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EXTENDED EXPERIMENTATION USING POLARIZATION TECHNIQUES

PAR Government Systems

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13. ABSTRACT *(Maximum 200 words)*
Polarization can yield image intelligence additional to that accessible from radiometric intensity, wavelength-dependence, texture, topography, or feature shape, size or relative disposition. In this study, investigations were performed to determine to what extent this is true, and to investigate controlling parameters.The objective of this effort was to extend the investigation of the use of polarized light to enhance target-to-background contrast in order to improve target feature detection and discrimination. This study demonstrated, using digital image data collected during 1997 and 1998, that there is great variation in polarization in and between each of the bandpasses, and this variation is comparable to the magnitude of the variation intensity. In addition, it is shown that the contrast in polarization is greater than for intensity, and that polarization contrast increases as intensity contrast decreases. It is also demonstrated that chromaticity can be used to make targets such as camouflage netting stand out more clearly against background. Multiband imaging polarimetry is likely to provide an advantage in feature detection and discrimination.

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1. INTRODUCTION

This scientific and technical report summarizes the work accomplished and information gained during the performance of the AFRL study contract #F30602-99-C-0051, Extended Experimentation Using Polarization Techniques. The objective of this effort was to extend the investigation of the use of polarized light to enhance target-to-background contrast in order to improve target feature detection and discrimination.

This study effort extended the research in the use of polarization techniques performed under the AFRL/IFEC sponsored Enhancement of Target Detection by Polarization Techniques effort, Contract #F30602-98-C-0150. Prior analysis of digital image data showed that through the use of polarization techniques, (1) detail in shadows may be enhanced; (2) differences between target and background may be enhanced; and (3) detail on relationships between polarization and recorded radiant intensity can be obtained using imaging polarimeters. For the studied images, it was determined that the log of the deduced polarization is linearly related to the log of the digital recorded radiance. It was further determined that this was independent of texture, shadow, or scattering. It was observed for each bandpass (and for each image) that 99% of the variance in the experimental data may be explained by a linear regression relationship; that there are consistent band-to-band variations in behavior; and similarity exists in data collected under different conditions from different scenes.

The Extended Experimentation Using Polarization Techniques study effort extended the analysis using digital polarimetric data acquired during the 1997 and 1998 Stockbridge and Global Patriot collections. Issues addressed in this study included:

- Polarization variation between bands.
- Increase of contrast in polarization, as intensity contrast decreases.
- Relationship of chromaticity in intensity to chromaticity in polarization.
- Use of chromaticity color representation to assist in feature extraction.

This study demonstrates that there is great variation in polarization in and between each of the bandpasses, and this variation is comparable to the magnitude of the variation in intensity. In addition, it is shown that the contrast in polarization is greater than for intensity, and that polarization contrast increases as intensity contrast decreases. It is also demonstrated that chromaticity can be used to make targets such as camouflage netting stand out more clearly against background. Multiband imaging polarimetry is likely to provide an advantage in feature detection and discrimination.

2. STOKES PARAMETERS

Polarization can yield image intelligence additional to that accessible from radiometric intensity, wavelength-dependence, texture, topography, or feature shape, size or relative disposition. In this study, investigations were performed to determine to what extent this is true, and to investigate controlling parameters.

Polarized radiation may be described by means of four parameters known as Stokes parameters. In 1852, G.G. Stokes introduced four quantities that are functions only of the observables of the electromagnetic wave and are known as Stokes parameters. Generally, radiometric information is contained within the first Stokes parameter, while polarimetric information is contained in the other three. Relatively few researchers have explored the possibility of using polarization as a source of contrast information for feature extraction. Little has been done to study the wavelength-dependence of polarization.

In a seminal paper, Walraven[1] used a 35mm camera to obtain sets of four slides of scenes using a polarizing filter at 0°, 45°, 90° and 135° relative orientation of the polarization direction about the optic axis of the camera. He measured the photographic density of the emulsion and related this to scene radiance. The intensity of the radiation that passes through the polarization filter is given by:

$$I'(\theta) = 1/2\,(I + Q\cos 2\theta + U\sin 2\theta) \qquad (1)$$

where θ is the angle of the transmission axis of the polarizer about the optic axis of the camera with respect to the horizontal. If measurements are successively made with $\theta = 0°$, 45°, 90° and 135°, then the resulting intensity is:

$$I'(0) = 1/2\,(I + Q) \qquad (2)$$

$$I'(45) = 1/2\,(I + U) \qquad (3)$$

$$I'(90) = 1/2\,(I - Q) \qquad (4)$$

$$I'(135) = 1/2\,(I - U) \qquad (5)$$

From these equations, Walraven[1] deduced the Stokes parameters in terms of the sum and difference images:

$$I = 1/2\,[I'(0) + I'(45) + I'(90) + I'(135)] \qquad (6)$$

$$Q = I'(0) - I'(90) \qquad (7)$$

$$U = I'(45) - I'(135) \qquad (8)$$

With the polarizer set at each of the four angles defined above, the four photographic images were obtained with the same f-stop. They were then digitized and registered. Images of I and of polarization (P), were obtained, where P is given by the expression:

$$P = \frac{1}{I}(Q^2 + U^2)^{1/2} \tag{9}$$

Also, the I, Q, U and V Stokes' parameters may be considered to form a vector:

$$[\, I, Q, U, V \,] \tag{10}$$

Which is the same as:

$$[\, S_0, S_1, S_2, S_3,] \tag{11}$$

S_0 is proportional to the mean intensity. S_1 is related to the difference between horizontal and vertical plane polarization. S_2 is related to the difference of the polarization at 45^0 compared to the polarization at -45^0, and S_3 is related to the degree of left-handed circular polarization minus the degree of right-handed circular polarization. One method for conceptualization of these parameters is the Poincare sphere. Here, the Jones vectors representing the completely horizontally polarized, completely vertically polarized, 45^0 polarized and -45^0 polarized, completely left-handedly circularly polarized, and completely right-handedly circularly polarized states are located orthogonally to each other.

Walraven showed that the polarization images provided new and useful information about a scene beyond that available from an intensity image. North[2, 3] used a four-lens camera with linear polarizers mounted in front of each lens and carefully digitized the resulting images to deduce the Stokes parameter images. While this technique worked well for studies of the sky, it was only later, using digital camera data, that it was possible to measure scene radiance at low levels with sufficient accuracy to relate polarization to scene radiance.[4-6]

3. EXPERIMENTAL DATA and ANALYSIS

Data was collected in 1997 and in 1998 with two different Kodak digital color infrared (CIR) cameras — Kodak DCS CIR 420 and 460. The silicon CCD focal plane array that is manufactured by Eastman Kodak has a focal plane, color filter array consisting of red, green, and blue filter elements with a separate filter element over each pixel. The array elements form a repeating motif consisting of a 2 x 2 kernel comprised of two green filtered elements on one diagonal, and a red and blue filtered element on the opposite diagonal. This arrangement is referred to as the Bayer pattern. The CIR cameras incorporate a bandpass filter on the lens that has -3dB cutoff wavelengths of 500 nm and 800 nm. Blue light is outside the filter's passband, so that none of the incident blue light reaches the sensor. The red, green and blue filter elements are all transparent to the reflected near infrared (NIR) radiance passed in the 700 nm to 800 nm region. Thus, the green filtered pixels respond to green and NIR, the red filtered array elements respond to red plus NIR radiance, and the blue filtered pixels respond to NIR radiance only. The results obtained by subtracting the blue filtered pixel response (NIR radiance, since blue radiance is blocked) in a proprietary weighted fashion from both the green filtered pixels, and the red filtered pixels in the array is a green and a red response value. A Kodak algorithm based on previous work with nearest-neighbor and next-nearest-neighbor[7, 8] performs color interpolation to produce three full image planes from the initial color subsamples. This algorithm also performs the color balance and subtraction operations required to eliminate NIR from the red and green channels, thereby creating a pleasing image. The gamma of such an image is 1.8. However, Duggin, Kinn and Schrader[5] discovered that images obtained over uniform targets (2%, 50% and 100% spectral reflectance Spectralon) appeared to have subtle colored patterns, and the spectral radiance frequency histograms were broadened. This was an artifact of the Kodak spatial averaging algorithm. The gamma 1.0 drivers provided by Kodak[9] were used.

