Active Multispectral Imaging

R G Clarke
BAE SYSTEMS – Advanced Technology Centre
PO Box 5, Filton
Bristol BS34 7QW

Abstract

Multispectral imaging sensors are widely seen as providing an improved detection and targeting capability in military applications. However, in the visible and near infrared region, these systems are restricted to daytime use and are compromised by the presence of shadows in the scene. In Active Multispectral Imaging it is hoped to overcome these restrictions by using an independent source of illumination, such as a laser. This paper examines the potential gains to be made from this approach and defines the source requirements (wavelengths power levels etc) necessary to achieve them. A model of the shadowing process, based on the application of the RX algorithm to statistically generated scene is described, along with a basic systems model of the relative influence of the active source and natural illumination.

Keywords: Multispectral, Active Imaging, Target Detection, Shadow, RX Algorithm

Introduction

Recent years have seen a growing interest in multispectral imagery as a potential means of combating the increasing sophistication of countermeasure and camouflage systems. In conventional multispectral imaging the ambient light reflected from the scene is analysed into many narrow spectral bands. By exploiting the, often subtle, band to band variations in the spectral signature of any target from the background it is possible to discriminate between the two, which might otherwise be indistinguishable in conventional broadband imaging.

However, such sensors are not without limitations; the most obvious being that systems operating in the visible and near infrared, where there is a wealth of spectral structure to exploit, are restricted to daytime use. Moreover, the image may be strongly influenced by the presence of shadows, which increases the clutter content of the scene and so can significantly compromise the performance of the detection algorithm. The concept behind Active Multispectral Imaging (Figure 1) is to augment the natural scene illumination using a collocated artificial high brightness source (e.g. a laser). This provides both a day/night capability and does much to alleviate the problem of shadowing.

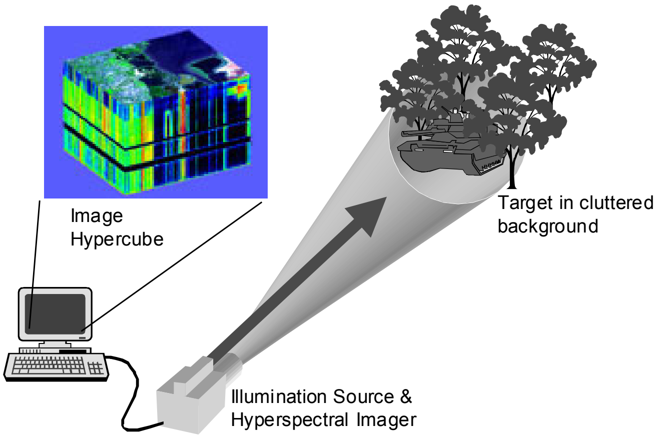

Figure 1: Multispectral Imaging Concept

Several groups have reported results obtained with active multispectral sensors in a variety of schemes. MIT Lincoln Labs (Johnson et al (1), Nischan et al (2), and Newbury et al (3)) report encouraging results using broadband Raman fibre lasers for short range (< 100m) applications such as mine detection. Simard et al (4), at the Canadian Defence Research Establishment Valcartier (DREV), have approached this same problem from aircraft using UV excimer lasers to stimulate fluorescence in the target scene. At the other end of the scale, Foy et al (5) at Los Alamos have attempted long range (~km) scene classification with frequency agile CO_2 lasers, concluding that speckle noise was the limiting factor in performance in their case.

The overall conclusion to be drawn from the reported work seems to be that Active Multispectral Imaging has potential, but that there are still questions and trade-offs to be addressed with regard to long range detection. For example, the speckle noise that afflicts narrow band systems may be alleviated by using broadband sources but the (inherently reduced) spectral brightness of these may not be sufficient to achieve the desired ranges. The present study has attempted to investigate some of these issues using a basic systems model (described below) to determine necessary source powers.

One observation by the MIT group was that the shadow content of the scene was dramatically improved by using the active source – resulting in a two order of magnitude improvement in target detectability. Improvements of this order are obviously highly attractive and it was decided that a further investigation of the impact of shadowing would be in order - the aim being to set limits on the necessary power levels of source required to achieve a given level of improvement. To this end a target detection model was developed, based on the application of a representative multispectral algorithm in the presence of varying degrees of shadow.

