IR Propagation in coastal Environment - Results of the VAMPIRA Trial

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ABSTRACT

The detection and tracking of missiles flying at a low altitude above the sea surface is one of the most urgent problems in ship self defence. These tasks are mainly managed by IR-Search and Track systems in the mid and long wave IR and by Radar systems. Both systems suffer severe limitations. The range efficiency of IR-systems is limited by atmospheric effects in the marine boundary layer.

The NATO AC/323 SET-56/RTG32 on “Integration of Radar and Infrared for Ship Self Defence” has investigated the radar and infrared synergism with respect to propagation in a coastal environment. In spring 2004, the members have held the “\textbf{VA}lidation \textbf{M}easurements for \textbf{P}ropagation in the \textbf{I}nfrared and \textbf{R}adar” (VAMPIRA). To have a direct comparison of RF and EO behaviour, several systems were set up at the same altitude above sea level (approx. 19 m).

This paper deals with the results of the IR measurements.

To simulate point-like targets at low altitudes, hot sources at different temperatures were installed onboard a small boat. Numerous mid and long-wave IR sensors made simultaneous measurements of the boat to analyse extinction versus range, maximum detection ranges and refraction effects. One efficient propagation model for the IR is IRBLEM (IR Boundary Layer Effects Model), developed by DRDC, CA. The measurements of the boat runs were compared to model predictions. Most of the measured data analyzed in this paper were gained by DDRE, DK. Based on the Danish results on the signal variations with range, a comparison with a Thermal Range Model for Point Target Detection (TRP) was done. TRP is an analytic model, which has been developed at FGAN-FOM, GE, to estimate the range performance of a point target detection system working in the infrared.

Keywords: Marine boundary layer, refraction effects, propagation model, VAMPIRA trial

1 INTRODUCTION

Propagation under atmospheric conditions with strong horizontal inhomogeneities has a severe impact on the radar and infrared sensor performance with respect of the detection and recognition of small targets. Individual onboard sensors are all differently affected by the environment, depending on height, frequency, bearing, range etc. Simultaneous exploitation of radar and infrared sensors and multi-sensor fusion can overcome these difficulties.

The RTG32 on “Integration of Radar and Infrared for Ship Self Defence” is a research study group under the Sensor and Electronics Technology Panel of the NATO Research Technology Agency (RTA) \cite{1}. The group has performed a
collaborative study to obtain insight into the radar and infrared synergism with respect to propagation in a coastal environment including horizontal inhomogeneity. In spring 2004 the group performed the VAMPIRA trial (Validation Measurements on Propagation in the IR and Radar) at the Eckernfoerde Bay in Northern Germany. Simultaneous radar and infrared measurements in a coastal environment at ranges up to and beyond the horizon were executed. The trial included all possible measurements that are required to characterise the environment (meteorology, sea state etc.). This paper deals with the experimental results of the IR measurements and their comparison with predictions of a propagation model IRBLEM. IRBLEM (IR Boundary Layer Effects Model) is a software package, which describes the overall atmospheric effects on passive IR detection and imaging in maritime environment. It was developed by DRDC (Defence Research Development Canada) [2]. The RF results are presented in paper 6364-11 of this Proceeding.

2 EXPERIMENT DESCRIPTION

The location of the trial was the Eckernförder Bay at the Baltic Sea. The sensors were installed at WTD71, Surendorf. To have a direct comparison of RF and EO behaviour, several systems were set up on a small hill. FGAN-FHR, GE, carried out RF measurements, the IR measurements were performed by FGAN-FOM, GE [3], DDRE, DK, Celar, FR, and CTNS, FR. All systems were at about the same altitude above sea level (approx. 19 m) (see Figure 1, left). The multi-purpose boat MZB Stollergrund (Figure 1, right) served as a target boat. To simulate point-like targets at low altitudes, several corner reflectors and hot sources were installed onboard Stollergrund.