The image data was downloaded onto CD ROMs, and subsequently (with great time savings) to disk and to Iomega Jazz cartridges. The DCS 420 and CIR 420 imaging systems require 4.522 Mbyte for each image. Tests were performed to determine appropriate exposure such that saturation did not occur. It was discovered that the camera's meter had different near infrared and visible light sensitivities, and many tests were performed to ensure that the image was not saturated at radiance levels, including most scene elements. To faithfully record very low radiance levels, limited saturation was permitted over the 98% reflectance Spectralon standard. Tests showed a radiometric response linearity of 5%, and 8-bit quantization, an order of magnitude better than achieved with film. Duggin et al[4-6] found the standard deviation of digital counts obtained from 56% and from 100% Spectralon, illuminated by solar irradiance under clear sky conditions, to be on the order of 2% to 5% of the digital reading obtained by analyzing the digital images with ENVI. Radiometric precision was estimated to be better than 1%.

The linear polarizer used was Polaroid HN38S film which was mounted in a holder that could be rotated on the front of the lens/interference filter assembly. Orientation of the polarizer was estimated to be within +/- 5 degrees. A sequence of exposures was made with the linear axis of the polarizer oriented at 0^0, 45^0, 90^0 and 135^0 relative to a reference direction (usually the vertical, except when nadir-view images of the standard reflector were obtained). The DCS 420 requires 4.522 MByte per extracted image, while the higher resolution DCS 460 (in CIR or in color mode) requires 18.258 Mbyte per extracted image. The images were processed using ENVI 3.0 on a PC network.

To study the between-band contribution of intensity and of polarization, the results of analyzing several scenes obtained obliquely of vegetation were studied. The ratio of the polarization in each bandpass to the sum of the polarizations in the NIR, red, and green bandpasses is referred to (somewhat loosely) as the polarization chromaticity.[10] The results of plotting the chromaticity of the intensity in the NIR (value of intensity of the NIR band, compared to the sum of the intensities in all three bands) and the chromaticity of the NIR band polarization vs. the NIR intensity for each region of interest studied are shown in Figure 1. The chromaticities for intensity and for polarization in the red and in the green bands are shown in Figures 2 and 3, respectively.

Figure 4 shows the chromaticities in intensity for all three bands versus the average (over all three bands) intensity for each region of interest. Figure 5 shows the polarization chromaticities in all three bands against the average intensity for each region of interest. The variance within and between bands for polarization is not very different than for intensity. This suggests that there is as much information in polarization multiband data as there is in intensity multiband data.

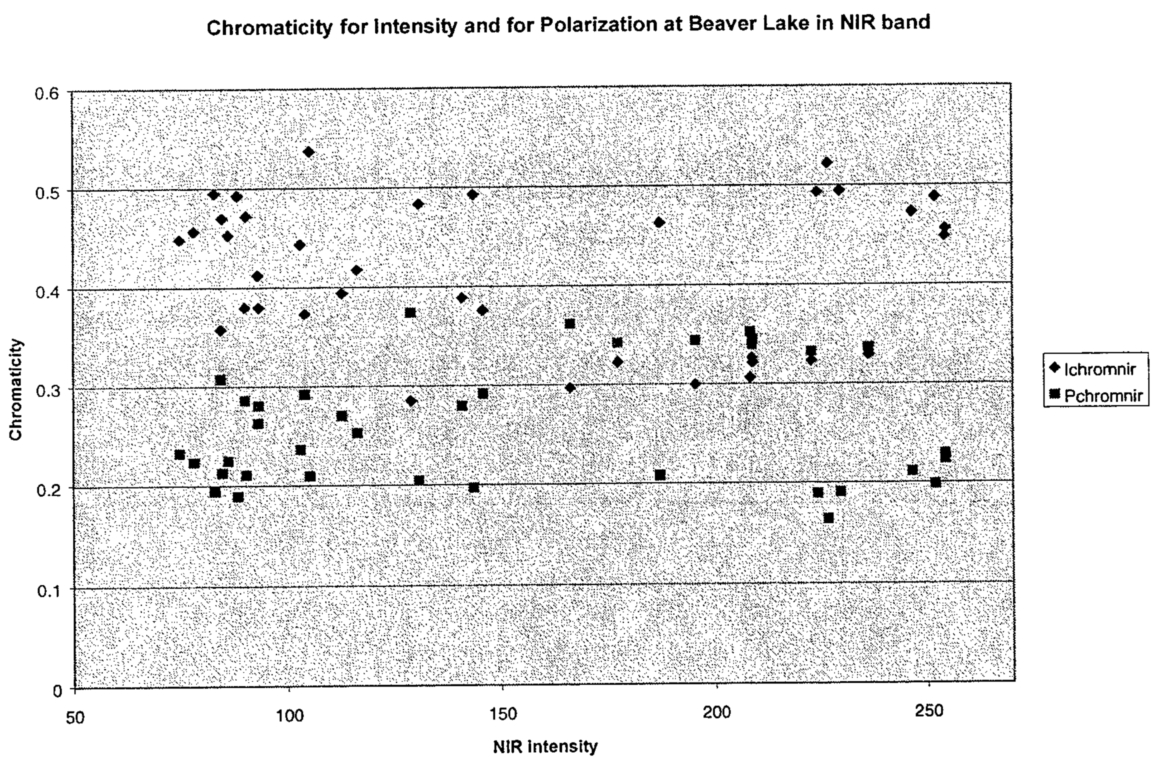

Figure 1. Intensity and polarization chromaticities for natural scenes in the NIR band.