Shadow Model

The shadow model is based on the application of a typical multispectral discrimination algorithm to a statistically generated scene in which we can vary the amount and degree of shadowing. For our purposes we choose to define the degree of shadowing as:

$$DoS = \frac{\left(L_{out} - L_{in}\right)}{L_{out}} \qquad (1)$$

…where L_{in} and L_{out} are, respectively, the radiance values of the pixel in and out of the shadow. The description of shadowing is somewhat arbitrary but this formalism has the merit that higher DoS values indicate stronger shadows and the full black-white modulation case corresponds to $DoS = 1$.

More specifically, the model is based on the RX detection algorithm, which is used to determine the probability of detecting a single pixel target in a spatially cluttered scene. The performance of the algorithm, as a function of the scene's shadow content, is then judged by the behaviour of the Receiver Operating Characteristics (ROC) which relates the probability of detection to the false alarm rate. The essence of the model is illustrated in Figure 2.

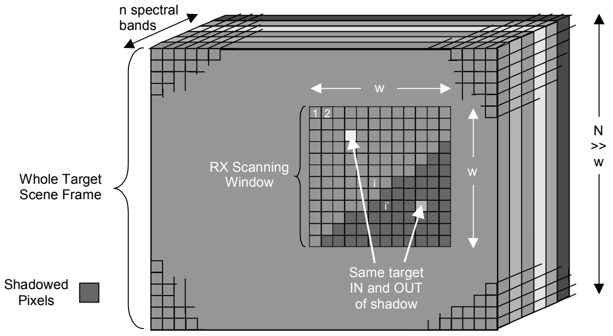

Figure 2: Elements of Shadow Model

The imaged scene is supposed to comprise a data-cube of $N \times N$ pixels, each of which is analysed into n spectral bands, and we wish to know if any of these are (single pixel) targets. On the common assumption that the background is multi-variate Gaussian, we can calculate the probability that the spectral vector of any pixel is simply characteristic of the background. If this probability is less than some pre-assigned threshold τ_q then the pixel is declared *anomalous* (i.e. unlike the background) and thus is a possible target. Mathematically, the probability of detection for each pixel i may be described as:

$$\textit{Probability of Detection} \quad P_D = \frac{1}{2}\left[1 + erf\left(\frac{SCR_i - \tau_q}{\sqrt{2 \times SCR_i}}\right)\right]$$

…where *erf(x)* is the error function (2)

This, in effect, is just a spatial noise analogue of the well-known electronics model of single pulse detection in the presence of white noise.

The quantity SCR_i in equation 2 is the background Signal to Clutter Ratio for any particular pixel i relative to the background of the others the RX scanning window. Statistically SCR represents the *Mahalanobis Metric* of the spectral vector and is derived from the window covariance matrix $\boldsymbol{c^i}$ as:

$$SCR_i = \sum_{j,j'=1}^{n} (L_j^i - \overline{L}_j^i)\left(\left[c^i\right]^{-1}\right)_{j,j'}(L_{j'}^i - \overline{L}_{j'}^i)$$

$$= (L^i - \overline{L}^i)\left[c^i\right]^{-1}(L^i - \overline{L}^i)^T \qquad (3)$$

…where the $()^T$ denotes a matrix transpose.

The quantities L_j^i are the pixel radiance values in each spectral bin j and the mean spectral vectors for the background are simply:

$$\overline{L}_j^i = \frac{1}{w^2}\sum_{i'=1}^{w^2} L_j^{i'} \qquad (4)$$

Finally, the covariance matrix, itself is given by:

$$c_{j,j'}^i = c(s,f)_{j,j'}^i = \frac{1}{w^2}\sum_{i'=1}^{w^2}(L_j^{i'} - \overline{L}_j^i)(L_{j'}^{i'} - \overline{L}_{j'}^i)$$

$$\approx (L^i - \overline{L}^i)^T (L^i - \overline{L}^i) \qquad (5)$$

The threshold value τ_q in equation 2 is determined by the desired False Alarm Rate, $P_{FA} = 10^{-q}$, as the inverse normal distribution of the quantity *(1-10^{-q}),* with mean = zero and variance = SCR_I.