![Figure 1: RF and IR systems at WTD 71, Surendorf, GE (left); Targets onboard Stollergrund (right).](image)

For the radar measurements trihedral reflectors were mounted at different heights and displaced by range. For the IR measurements two blackbodies were mounted on a boom on each side of the boat. Their height above the waterline was 5 m. The temperatures of the blackbodies were set to 100 and 200 °C. Moreover, the hot exhaust of the boat at 11 m amsl served as an IR source. The boat was instructed to perform straight inbound and outbound runs. A GPS unit was installed on the boat to determine its location throughout the experiments. The RF and IR systems made simultaneous measurements on the boat to analyze extinction versus range, maximum detection ranges and refraction effects. Altogether, 24 runs were achieved during day and nighttime. A list of all runs is given in Table 1.
<table>
<thead>
<tr>
<th>Run</th>
<th>Inbound</th>
<th>Outbound</th>
<th>Date</th>
<th>Start UTC</th>
<th>End UTC</th>
<th>ASTD (°C)</th>
</tr>
</thead>
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<tr>
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<td></td>
<td>March 25</td>
<td>09:30</td>
<td>11:30</td>
<td>-2.5</td>
</tr>
<tr>
<td>2</td>
<td>I1</td>
<td></td>
<td>March 25</td>
<td>13:08</td>
<td>14:14</td>
<td>-1.24</td>
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<tr>
<td>3</td>
<td>O2</td>
<td></td>
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<td>14:54</td>
<td>15:58</td>
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<tr>
<td>4</td>
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<td>12:40</td>
<td>-2.2</td>
</tr>
<tr>
<td>5</td>
<td>I2</td>
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<td>March 26</td>
<td>13:46</td>
<td>14:42</td>
<td>-1.66</td>
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<tr>
<td>6</td>
<td>O4</td>
<td></td>
<td>March 27</td>
<td>14:00</td>
<td>15:14</td>
<td>0.2</td>
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<td>7</td>
<td>I3</td>
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<td>March 27</td>
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<td>18:00</td>
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<td>8</td>
<td>O5</td>
<td></td>
<td>March 27</td>
<td>18:08</td>
<td>19:17</td>
<td>0</td>
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<td></td>
<td>March 27</td>
<td>20:00</td>
<td>21:19</td>
<td>0.47</td>
</tr>
<tr>
<td>10</td>
<td>O6</td>
<td></td>
<td>March 29</td>
<td>16:52</td>
<td>18:18</td>
<td>0.6</td>
</tr>
<tr>
<td>11</td>
<td>I5</td>
<td></td>
<td>March 29</td>
<td>18:45</td>
<td>19:56</td>
<td>2.57</td>
</tr>
<tr>
<td>12</td>
<td>O7</td>
<td></td>
<td>March 29</td>
<td>20:23</td>
<td>21:36</td>
<td>1.2</td>
</tr>
<tr>
<td>13</td>
<td>I6</td>
<td></td>
<td>March 29</td>
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<tr>
<td>14</td>
<td>O8</td>
<td></td>
<td>March 31</td>
<td>00:34</td>
<td>01:31</td>
<td>0.4</td>
</tr>
<tr>
<td>15</td>
<td>I7</td>
<td></td>
<td>March 31</td>
<td>01:55</td>
<td>03:27</td>
<td>0.7</td>
</tr>
<tr>
<td>16</td>
<td>O9</td>
<td></td>
<td>March 31</td>
<td>22:03</td>
<td>23:10</td>
<td>0.3</td>
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<tr>
<td>17</td>
<td>I8</td>
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<td>23:30</td>
<td>01:02</td>
<td>0.9</td>
</tr>
<tr>
<td>18</td>
<td>O10</td>
<td></td>
<td>April 01</td>
<td>01:49</td>
<td>02:54</td>
<td>-0.2</td>
</tr>
<tr>
<td>19</td>
<td>I9</td>
<td></td>
<td>April 01</td>
<td>03:31</td>
<td>04:30</td>
<td>0.12</td>
</tr>
<tr>
<td>20</td>
<td>O11</td>
<td></td>
<td>April 01</td>
<td>05:13</td>
<td>06:23</td>
<td>-0.4</td>
</tr>
<tr>
<td>21</td>
<td>O12</td>
<td></td>
<td>April 03</td>
<td>08:26</td>
<td>09:48</td>
<td>2.3</td>
</tr>
<tr>
<td>22</td>
<td>I10</td>
<td></td>
<td>April 03</td>
<td>10:10</td>
<td>11:02</td>
<td>0.94</td>
</tr>
<tr>
<td>23</td>
<td>O13</td>
<td></td>
<td>April 03</td>
<td>11:23</td>
<td>12:12</td>
<td>1.3</td>
</tr>
<tr>
<td>24</td>
<td>I11</td>
<td></td>
<td>April 03</td>
<td>12:22</td>
<td>13:45</td>
<td>0.99</td>
</tr>
</tbody>
</table>

*Table 1.* List of all boat runs during the VAMPIRA trial.