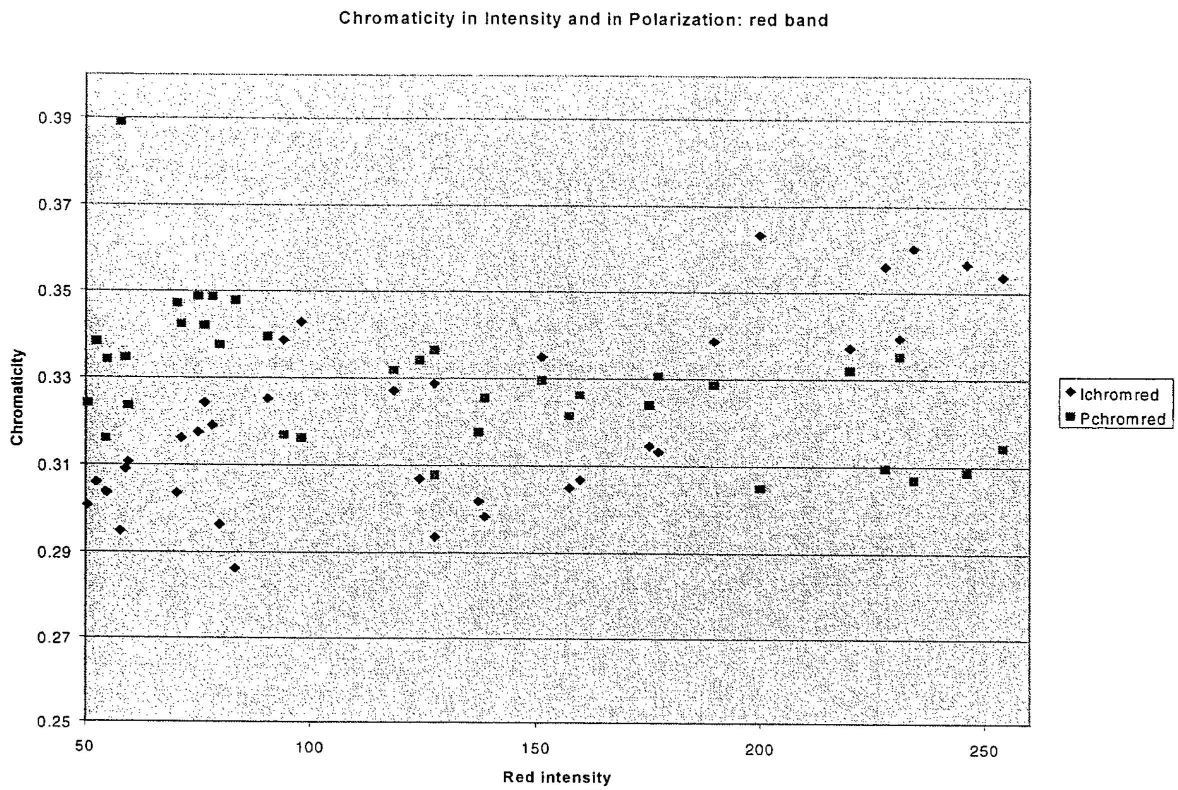

Figure 2. Intensity and polarization chromaticities for natural scenes in the red band.

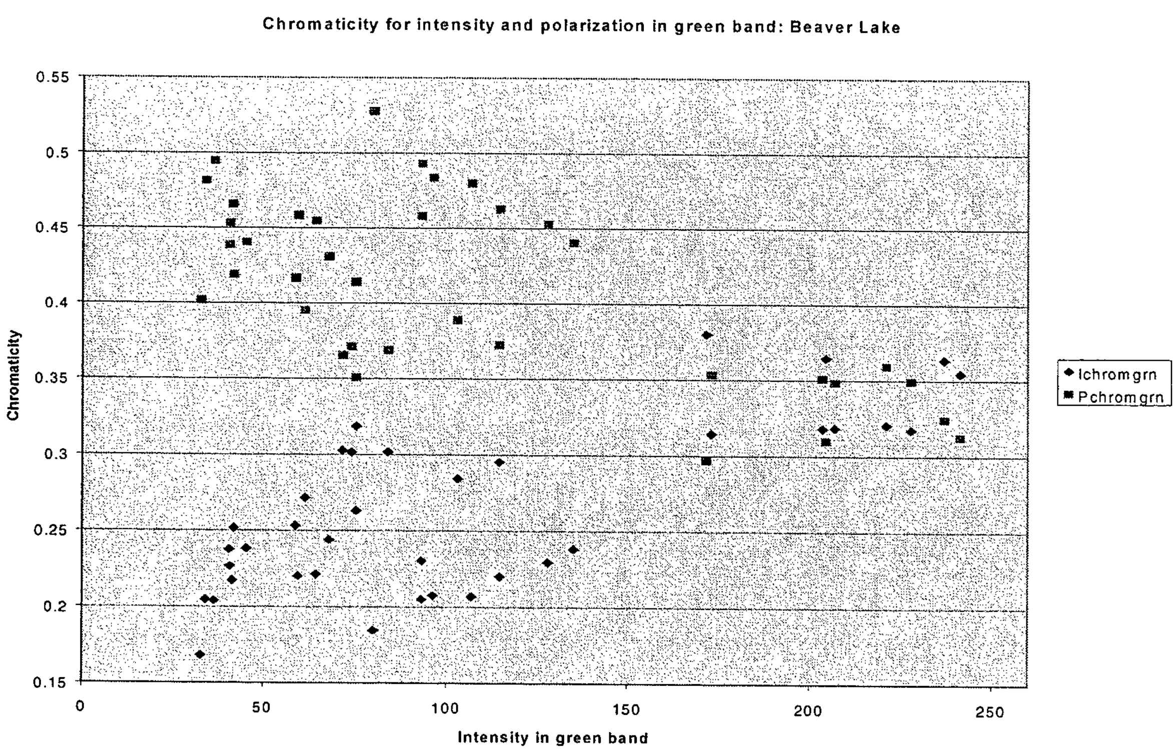

Figure 3. Intensity and polarization chromaticities for natural scenes in the green band.

Chromaticity in intensity for nir, red and green bands: Beaver Lake

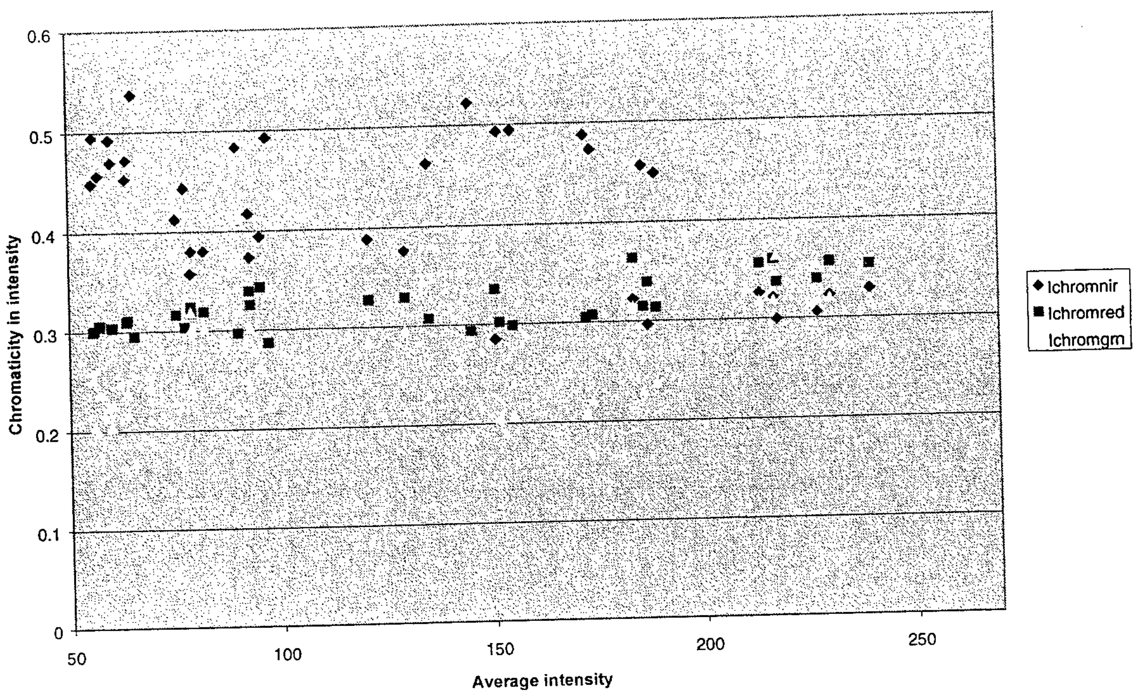

Figure 4. Cromaticities of intensity in each of three bands vs. average (over all three bands) for natural scenes.