Some results obtained with this model are summarised in Figure 3. This particular example shows the effects of various degrees of shadow covering 30% of the scene. The gains to be had from removal of the shadow can be dramatic but it is also apparent that quite significant benefits may result from quite modest reductions in shadowing.

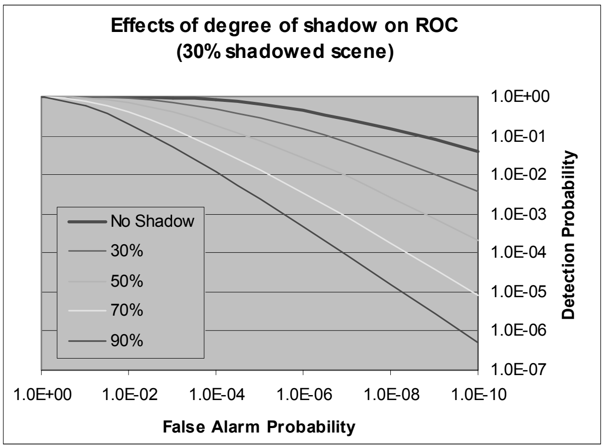

Figure 3: Effects of Shadow on System Performance

Accepting that reduction in shadow content is worthwhile raises the question of what level of source power/energy is required to achieve this. To investigate this further a basic systems model was developed.

Systems Model

Modelling the radiance of the background scene is a complex problem. For our purposes we have assumed the very simple scenario of a flat target plate, viewed against a uniform diffuse background.

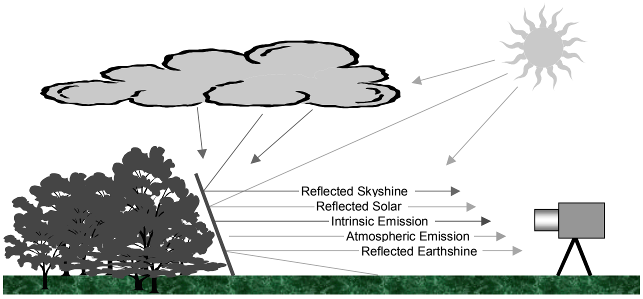

Figure 4: Elements in Systems Model

The various sources of background radiation which irradiate, and are subsequently reflected from, the target plate are then as shown in Figure 4. A similar (though more sophisticated) approach has been reported by Schwartz et al (6) and their published results form a useful means of verification of our findings.

Mathematically the apparent radiance of the target resulting from all these contributions (i.e. as seen through the atmosphere by a purely passive sensor) may be expressed as:

$$L_{PAS} = L_{BB} \cdot (1-\rho) \cdot \tau + (L_{sky} + L_{sun} + L_{gnd}) \cdot \rho \cdot \tau + L_{path} \quad (6)$$

… the various parameters of which, together with the source of raw data are described in Table 1

Table 1: Quantities used in Systems Model

Quantity	Symbol	Data Source
Intrinsic Emission	L_{BB}	Planck's Law
Reflected Sunshine	L_{sun}	MODTRAN
Reflected Skyshine	L_{sky}	MODTRAN + Integral
Reflected Earthshine	L_{gnd}	MODTRAN + Integral
Path Transmission	τ	MODTRAN
Target Reflectivity	ρ	JPL Database
Path Radiance	L_{path}	MODTRAN

All these quantities are spectrally varying and most are also dependent upon other variables, e.g. temperatures of ground & atmosphere, position of sun, atmospheric aerosol content, etc.. All the atmosphere related quantities are derived from MODTRAN (Ver. 4.2) at a resolution of 20 cm^{-1}.

Figure 5 serves to illustrate the various factors contributing to a typical component term of the model (in this case the earthshine component originating from a 30 degree look-down angle). The lower frequency end of this is dominated by Planckian emission terms (which rapidly fall off outside the infrared) whilst the higher frequencies are almost solely the result of direct and scattered solar flux. It should be noted that to derive the overall earth/skyshine components in equation (6) a number of such curves are used to determine the overall radiance distribution across the hemisphere seen by the target plate. The quantities (L_{gnd}, L_{sky}) are then derived by integration of this distribution.