The propagation of optical radiation through the marine boundary layer is predominantly influenced by the vertical temperature gradient. The distance to the apparent horizon varies with the Air-Sea Temperature Difference (ASTD). In *Table 1* included are the ASTDs, which prevailed during the runs. At the beginning of the trial, the ASTD was negative, followed by a period of stable conditions (positive ASTD).

### 3 OVERVIEW OF THE METEOROLOGICAL CONDITIONS

A detailed analysis of propagation effects requires a complete set of meteorological data. Throughout the VAMPIRA trial, meteorological measurements were made at various locations. Most important parameters are the air and sea temperatures. Figure 2 (left) gives these temperatures measured at the sensor site during the trial (March 25 to April 4, 2004). At the beginning of the trial the air temperature was lower than the sea temperature (negative ASTD), the temperature increased and the ASTDs were mainly positive at the end of the measurement period. The data on absolute humidity are shown on the right hand side of Figure 2. The VAMPIRA experiment took place in cold and dry climate.
During most of the measurement period, the wind speed was relatively high for this area (6 – 15 m/s). As a result, the sea was very rough with high waves. An overview of the wind conditions is given in Figure 3.

4 ANALYSIS OF THE BOAT RUNS

The distance to the apparent horizon varies with the ASTD. One aim of the IR ship measurements was to analyze the maximum detection ranges under various atmospheric conditions. All IR and visible cameras took sequences of the boat until they lost sight of its hot exhaust. The height of the exhaust was 11 m above the water line. The camera systems were located at an altitude of 18.5 m. Considering straight line propagation, the maximum range of sight is approximately 27 km for the hot exhaust. For sub-refraction the maximum detection range would be less, for super-refraction more than this geometric limit. On each side of the boat, 5 m above the waterline, a blackbody source was mounted (see Figure 1, right). The geometrical detection limits of these blackbodies were – due to the sensor height – 23.5 km. The emitting areas of the blackbodies were 23 cm in diameter, each. They were set to a temperature of 100 °C (portside) and 200 °C (starboard). The measurements on the blackbodies were used for quantitative analysis of the extinction with range.

Several Cameras were set up at WTD 71. Their optical bands were ranging from the visible to the long-wave IR. One objective was to compare mid and long wave IR (MWIR and LWIR). The cameras of DDRE, DK, had the highest resolution and therefore they measured the longest detection ranges. DDRE used two focal plane array mid and long-wave IR cameras. Their specifications are found in Table 2. The IFOVs of the
DDRE systems are high enough to separate the blackbodies of the boat over a long distance. For a detailed analysis these camera results were chosen.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Mid Wave</th>
<th>Long Wave</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral band</td>
<td>3.56 – 4.14 µm</td>
<td>7.5 – 11 µm</td>
</tr>
<tr>
<td></td>
<td>(50%-values), cooled filter</td>
<td></td>
</tr>
<tr>
<td>Size of array</td>
<td>256 * 256</td>
<td>256 * 256</td>
</tr>
<tr>
<td>Detector material</td>
<td>InSb</td>
<td>CMT</td>
</tr>
<tr>
<td>Detector Pitch</td>
<td>30 µm</td>
<td>40 µm</td>
</tr>
<tr>
<td>Used Optics:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Focal length</td>
<td>500 mm</td>
<td>400 mm</td>
</tr>
<tr>
<td>• F Number</td>
<td>2.6</td>
<td>2.0</td>
</tr>
<tr>
<td>• Aperture (diameter)</td>
<td>0.19 m</td>
<td>0.20 m</td>
</tr>
<tr>
<td>• IFOV</td>
<td>0.06 mrad</td>
<td>0.1 mrad</td>
</tr>
</tbody>
</table>

Table 2. Main characteristics of the MWIR and LWIR cameras used by DDRE.

4.1 Analysis on the detection ranges

The detection ranges measured by the Danish systems in mid- and long-wave IR are given in Figure 4 (left). Next to the diagram (Figure 4, right) the prevailing visibilities are shown (for the run numbers see Table 1). At the beginning and in the end of the measurement period, the visibility was quite good. The visibility decreased very much during the middle of the trial, when absolute humidity was also quite high. LWIR is very much influenced by atmospheric conditions. If the visibility is low, the detection in the LWIR is less than that of MWIR. Whereas, during good visibility conditions, the detection ranges in mid and long wave IR show not much differences.