Chromaticity in polarization vs mean intensity for nir, red and green bands

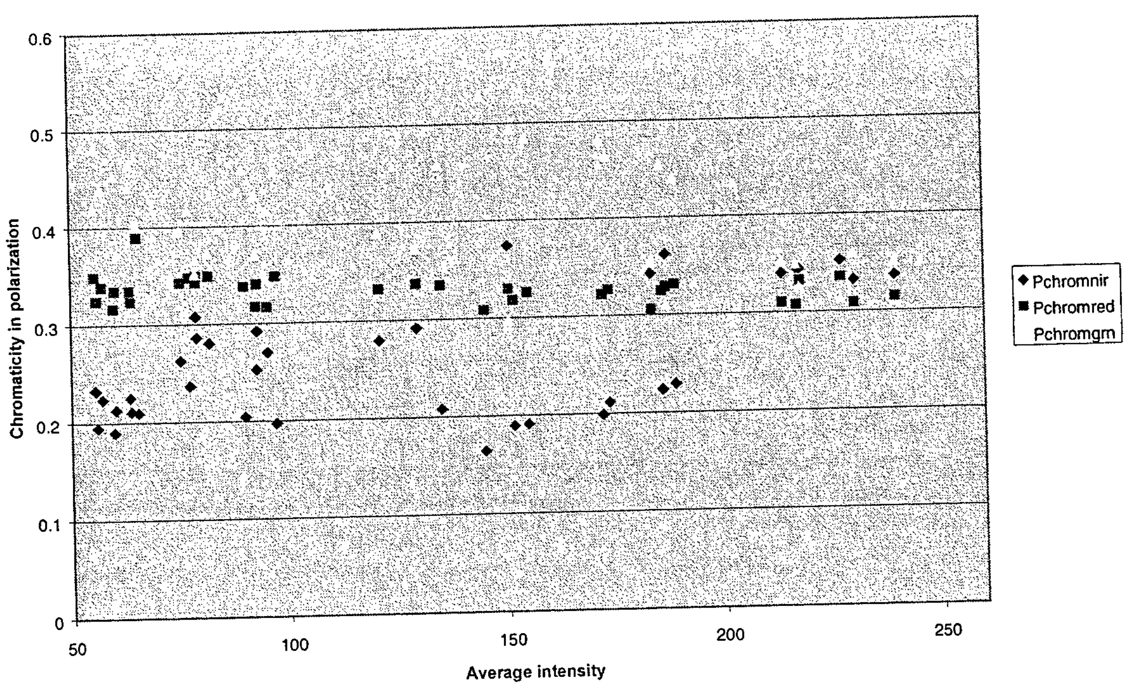

Figure 5. Cromaticities of polarization in each of three bands vs. average (over all three bands) for natural scenes.

An example of an image of a selection of reflectors is shown in Figure 6. This image is the average of the four images taken with the linear polarizer rotated at 45^0 relative orientations about the optic axis of the camera between exposures. The camera was mounted on a very rigid tripod to prevent camera movement between exposures.

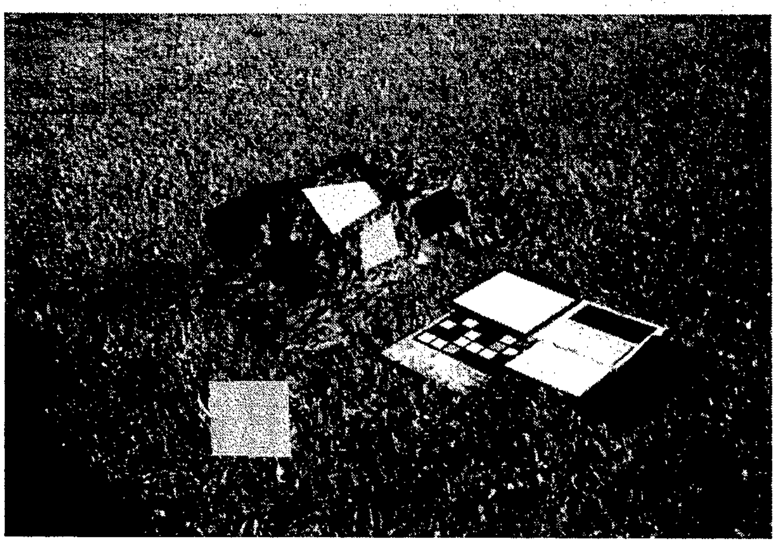

Figure 6. MacBeth color targets, Spectralon Panels and gray cards. Some of the regions of interest studied are indicated.

The corresponding polarization image, calculated using the expression scaled U and Q values (using an offset of 256 for the 8-bit data used) to prevent calculated error in P due to negative values in the U and Q images is shown in Figure 7. In order to examine if there is some band-to-band variation in polarization, the polarization chromaticity is plotted in Figure 8 as a function of mean intensity. The grass or camouflage nets in Figures 6 and 7 are not considered in the data shown in Figure 8. If regions of interest on the grass and camouflage net are included, then the plot shown in Figure 9 is obtained.

Figure 7. Polarization image calculated from the four images of the scene shown in Figure 6, obtained with the linear polarizer sequentially incremented 45^0 about the camera optic axis.

