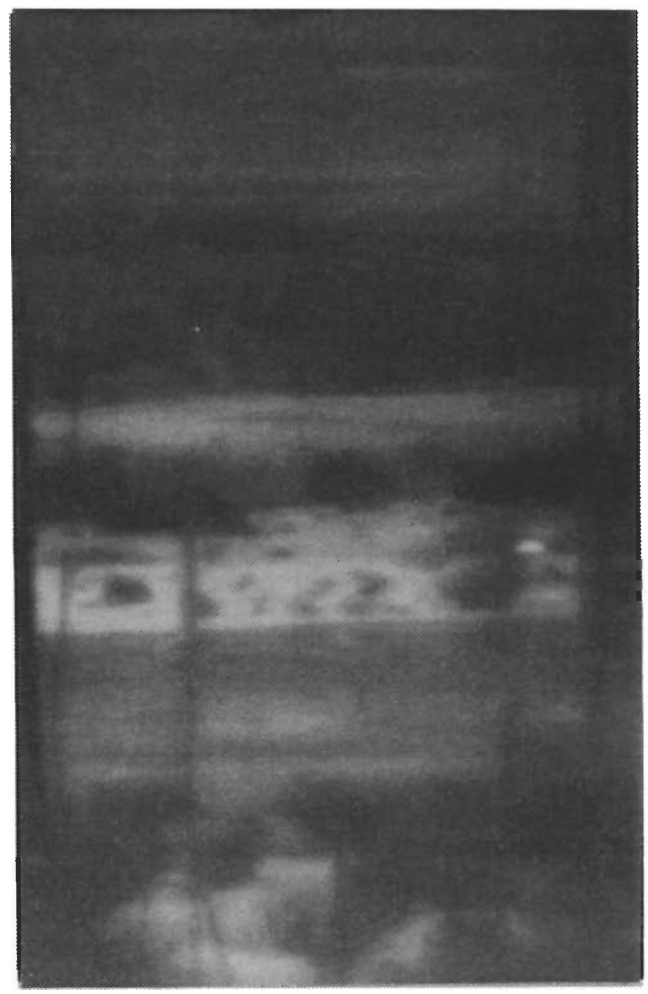

Figure 2. TNT Perpendicular Polarization - Band 14.

Figure 3. TNT Band Ratio Image.

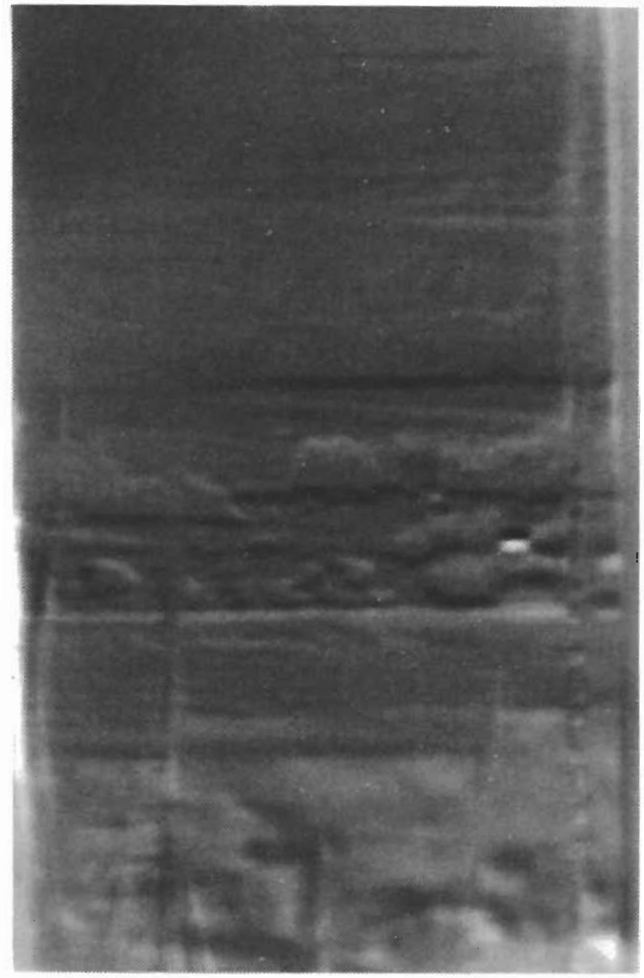

Figure 4. TNT Band 14 Polarization Difference Image.

