Requirements for laser countermeasures against imaging seekers

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ABSTRACT

Conventional anti-aircraft infrared seekers all operate on the principle of detecting the position of a IR source by modulating the FOV to encode the track of the target. This is a fundamental susceptibility of this class of seeker that renders them vulnerable to laser jamming. There are several DIRCM systems available that meet these requirements and provide a high degree of protection against reticle seekers.

The latest generation of IR seekers use imaging technology that discriminates the target position in an essentially different manner. This class of seeker is not susceptible to DIRCM jamming. This paper examines the effectiveness of laser jamming against imaging seekers to derive requirements for laser countermeasures.

Imaging seekers processing techniques that can be used to track the target and reject countermeasures are entirely defined by the on-board software of the seeker.

Imaging seekers may be vulnerable to higher power laser jamming. The effect of laser dazzle appears to degrade the image quality. However, actual scatter levels can be modelled and it can be shown that usable information is still available to the seeker under dazzle.

If neither decoy expendables nor dazzle lasers are expected to be effective against imaging seekers then the logical next step is to increase the laser power to produce damage. Estimates are provided to indicate the laser power levels that would be required against an imaging seeker focal plane. Although it is possible to design seekers that are hardened against laser damage, it is not clear that such designs are practical.

Keywords: Imaging seeker, DIRCM, laser jamming, image processing, scatter, countermeasures, damage

1. INTRODUCTION

Conventional anti-aircraft infrared seekers all operate on the principle of detecting the position of a IR source (target) by modulating the field of view (FOV) to encode the track of the target. This is a fundamental susceptibility of this class of seeker that renders them vulnerable to laser jamming with DIRCM. What the DIRCM needs are two things: modulation techniques and sufficient power for a J/S of 100 – 1000. There are several DIRCM systems available[1] that meet these requirements and provide a high degree of protection against reticle seekers.

The latest generation of IR seekers[2,3] use imaging technology that discriminates the target position in a fundamentally different manner. This class of seeker is not susceptible to DIRCM jamming. This paper examines the effectiveness of laser jamming against imaging seekers to derive requirements for laser countermeasures against imaging seekers

Since reticle seekers are constructed with optical components that define the modulation of point sources in the FOV, designing countermeasure modulation techniques against them is straightforward once a example of the model is obtained for laboratory testing. The long standing practice[4] of evaluating threat seeker hardware to exploit susceptibilities is no longer sufficient for the latest generation seekers.

This paper presents in the following sections the image processing functions and then the home on jam (HOJ) capabilities that can be expected in modern imaging seekers.

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2. IMAGE PROCESSING

Imaging seekers present a difficulty for countermeasure design in that the image processing techniques that can be used to track the target and reject countermeasures are entirely defined by the on-board software of the seeker. It is practically impossible to know in advance what algorithms are used, especially considering that software changes are easy to implement even after the particular models are in service.

Although it is difficult if not impossible to establish in detail the image processing capability of such a threat, basic image processing functions can be assumed. In this paper we will show examples of typical and straightforward techniques, and then assert that the capability represents at the most a low to medium estimate of an actual seeker capability.

Image processing in the seeker discriminates between the target and non-target clutter objects in the FOV. A jamming laser might obscure some of the target features, but as long as any feature of the target is detectable, the seeker can continue to guide to intercept. A later section in this paper will describe the ability of the seeker to locate the target from the jamming beam itself in the home-on-jam mode. This section describes the ability of image processing to detect the target and maintain track.

This is important in that some jamming techniques have been described where the jamming laser is switched on and off rapidly, forcing the imaging seeker processing modes to switch back and forth between target feature track and a home on jam mode. Home on jam is discussed further in the section on dazzle; here we show feature tracking capability.

Image processing features

In a recent publication[5] a good overview of image discriminants is presented. Simple algebraic formulas quantify 12 discriminants that can be exploited: such quantities like maximum intensity normalized to the average, variance of the intensity distribution, radius of object normalized to the square root of number of pixels, all provide a straightforward calculation to identify objects that resemble the dazzle area.

One of the features which is most appropriate for discriminating dazzle from target feature is referred to in that paper as roundness, which has earlier been called eccentricity[6]. (Eccentricity is defined differently in the recent paper as a more complex calculation of moments of inertia - the names of many image discriminants are not standardized).