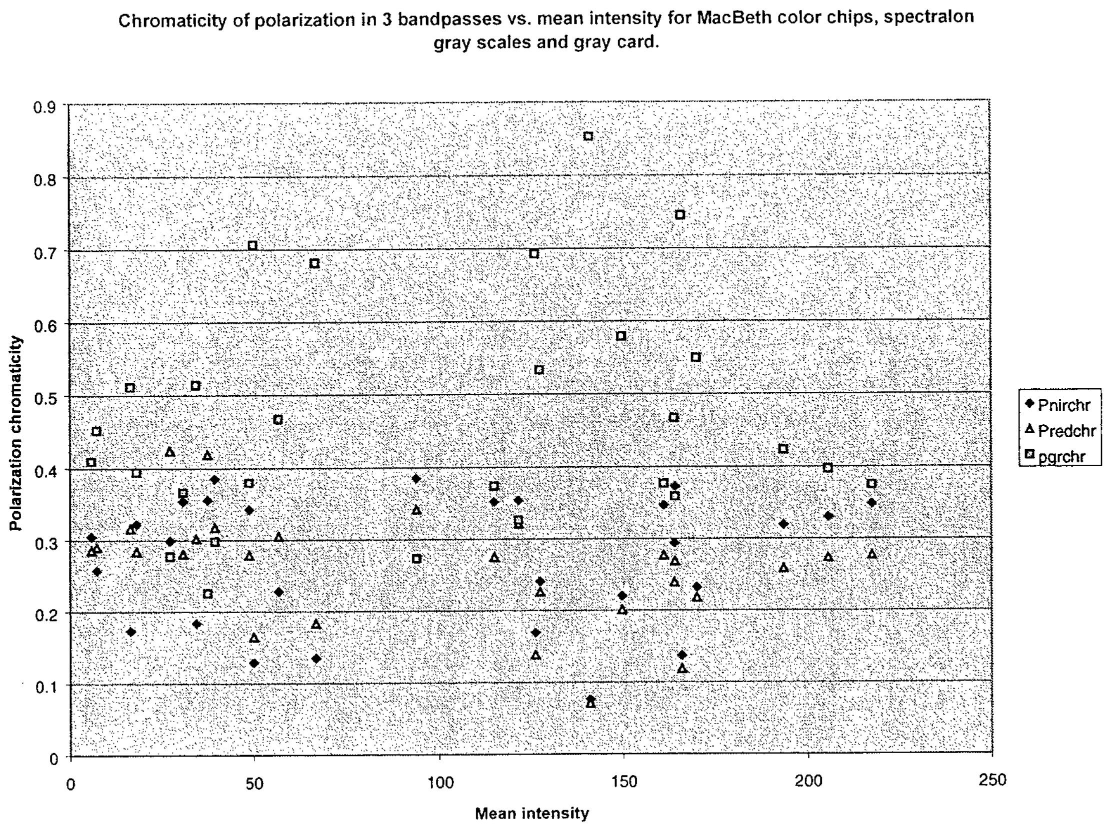

Figure 8. Polarization chromaticity in 3 bandpasses vs. mean intensity for MacBeth color chips and gray panels.

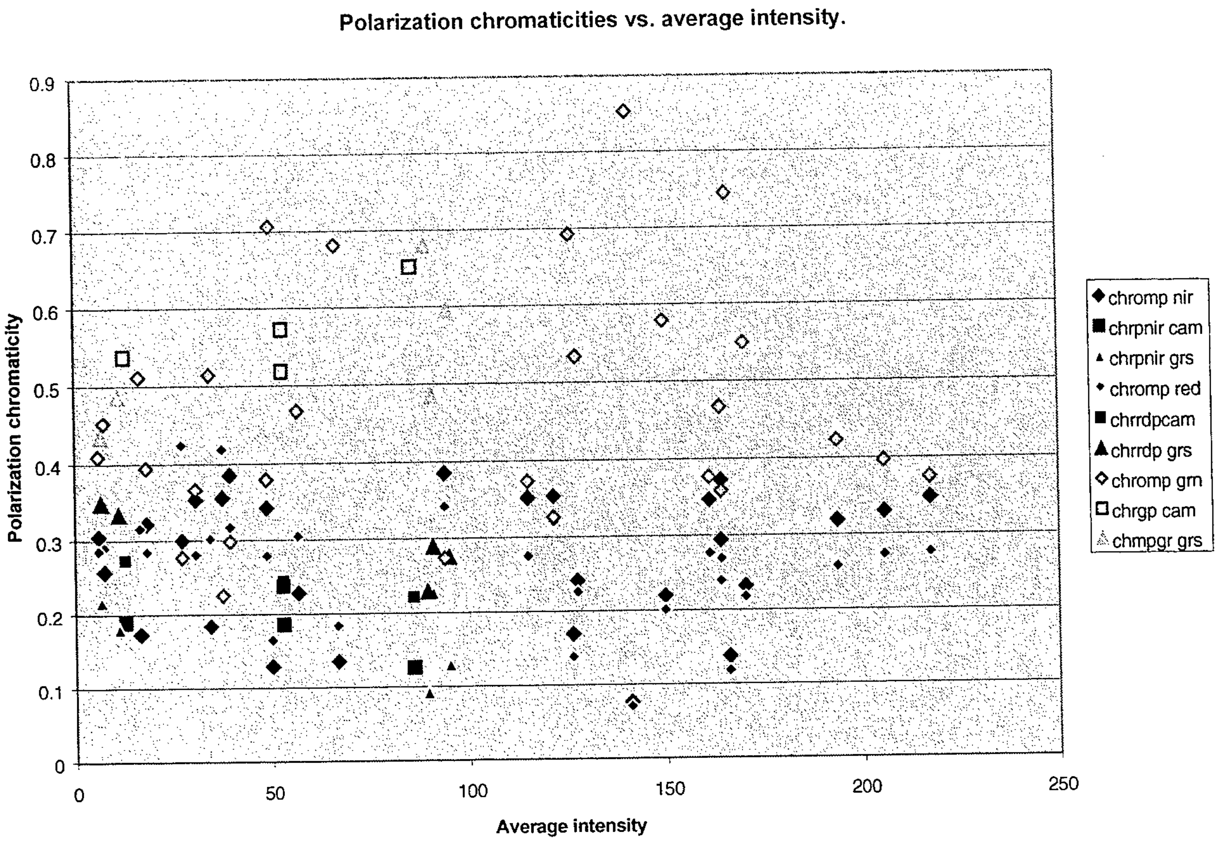

Figure 9. Polarization chromaticity in 3 bandpasses vs. mean intensity for MacBeth color chips, gray panels, grass and camouflage netting.

If only the artificial targets (color chips and gray scale) are considered, much of the variance in the data for each band can be explained by power regression fits for the data, as shown in Figure 10.

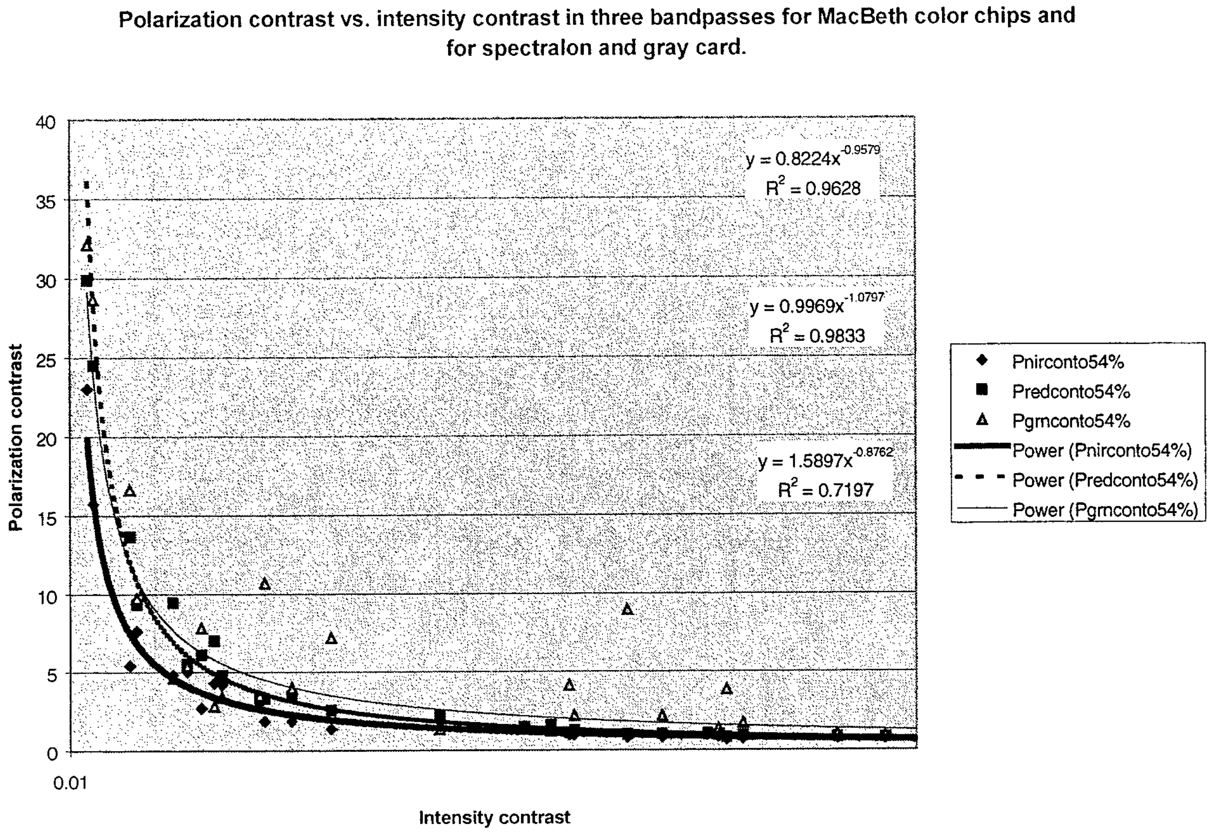

Figure 10. Polarization contrast in each bandpass plotted against the intensity contrast in the same bandpasses.