Figure 5. TNT Convolution Image

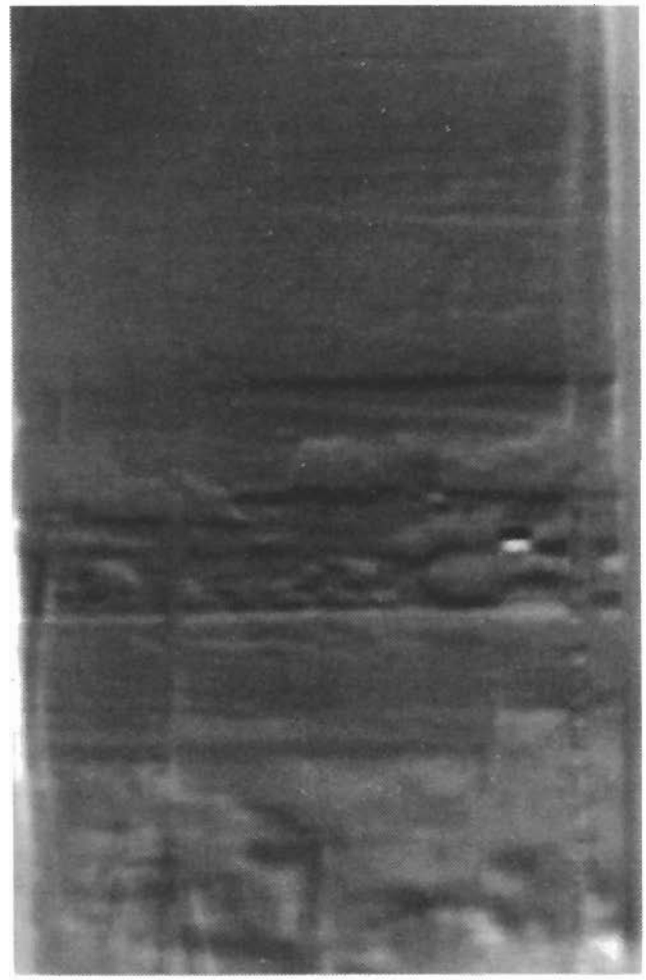

Figure 6. BRT Parallel Polarization - Band 13.

Figure 7. BRT Perpendicular Polarization - Band 13.

Figure 8. BRT Band Ratio Image.

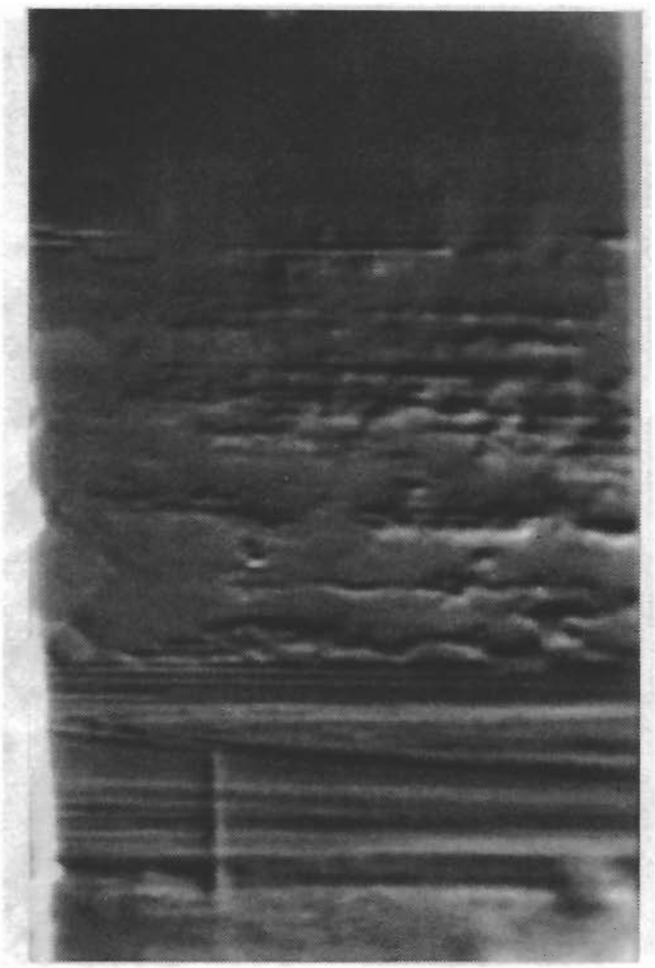

Figure 9. BRT Band 13 Polarization Difference Image.

Figure 10. BRT Convolution Image