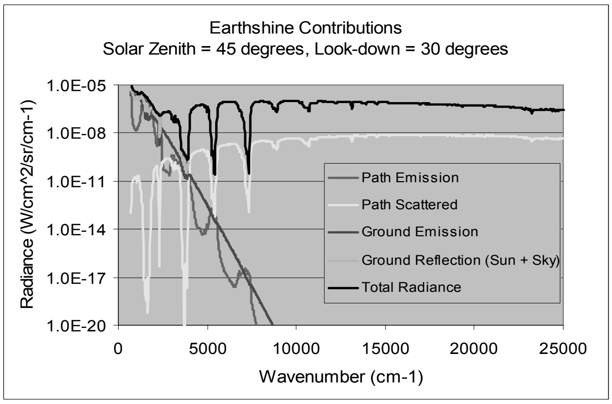

Figure 5: Typical systems model component (earthshine)

Irradiance of the target with an active source of power spectral density P (W/cm^{-1}) gives rise to an additional apparent target radiance term of:

$$L_{ACT} = \frac{4 \cdot P \cdot \rho \cdot \tau^2}{(\pi \cdot R \cdot \theta)^2} \quad (7)$$

…where R is the target range and θ the source divergence.

Systems Model Results

The systems model provides various forms of final output, a typical example being that of Figure 6.

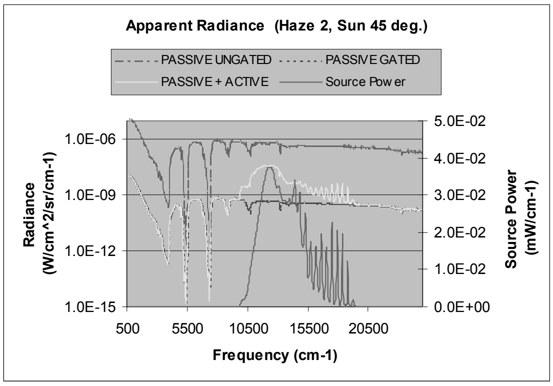

Figure 6: Typical Systems Model Output

This shows the final apparent radiance that would be seen by a sensor; in this case, range gated (illustrating the benefits of this technology). Typically, this output would then feed in to a sensor model to determine signal:noise performance.

The curve labelled "PASSIVE UNGATED" is the raw background radiance, such as would be observed by any passive system. The spectrally similar curve, shifted down the radiance axis and labelled "PASSIVE GATED", is the effective radiance which the background appears to have as a result of the shortened integration time (50 nS in this example) provided by the range gate. For the most part the previous curve is obscured by the one labelled "PASSIVE + ACTIVE", which is the overall radiance resulting from the addition of the active source.

The final curve, plotted on the right hand ordinate, is the source spectral density and is included mainly for reference and as a graphic indicator of where the influence of the active source should be expected. In this example the spectrum is that of a Raman fibre laser pumped by a 532nm doubled Nd:YAG.

Shadow Reduction Requirements

The final output from the model provides a direct measure of the degree of shadow reduction achievable, at range with a given source power.

In the presence of the active source L_{ACT} the degree of shadowing, as defined in equation 1, is reduced to:

$$DoS_{active} = \frac{(L_{out} + L_{ACT}) - (L_{in} + L_{ACT})}{(L_{out} + L_{ACT})}$$

$$= \frac{(L_{out} - L_{in})}{(L_{out} + L_{ACT})} \qquad (7)$$

A typical result, in this case with with an extrapolated Raman fibre source power and gated sensor, is plotted in Figure 7. In this example, for the worst case scenario of $L_{in} = 0$, the source is seen to be capable of achieving almost complete cancellation of the shadowing at 1km range, and should still provide a useful reduction even at 3km.