Most of the variance appears to be explained by an inverse relationship between the polarization contrast and the intensity contrast, as observed by Egan,[11, 12] and by Duggin, Egan and Gregory[13] for polarization plotted against intensity. However, the fact that the variance is not completely explained by such a relationship, and that there appears to be a band-dependence in the degree of variance suggests that there may be a role for multiband polarization imaging in feature mapping.

It was found by plotting the chromaticity of the intensity in the red and NIR bands for regions of interest over natural scene, color patches, camouflage net, gray scale targets, and Spectralon, that there is a separation of the camouflage net from natural surroundings. This is shown in Figure 11. By plotting the polarization chromaticities of vegetation and of the camouflage net, the graph shown in Figure 12 is obtained where it may again be seen that the camouflage net stands distinctly from vegetation. Similar discrimination is obtained by plotting the green vs. the red chromaticities, as shown in Figure 13.

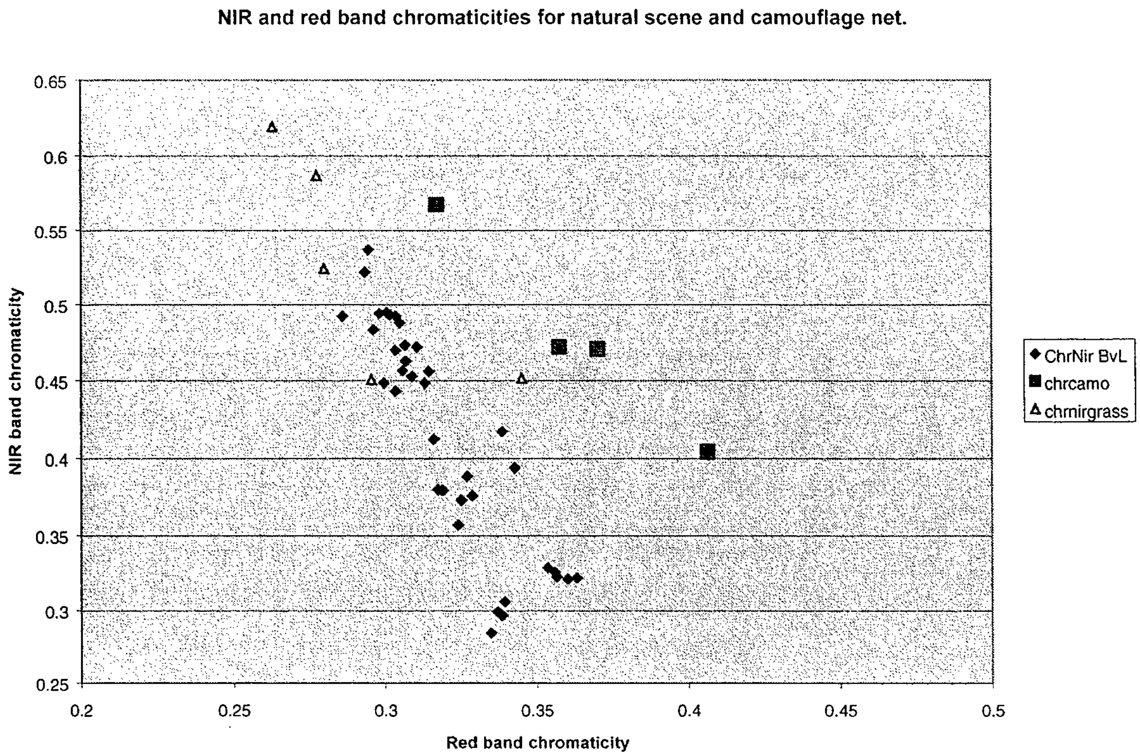

Figure 11. Plot of the intensity chromaticities in the red and NIR bandpasses. The camouflage net is seen to stand out from the vegetation.

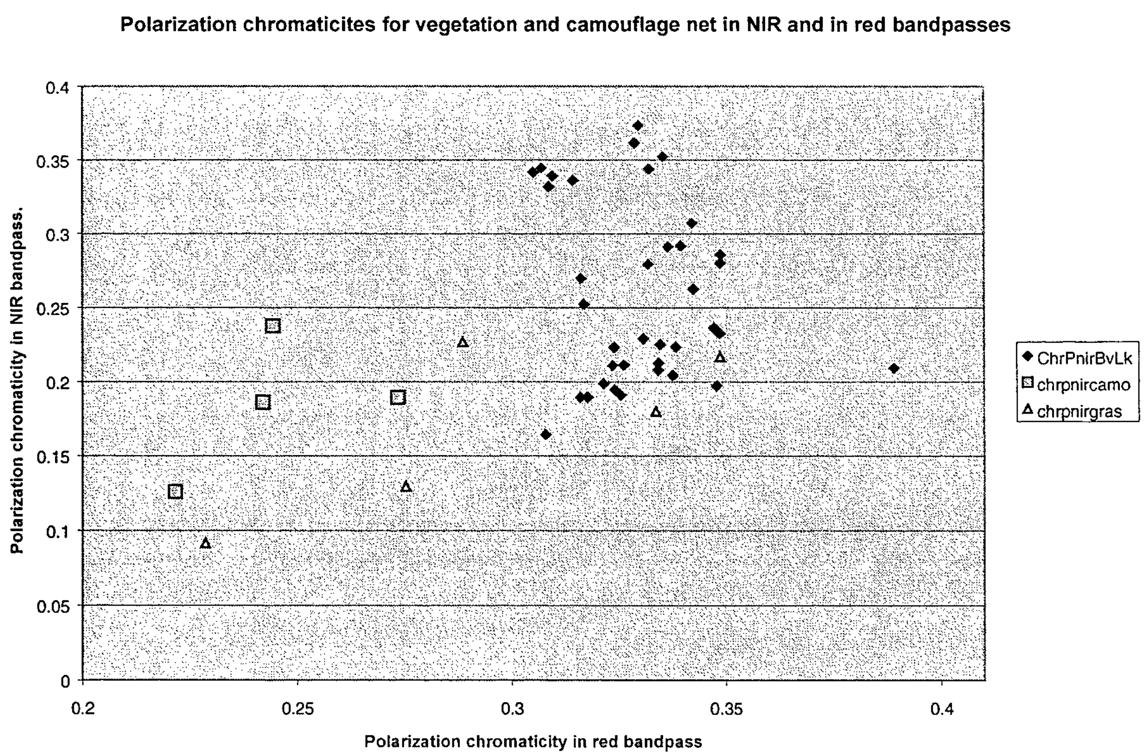

Figure 12. Plot of the polarization chromaticities in the red and in the NIR bandpasses. The camouflage netting stands out as distinct from vegetation.