The eccentricity is given by

$$\mathrm{ecc} = (\mathrm{perimeter})^2 / (4\,\pi\,A)$$

where A is the area of the feature, and will be equal to 1 for a perfect circle. The values for target and decoy were calculated for a large set of training images, and the occurrence probability density function displayed in Fig. 1 with a solid and dashed line respectively. The nearly circular image areas of the decoys produce discriminant values around a sharp peak, which provides a strong discriminant versus target values.

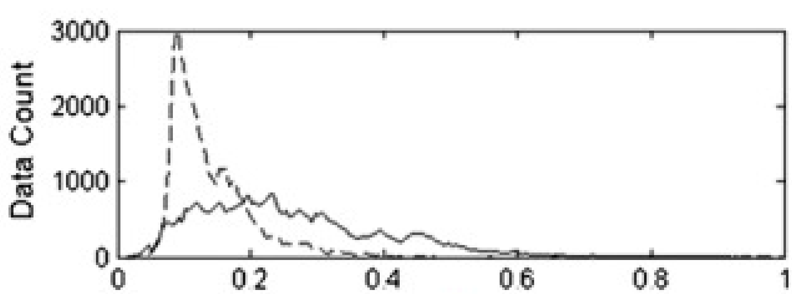

Figure 1 Target and decoy values of eccentricity

Most of the open literature on imaging seeker countermeasures discuss rejection of expendable decoys. In some cases the image of a decoy is very much like that of a laser dazzle, and the image processing capability can be expected to function in the same way.
Some simulation images from Reference 7 illustrate this in Figures 2 and 3 where the decoy area is similar to what the dazzle image would be like. Even though most of the target image is obscured or mixed with the decoy image, features are easily detected and therefore the seeker can maintain track on the target.

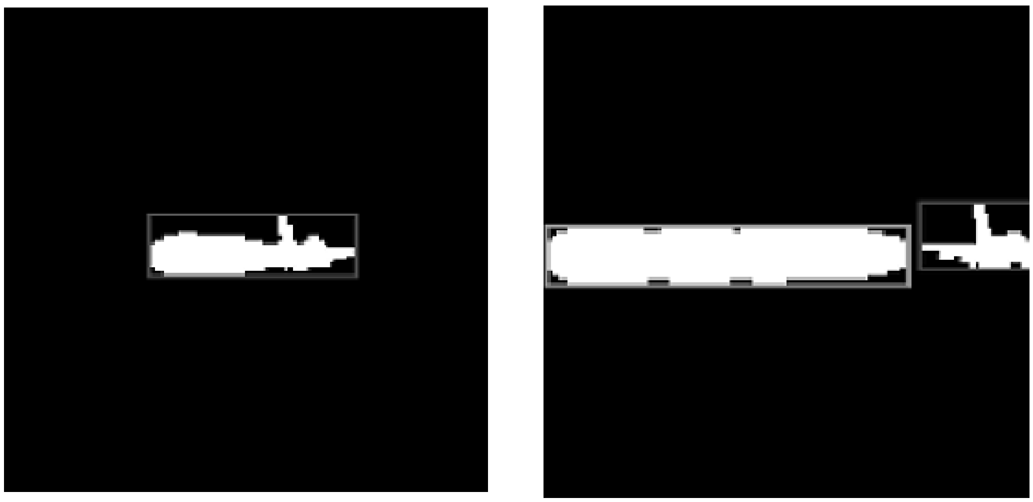

Figure 2 Target track maintained on mixed image

Figure 3 Feature tracking with dazzle area

Image processing summary

There are many techniques to distinguish the image pattern of a target from that of the laser dazzle pattern in the image. As long as there are a minimal number of features resolved by the seeker, the missile tracking system can simultaneously run feature extraction and HOJ modes, so laser dazzle is not likely to be a successful countermeasure.

3. LASER DAZZLE

Imaging seekers may be vulnerable to higher power laser jamming. The effect of laser dazzle against imagers as it is published in numerous studies appears to degrade the image quality. However, actual scatter amplitude levels can be modelled and it can be shown that usable information is still available to the seeker under dazzle. (To distinguish between jamming by modulation techniques against reticles and techniques against focal plane arrays we use the term laser dazzle).

Some images from focal plane array cameras give a deceptive impression that the focal plane is overloaded with optical signal when a laser is directed at the sensor. This visual impression derives mainly from the limited dynamic range of the image display.