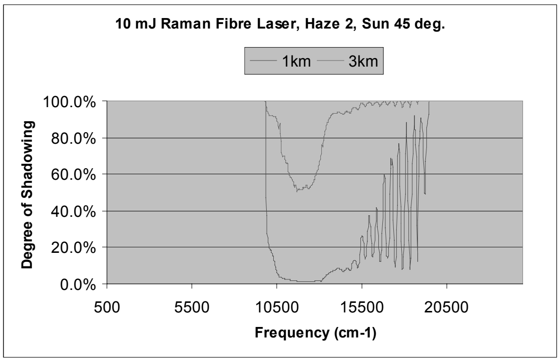

Figure 7: Effectiveness of Shadow Reduction

Conclusions

This paper has concentrated only on the idea of shadow reduction, which might justly be regarded as merely a side effect of active multispectral imaging. Even so, the practical experience of the MIT group and the statistical shadow model developed here suggests that there may be major gains in systems performance to be had in this area.

The limited systems modelling performed to-date has been based largely on extrapolation of currently available broadband source powers. Whether these are valid or not is of course debatable, but this is a maturing field and the extrapolation is not considered excessive. Moreover, our calculations have been based on the most stringent assumptions of full sun on the target; overcast conditions would lower these requirements ten-fold. On this basis it seems likely that useful degrees of shadow reduction could be achieved, ultimately, at ranges out to around 3km.

The results described above all feature range-gated detection. This is seen as a necessity in any system operating in daylight at any significant range (>100m). At night, however, useful results have been achieved with quite modest powers. The small US company *Surface Optics* have recently demonstrated target discrimination, in the presence of camouflage, out around 2 km with a relatively simple sensor and 30W cw diode power

The alternative scheme of using frequency agile lasers has not been considered in any depth. The power spectral density of such sources is inherently far brighter than the broad band ones discussed so far and there is no doubt that they could provide sufficient power, even without range-gating. However, there are difficult questions to be answered regarding the optimum wavelengths and above all the implications of speckle. Whilst the latter is not considered to afflict broadband systems it may pose a significant problem to narrow band ones. Speckle exhibits a 100% modulation, from black to white, and significant speckle in the image is thus likely to be every bit as detrimental as shadow. Whilst such effects could in principle be modelled this would be an obvious area for direct experimental investigation.

The alternative techniques of fluorescence and spectral polarimetry are worthy of mention. The former has briefly been looked at within the overall DTC study and there is undoubtedly a significant interest in the biological resource monitoring field, e.g. Romanovskii et al (7) and Hilton (8); but any military application is likely to be restricted to short range applications. The efficiency of the process is not high, and there is appreciable background emission from vegetation (chlorophyll) which must be differentiated, but the principal problem stems from the fact that the emission is completely isotropic – what little signal there is therefore falls off rapidly with range.

The study has made only a cursory reference to active multispectral polarimetric techniques. Since active sources are likely to be strongly polarised as a matter of course there is, not surprisingly, considerable work going on in this area, e.g. Miller et al. (9) and Clemenceau et al (10). It was therefore decided that this technique would not be covered within the active multispectral programme.

Overall, it is conclude that Active Multispectral Imaging is a promising adjunct to conventional passive systems. From a technical standpoint the limiting factor at the present time is the source technology but this is a maturing field. Ultimately, any military application will depend upon operational considerations; the technique is by definition not covert and this may outweigh any advantages.

References

1. Johnson B. et al, 1998, Proc. SPIE, 3710, 144-153
2. Nischan M. et al, 2000, Proc. SPIE, 4132, 107-117
3. Newbury A. et al, 2000, Proc. SPIE, 4132, 126-135
4. Simard J-R. et al, 2000, Proc. SPIE, 4035, 180-191
5. Foy B. et al, 2002, Proc. SPIE, 4722, 98-109
6. Schwartz C. et al, 1994, Proc. SPIE, 2235, 162-184
7. Romanovskii O. et al, 2000, Proc. SPIE, 4035, 143-149
8. Hilton, P., 2000, Proc. SPIE, 4124, 223-231

9. Miller, M. et al, 2002, Proc SPIE, 4481, 87-99
10. Clemenceau P. et al, 2000, Proc. SPIE, 4035, 401-409

Acknowledgements

The author wishes to acknowledge the major contribution to this work by Dr Michael Caola, who developed the statistical shadow model.
BAE SYSTEMS wishes to acknowledge that this work was performed within the UK Ministry of Defence Electro-Magnetic Remote Sensing Defence Technology Centre programme (contract DTC/DG(R&T)/13/25).