Polarization chromaticities in the green and red bandpasses for camouflage net, grass and natural scene elements.

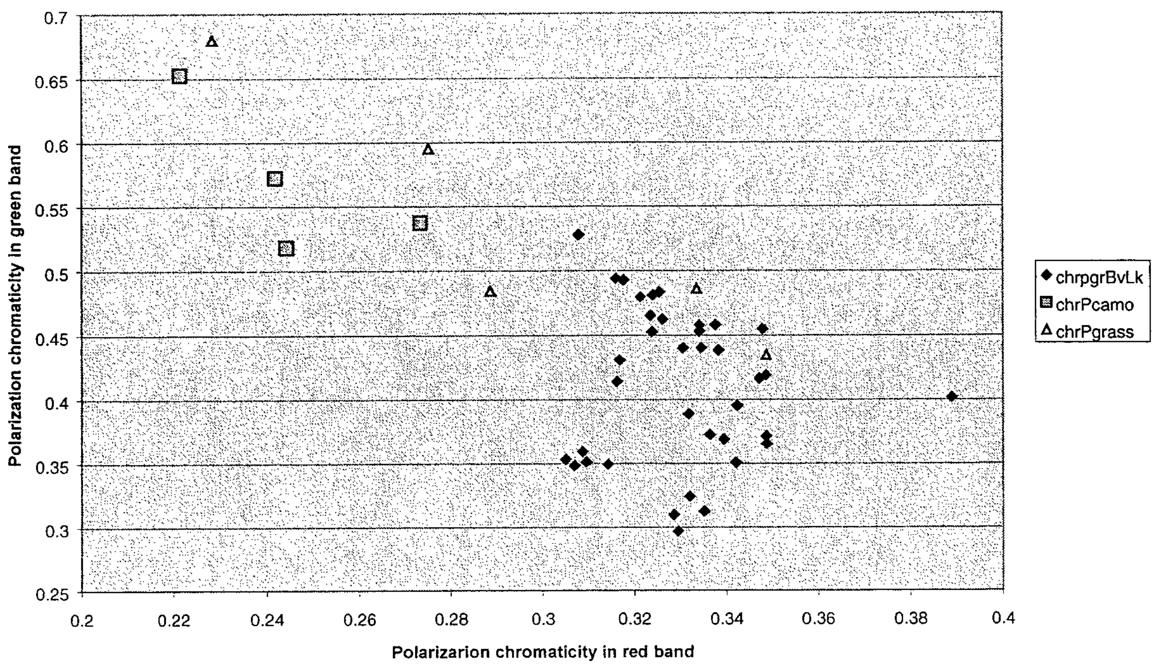

Figure 13. Plot of the polarization chromaticities in the red and in the green bandpasses. The camouflage netting stands out as distinct from vegetation.

In order to determine whether there is a greater likelihood of detecting selected features using contrast in polarized light, as opposed to contrast in intensity, a polarization image obtained at the US Air Force Stockbridge NY site was examined. Here, a C130 aircraft was mounted on a pedestal and the method of imaging was as discussed above. The intensity image is shown in Figure 14, while the polarization image is shown in Figure 15. The intent was to take the simplest case and examine the enhancement of shadowed detail on a potential target to see if this target as a whole may be more easily discriminated in polarized light than in the corresponding intensity image. This was a preliminary study. More geometries need to be studied to check the preliminary findings reported here.

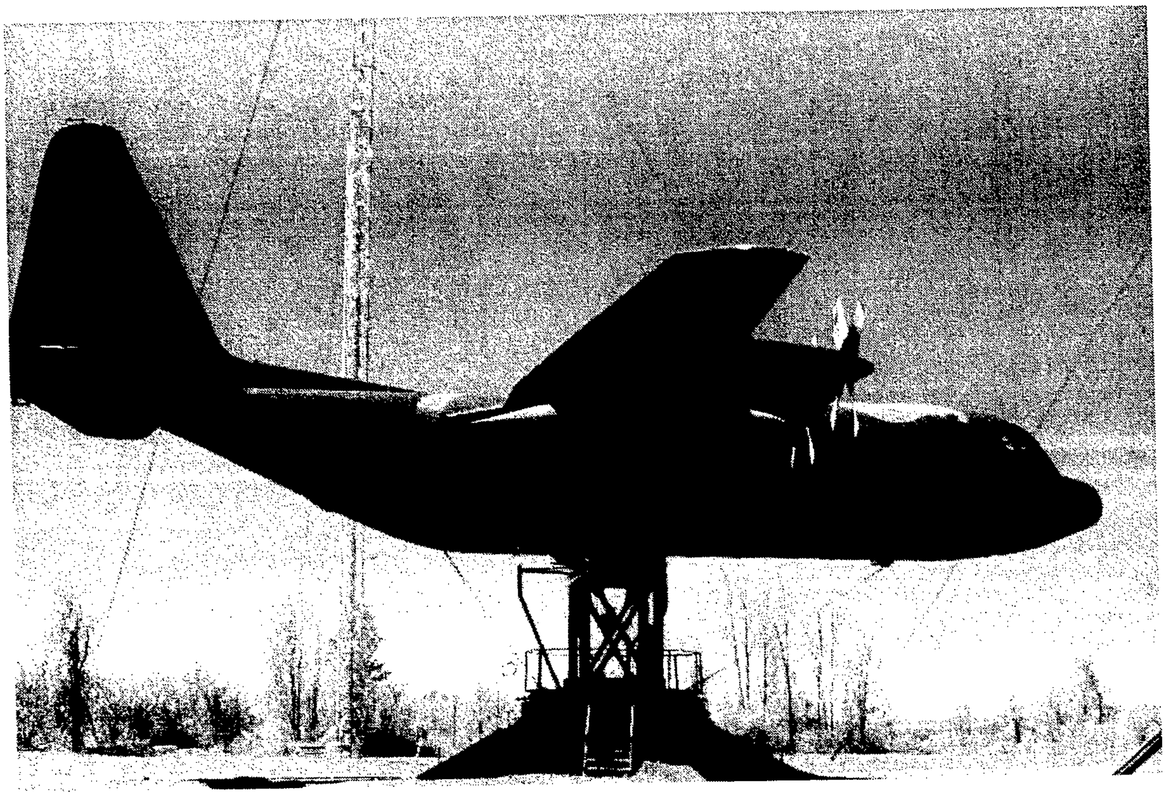

Figure 14. Grayscale image showing C 130 on pedastal with clear sky background, and shadow concealing detail.

Figure 15. Grayscale polarization image of C 130 shown in Figure 14.