We can model the laser energy across the full FPA and calculate what laser power would be required to jam the focal plane of the seeker. When a laser is within the field of view of the seeker, the higher energy may mask or swamp the image of the aircraft, which is generally low contrast. But when the laser is on, the seeker has a good indication of the aircraft position and can switch to a Home-On-Jam (HOJ) mode. Only if the optical signal drives the entire focal plane into saturation is there no target location information available to the seeker

The basic principle here is that if there is any signal intensity gradient information available from the focal plane, a seeker processor algorithm could exploit this data and continue to track the target.

Scatter prediction

The susceptibility of the seeker to laser jamming depends on the scatter in the optical system. Scatter in the optical elements is caused mainly by imperfections and impurities in the glass and surfaces. Good quality glasses are widely available, so in practice the surfaces create as much scatter as the bulk material. Optical surface quality and finish are under the control of the manufacturing process. Most optical components have one or two coating layers to reduce internal reflections and thereby improve the transmission of the system. If the seeker design requires, the optical surfaces can be polished and coated to a much higher quality level, in order to reduce susceptibility.

Published experimental data on optical material scatter usually reports the scatter from particular samples. The scatter from the surface and the bulk material is not reported separately. Within this limitation, optical surface quality can be regarded as a design-specific parameter. It is conceivable that a seeker could be designed and built with very low susceptibility to laser scatter.

The amount of light scattered by an optical component is defined by the Bi-directional Scatter Distribution Function (BSDF). This is a curve that shows how much light is scattered as a function of angle away from the input beam. Some typical BSDF values are shown in Fig. 4. For this application, we are interested mainly in the angular range of 1 to 5 degrees, since the FOV of the seeker of interest is 4.4 degrees. In this region, there is a difference of four orders of magnitude between poor and good quality ZnSe samples.

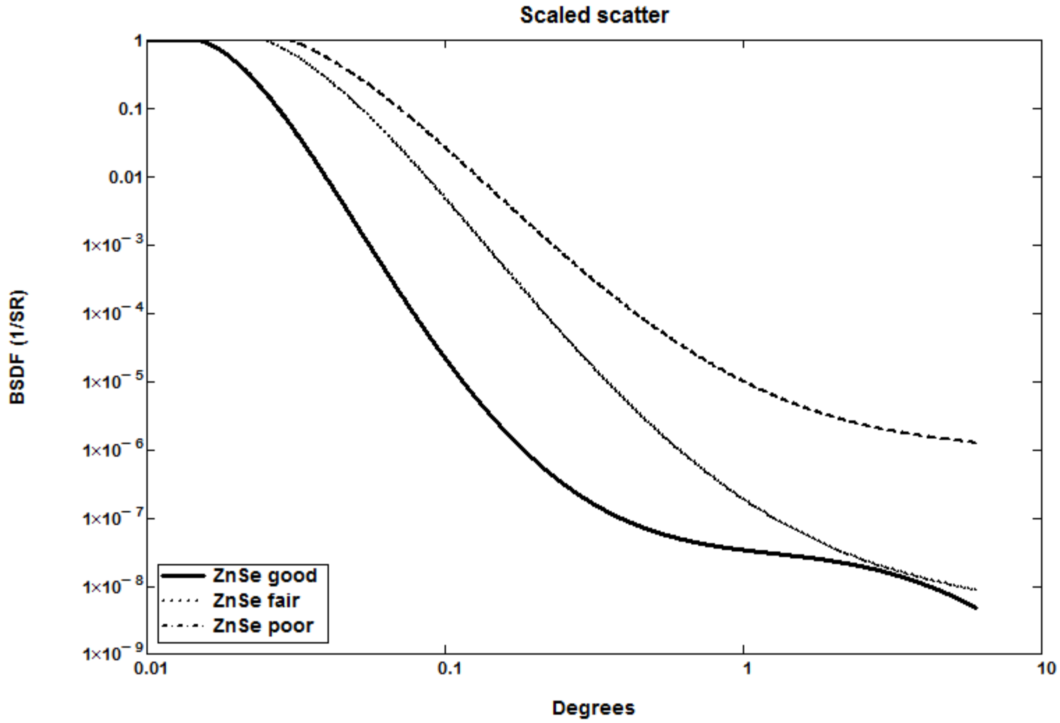

Figure 4 Bi-directional Scatter Distribution Function

Scatter spot size

The predicted results of scatter in one seeker example can be compared favorably with experimental results from another test[8]. In this report the results of laser dazzle against a HgCdTe focal plane array are shown in Fig. 5. The central area around the beam is saturated in a circular pattern, and the signal reduces with radial distance from the beam as shown in Fig. 6.