For the first five runs (March 25 and 26) the air temperature was lower than the water temperature causing sub-refraction: The detection range was shorter than the geometrical limit (GOS = 27 km). Figure 5 gives the results of the IRBLEM ray tracing calculations for the outbound runs during these days. Marked is the zone in which mirages occur. The rays do not reach the geometrical limit. In case of strong sub-refraction (run 1 and 4, ASTD = +2.5 °C and -2.2 °C, respectively) the maximum intervision range is about 4 km shorter than the horizon. For run 3 with an ASTD of -0.9 °C the detection of the hot exhaust is about 2 km less than the horizon. The measurements of the maximum detection ranges under sub-refractive conditions (see Figure 4) are very well predicted by the model.
During the outbound runs on March 25 and 26, mirages of the blackbodies were observed. Figure 6 gives an impression of the mirage in mid- (left) and long-wave (right) IR. Both images were taken by DDRE on run 4 (Outbound O3).

For runs 6 to 24, the ASTD was positive most of the time. Super-refraction on these days led to an extension of the detection range beyond the geometrical limit. According to weather conditions and system parameters, the detection exceeds the geometrical limit by 10 km. Figure 7 shows the detection ranges versus the ASTD. For equal ASTD the detection range varies with wind speed: high wind speeds lead to shorter detection ranges.
The peak signals of all outbound runs have been analyzed. The peak average signal versus range is plotted in Figure 8 for two outbound runs: one sub-refractive case with an ASTD of -2.2 °C and one super-refractive case for an ASTD of +2.3 °C. Figure 8 shows the results for the hot blackbody (200 °C) in mid- (left) and long-wave (right) IR.

![Figure 8](image)

The results of March 26 show an increase of the signal in the mirage zone (16 – 19 km) as predicted by IRBLEM (compare Figure 5). The maximum detection range (19 km) calculated by the model is verified. In super-refractive conditions, observation is not limited by the geometric horizon. On the other hand it leads to a loss in transmission. The signal drops significantly beyond the geometric horizon. The MWIR system observed the hot blackbody up to 30 km, which is 7 km more than the geometric horizon.

4.2 Analysis on the radiance of the two blackbodies

For the investigation of the blackbody irradiance, the signal measured in the mid- and long-wave IR has been analyzed. The variations of the signal with respect to range correspond to the incident radiant flux $\Phi_{\text{eff}}(R)$ upon the detector element.

$$\Phi_{\text{eff}}(R) = \tau_{\text{opt}} \cdot A_{\text{opt}} \cdot \Delta E_{\text{eff}}(R)$$

(1)

With:

- $R$: range from the sensor to the target
- $\tau_{\text{opt}}$: transmission of the camera optic
- $A_{\text{opt}}$: area of the entrance pupil
- $\Delta E_{\text{eff}}(R)$: effective difference of the target and background irradiance

$$\Delta E_{\text{eff}}(R) = \frac{A_T}{R^2} \cdot \tau_{\text{eff}}(R) \cdot \int \Delta L(\lambda) \cdot R_b(\lambda) d\lambda$$

(2)

- $A_T$: target area
- $\tau_{\text{eff}}(R)$: effective transmittance of the atmosphere
- $\Delta L(\lambda)$: difference of the target and background radiance
- $R_b(\lambda)$: normalized spectral responsivity of the detector

The effective transmittance is the cumulative transmittance of molecular transmittance, aerosol transmittance, and the refractance $\rho$ calculated by IRBLEM.

$$\tau_{\text{eff}}(R) = \tau_{\text{mol}} \cdot \tau_{\text{aer}} \cdot \rho$$

(3)
In a first approach, the background is taken as a blackbody of ambient temperature. The spectral difference of the target and background radiance is then given by:

$$\Delta L(\lambda) = \varepsilon_T \cdot [L_{BB}(\lambda, T_T) - L_{BB}(\lambda, T_B)]$$  \hspace{1cm} (4)

with:

- $\varepsilon_T$: target emissivity
- $T_T$: target temperature
- $T_B$: background temperature

The measured signal $S(R)$ can be compared to the model prediction:

$$S(R) \cdot R^2 \sim \tau_{\text{eff}}(R) \cdot \Delta L_{\text{eff}}$$  \hspace{1cm} (5)

with:

$$\Delta L_{\text{eff}} = \int \Delta L(\lambda) \cdot R_{\text{eff}}(\lambda) d\lambda$$  \hspace{1cm} (6)

For simplicity reasons the values in Equation (5) are mentioned apparent radiant intensity. A comparison of model and measurement is done for the results of the Danish systems.