Examination of a plot of polarization contrast vs. mean intensity contrast, shown in Figure 16, shows that the contrast in the polarization image between sky and aircraft is about an order of magnitude more than that in the intensity image. The relationship between the polarization and intensity contrasts also follows the same hyperbolic relationship as the relationship between polarization and intensity pointed out by Egan[11,12] and by Duggin, Egan and Gregory.[13]

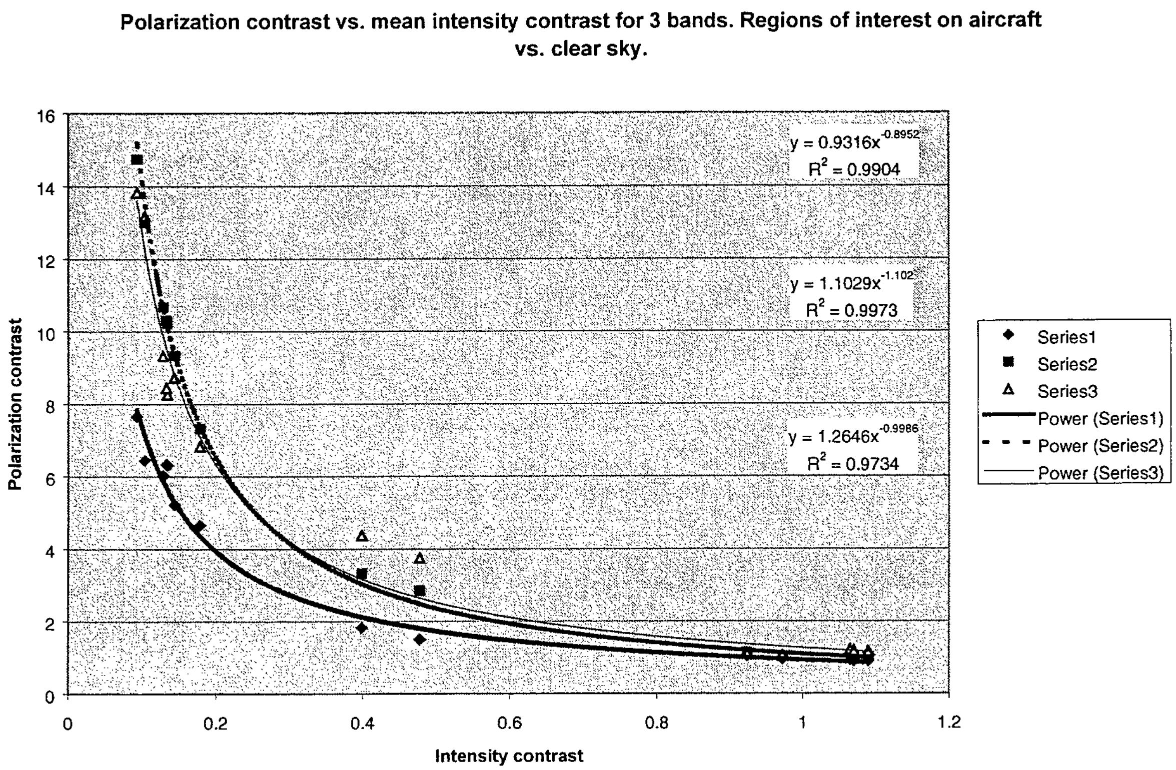

Figure 16. Polarization contrast vs. mean intensity contrast for regions of interest on C 130 compared to region of interest on clear sky.

The contrast between the radiance and the polarization of the radiance from the other regions of interest relative to this region of interest was considered for a light camouflage area selected on the vertical stabilizer. The results are shown in Figure 17. As in Figure 16, the relationship between polarization contrast and intensity contrast follows the same hyperbolic relationship as in the case of contrast between regions of interest on the aircraft and clear sky. The contrasts are lower than in the case of contrast to the sky, but polarization starts to greatly improve contrast when the intensity contrast falls off. In both cases the regression curves are shown for each band, and the equations and the fraction of the variance explained by the fit are shown on each graph (nir at the top, then red, and green at the bottom). The excellence of the fit suggests the potential utility of looking for predictive equations for target detection.

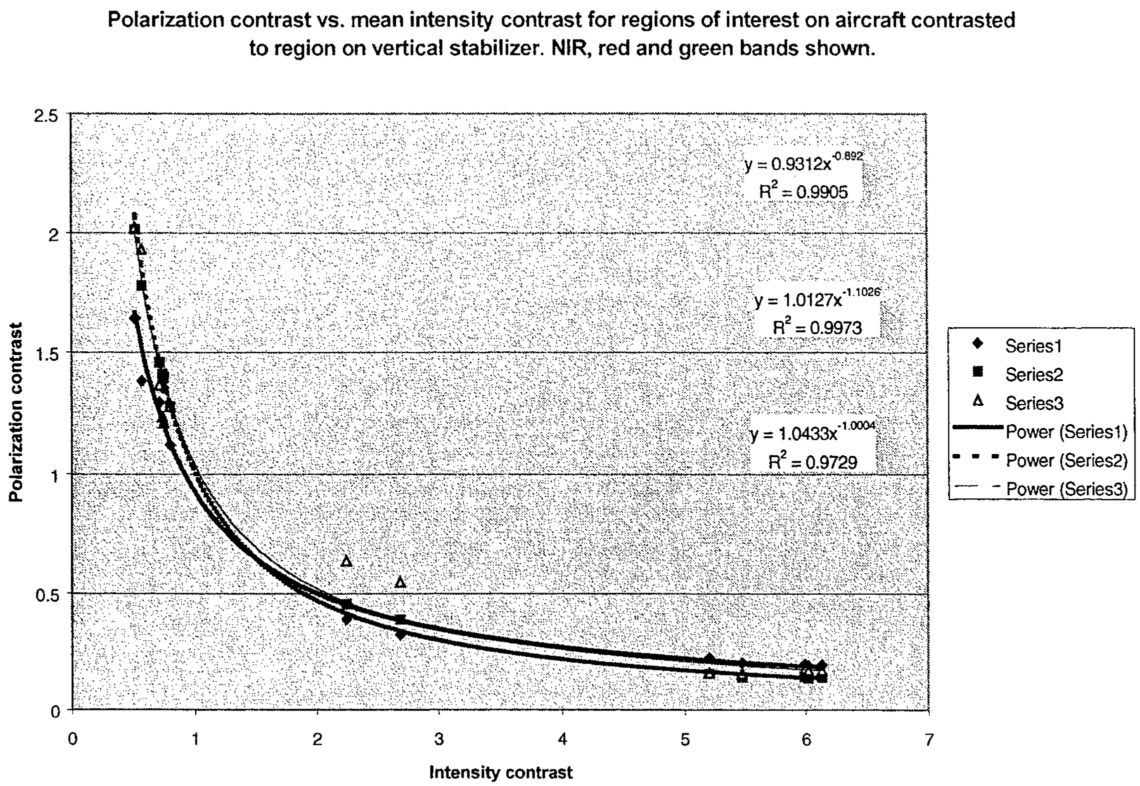

Figure 17. Polarization contrast vs. mean intensity contrast for regions of interest on C 130, compared to region on vertical stabilizer.

4. CONCLUSIONS

Based on the analytical results presented in the previous section, the following conclusions may be reached.

- The band-to-band distribution of polarization exhibits substantial variance.
- Polarization increases contrast enhancement as the contrast between features in intensity decreases.
- The use of polarization can improve the contrast between target and background by an order of magnitude.
- Information may be extracted from several images and pooled, since the relationships between intensity and polarization values appear scene-element dependent, rather than image-dependent.
- The use of chromaticity can make targets such as camouflage netting stand out more clearly against background; the use of chromaticity color representation assists feature extraction.
- Discriminability appears to be more easily achieved using chromaticities than by using raw intensity data or polarization data.
- Multiband imaging polarimetry is likely to provide an advantage in feature detection and classification.

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