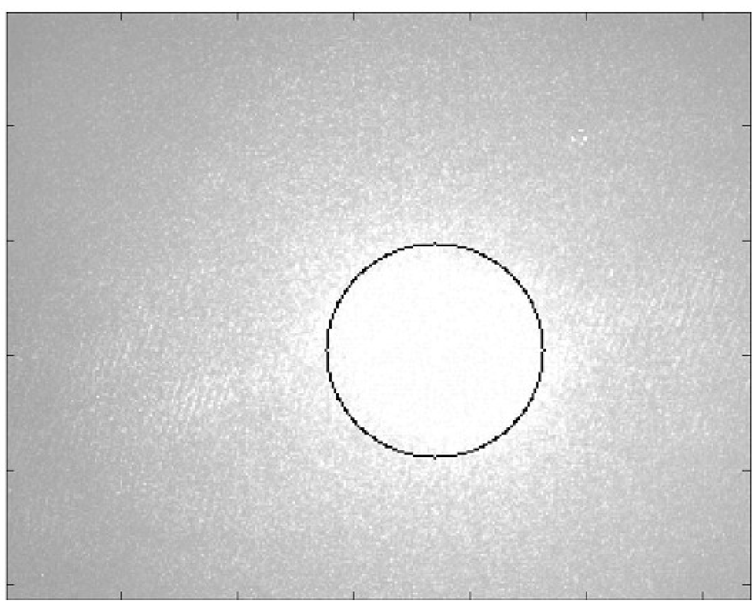

Figure 5 Dazzle against HgCdTe FPA

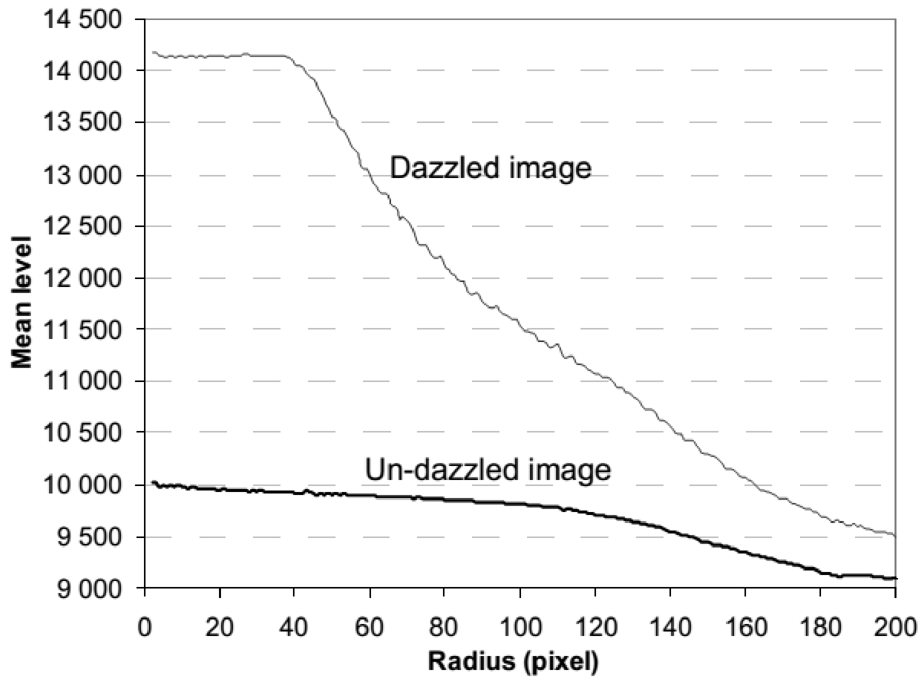

Figure 6 Dazzle energy vs. radial distance

It is clear that the laser signal does not saturate the entire focal plane array, and therefore signal is available in the FOV to allow home on jam.