Based on the Danish results on the signal variations with range, a comparison with the Thermal Range Model for Point Target Detection (TRP) model was done. TRP is an analytic model which had been developed at FGAN-FOM to estimate the range performance of a point target detection system working in the infrared [4]. Sub-models consider the electro optical transfer from the source (point target) to the sensor output. Input data of TRP are target and background radiance, atmospheric transmission and sensor parameters. One of the results of the TRP computation is the Signal-to-(Detector)-Noise-Ratio and the spatial distribution of the target signal at the sensor output.

The comparison of measured $S(R) \cdot R^2$ and modeled $\tau_{\text{eff}}(R) \cdot \Delta L_{\text{eff}}$ data is presented in Figure 9, according to the method explained before (Equation (5)). Plotted are the values for the hot (200 °C) and cold (100 °C) point source. The effective transmittance in the two spectral bands was calculated for the prevailing meteorological conditions by IRBLEM. For a detailed analysis and comparison with IRBLEM predictions the following four runs were selected: March 25 (run O2), March 26 (run O3), March 29 (run O6), and April 3 (run O12).

The measured signals correspond well with the predictions, based on the spectral radiance of the blackbody sources and the spectral transmission versus range. Only in the mirage zones (run O2 and O3) the measured signal raises to much higher values than expected by the model.

The Signal-to-Noise-Ratio on a single detector element is given by:

$$\left(\frac{S}{N}\right)_{BP} = \Phi_{\text{eff}} \cdot D_{\lambda_p}^* \cdot \sqrt{\frac{2 \cdot \tau_{\text{int}}}{A_D}}$$  \hspace{1cm} (7)

with:

- $D_{\lambda_p}^*$: peak detectivity of the detector element
- $\tau_{\text{int}}$: integration time of the detector
- $A_D$: size of the detector element
Figure 9. Comparison of measured and modeled apparent radiant intensity (see Equation (5)).
Considering a homogeneous background this value can be compared to the Signal-to Background-Ratio extracted from the recorded sequence. This was done for two sequences in the MWIR: run O3 on March 26 and run O12 on April 3. The results are presented in Figure 10.

![Figure 10](image1.png)

Figure 10. TRP calculation on Signal-to-Noise-Ratio in comparison with the measured Signal-to-Background-Ratio. Left for March 26, right for April 3.

The calculations predict the measured SNR values quite well. Again, the rapid increase of signal in the mirage zone is not reproduced by the model.

5 CONCLUSION

An analysis of the maximum detection ranges in the infrared under different atmospheric conditions was done. The experiment was performed in cold waters, in the Baltic Sea in Spring 2004 (VAMPIRA). MWIR and LWIR cameras were set up approximately 18.5 m above the water level recording sequences of an outbound going boat. The boat was equipped with a blackbody source at 5 m altitude. A complete set of meteorological parameters was measured. The signal decrease with range was analysed. We compared our results to the atmospheric IR Boundary Layer Effects Model (IRBLEM, DRDC, Canada) and to the Thermal Range Model for Point Target Detection (TRP, FGAN-FOM, Germany).

The VAMPIRA trial showed great variety of meteorological situations. The Air-Sea-Temperature-Differences ranged from -2.5 to +2.5 °C. The transmission in the long wave IR was superior to that in the mid wave IR.

For sub-refractive conditions, the maximum detection range is similar for all systems, regardless of waveband and camera resolution. IRBLEM predictions show good accordance to the measurements: the beginning of mirage zones and the maximum detection ranges are given within an accuracy of 1 km, whereas, the increase of signal in the mirage zone is measured to be much stronger than predicted by the model. According to weather conditions, the detection exceeds the geometrical limit by 10 km. The maximum detection range varies very much with wind speed: high wind speeds lead to shorter detection ranges. Depending on the visibility, LWIR detects as far as MWIR (in good visibility) or is inferior to MWIR (in low visibility).

REFERENCES