In order to model the laser effect of a DIRCM we set a baseline laser performance of one-watt power output, and a beam divergence of 0.001 radians. The power output of one or two watts is indicative of what we may expect to see in an airborne laser jammer. It would be difficult to predict when a ten-watt laser may be available that is suitable for operational use. Another method to increase laser power incident on the seeker head is to reduce the beam divergence. Beam divergence is determined by beam quality and diffraction of the beam projector aperture, and in principle increasing the projector optics size can reduce divergence. The beam divergence must also be part of the overall DIRCM system design, since the beam must be spread wide enough to allow for alignment errors in the DIRCM pointing and tracking system. The DIRCM system design is a compromise between a narrow beam for increased jamming energy on the seeker, and a wider beam to allow for tracking error.

The plot of scattered energy across the focal plane shown above in Fig. 4 indicates there may be several orders of magnitude difference between the peak energy and the edge of the focal plane. If the scattered energy at the edge of the focal plane is below saturation level then the location of the beam in the FOV is still detectable.

To calculate laser irradiance on the focal plane, we use a set of parameters defined for the baseline seeker and other parameters related to an experimental prototype[9], the NATO ISS (Imaging Seeker Surrogate). Table 1 sets out the specification of the ISS. This experimental model is specifically developed to provide a realistic test bed representative of an operational seeker. Several studies of countermeasure effectiveness refer to this common baseline and this allows results to be combined. For example, the modelled scatter is that shown in Fig. 4 above.

Table 1: ISS specifications

Mechanical (Seeker Head)	
Forebody length	38 cm (to rear mounting bulkhead)
Forebody diameter	15 cm
Weight	< 25 kg
Pitch axis inertia	< 1.4 kg-m/s
Yaw axis inertia	< 1.4 kg-m/s
Optical	
Operating waveband	3.7 – 4.8 μm nominal
Transmission	50%
Field of view	4.4° x 4.4°
Field of regard	> 0.7 rad (radial)
Optical resolution	Rayleigh limit < 0.2 mrad
MTF (center)	> 0.75 of diffraction limit at 2 cy/mrad
(edge FOV/FOR)	> 0.62 of diffraction limit at 2 cy/mrad
Focal length	100 mm
Aperture	35.7 mm
Focal ratio (F#)	F/2.8
Detector angular subtense	0.3 mrad
Optical sightline rate	> 5 rad/s each axis
Optical sightline acceleration	> 3000 rad/s (aim)
Angular position accuracy	0.2 mrad
Dome material	ZnS Cleartran
Detector	
Type	3 – 5 μm focal plane array
Material	HgCdTe
Array size	256 by 256 elements
Array pitch	30 μm
Read-out technique	‘snapshot’ method with variable stare time
Cooling	Integrated Stirling cycle cooling engine
System Performance	
Frame rate	> 100 Hz
System NETD	< 100 mK
Target acquisition range	> 10 km for fast jet (approx. 250W/sr)
Environmental	
Maximum angular rate	650 °/s (pitch & yaw)
Max angular acceleration	1200 °/s^2 (pitch & yaw)

The effect of dazzle dependent on range is shown next in Fig. 7, where the laser power incident on the center and edge of the focal plane are modelled. The solid line is the power on the focal plane from the baseline one-watt laser. The dashed line is the power from this laser scattered to the edge of the FPA. The upper dotted line shows the power from a 100-watt laser.

With reference to the graph below, we can compare the signal levels at the focal plane from the laser versus the pixel saturation level. The ISS detector well capacity is 3.7×10^{7} electrons, which relates directly to the detector integration time. A saturation level using a typical integration time of 3.8 msec (implemented in the ISS), and a short integration time of 3.0 usec. correspond to saturation levels of 3.03×10^{-5} (W/cm^2) and 3.84×10^{-2} (W/cm^2) respectively.

The dashed line of the scattered energy from the one watt laser shows that the signal would be almost two orders of magnitude below saturation at 1000 meters range. This laser power would not saturate the entire focal plane, and would not defeat the seeker HOJ mode.

Damage levels

Also indicated with a horizontal line of triangle points is the nominal irradiance that would be required to damage the focal plane, around 10,000 (W/cm^2). This is derived from the Bartoli model[10], under continuous wave illumination.

This graph illustrates that even if we were to postulate a 100 watt laser which might produce enough scatter to saturate the entire FPA, this laser would deliver enough energy to damage the FPA at 1000 m.

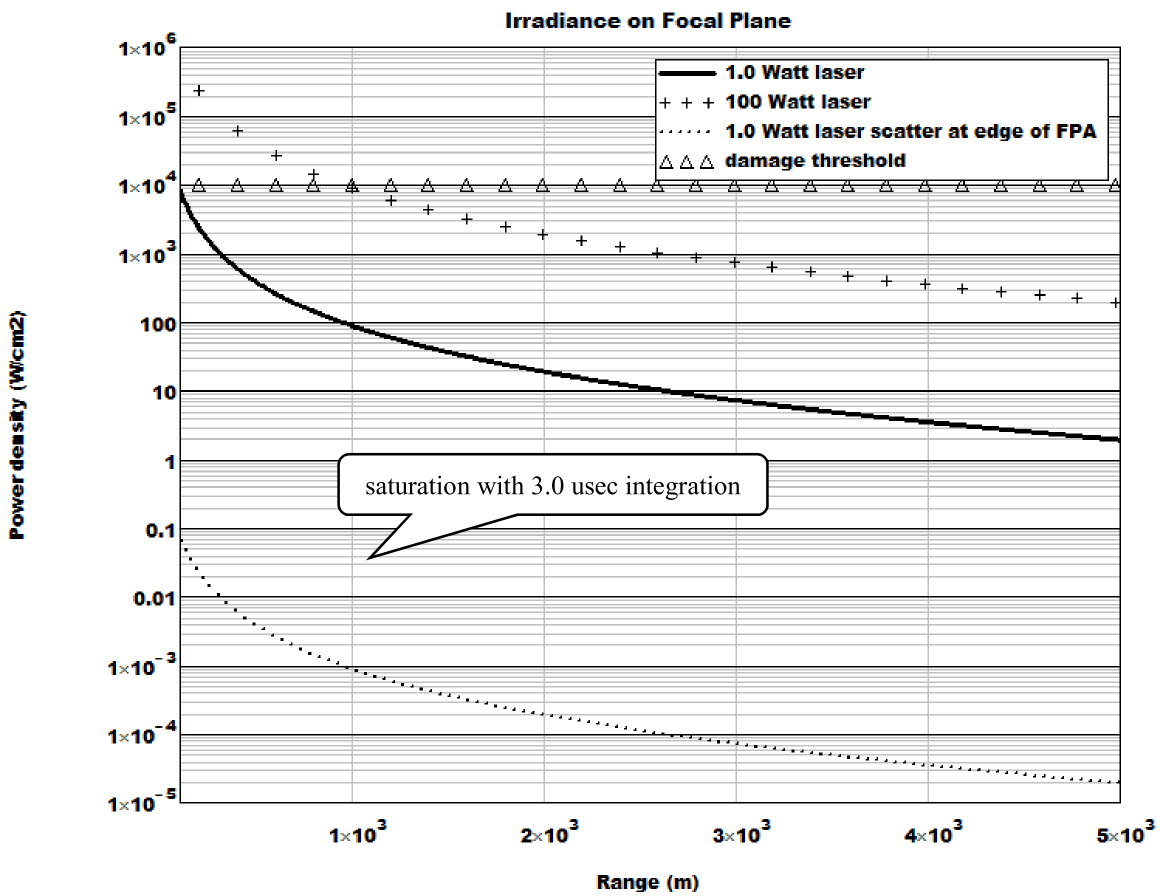

Figure 7 Incident energy vs. range

The ISS report[9] examined the size of the saturation area against the ISS, as shown in Fig. 8. The fact that the laser power had to be limited to avoid damage, while producing a saturated area les than 100 pixels in diameter, reinforces the fact that power for total FPA saturation is near the damage limit.

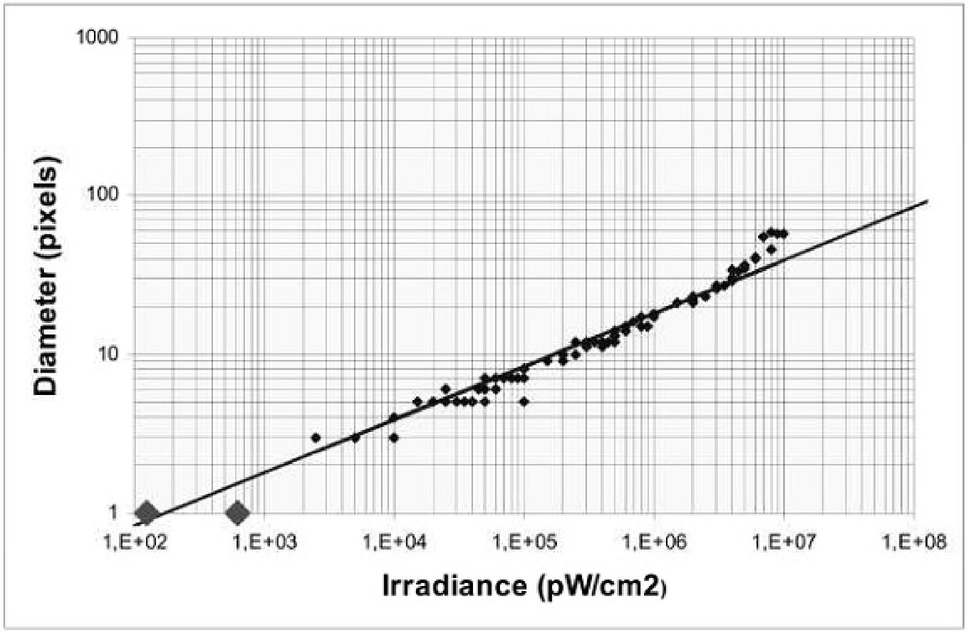

Figure 8 Spot size vs. laser power

The logical extension to laser power required to defeat imaging seekers is to consider the laser power required for damage. There are many publications[11,12] that discuss optical technologies that may protect against higher power lasers. This may be the future of imaging countermeasures. It seems that the competition between seeker design and laser power favors the laser, since practical laser power levels continue to make progress Protection techniques under investigation show some limiting effects, but high enough laser power can eventually overcome this technique. For example, in Ref. 12, a limiting material attenuates the beam above a certain level as shown in Fig. 9. The technique attenuates a little less than 70% of the laser energy, but this would not be sufficient if a damage laser three orders of magnitude more powerful would be used.

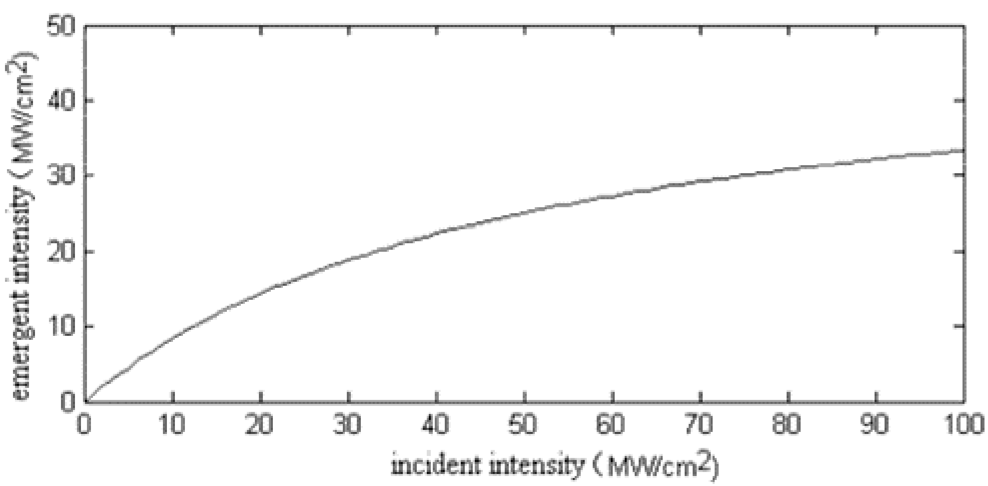

Figure 9 Higher power beam attenuation

4. CONCLUSION

The first section of this paper illustrated the capability of an imaging seeker to track as long as any target feature is detected, even in the presence of a large area masked by a jamming laser. The second section showed that the laser jamming signal does not saturate all of the focal plane and therefore the jammer (and target) location is still detectable, even when there is sufficient jamming energy to cause damage to the focal plane. It seems that the future countermeasures for imaging seekers are more like a DEW (Directed Energy Weapon) than a jammer, and such technology will soon be within reach[13]. Until DEW are used, the data shown above leads to the conclusion that simple laser jamming or dazzle will not be effective against imaging seekers.

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