SHIP INFRARED DETECTION/VULNERABILITY

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ABSTRACT

The IR contrast of ships at sea is of importance for those who want to detect or identify the ship and for those who worry about this. This IR contrast is determined by a large number of parameters. Of course temperatures of the ship's structure and those of the ambient sea and air are important, but also the reflection properties of the sea background and the radiance distribution of the surrounding sky. The dynamic behaviour of the temperature of a surface element of the ship is governed by the local heat balance. The reflection properties of the sea are governed by the sea state.

Modelling of these phenomena appears to be very complicated and the accuracy of the results is rather course in many cases. Therefore, at FEL-TNO an approach has been followed, using a package of sensors on board of the ship, giving radiometric or real temperature data of specific surface elements and background radiometric data.
These data are taken into a PC system, providing radiant contrast data in any IR-spectral band. Taking into account atmospheric propagation effects and sensor performance, a simplified detection model provides range data in the form of polar diagrams with elevation as parameter. The commander of the ship uses the system as an IR Tactical Decision Aid (TDA), as he may decide upon countermeasures, if the vulnerability of his ship exceeds certain limits.

1. INTRODUCTION

Since many years ship users are worried about the threat of IR anti-ship homing missiles. Therefore many research programmes have been carried out in different nations in order to quantify this threat. The programmes followed different approaches like simple temperature measurements, or more sophisticated imaging sensors flying around, or just modelling in a theoretical way.

In all cases a great variety of IR contrast has been found. One of the bigger experiments, carried out in a multinational exercise in Livorno[1], showed clearly the variation in contrast with changing weather, aspect angle, background, time of the day and range. An example is given in figure 1, showing a positive IR ship contrast for one day and a negative contrast for a similar ship the next day due to drop in the air temperature of 5 degrees C.

This is just one example of a contrast effect that may be observed but sometimes not expected on board of the ship. This may be due to poor weather recording sensors on board of the ship. By comparison of weather data from 7 ships in the same area, air temperature differences of 8 degrees C were noted at a certain time.

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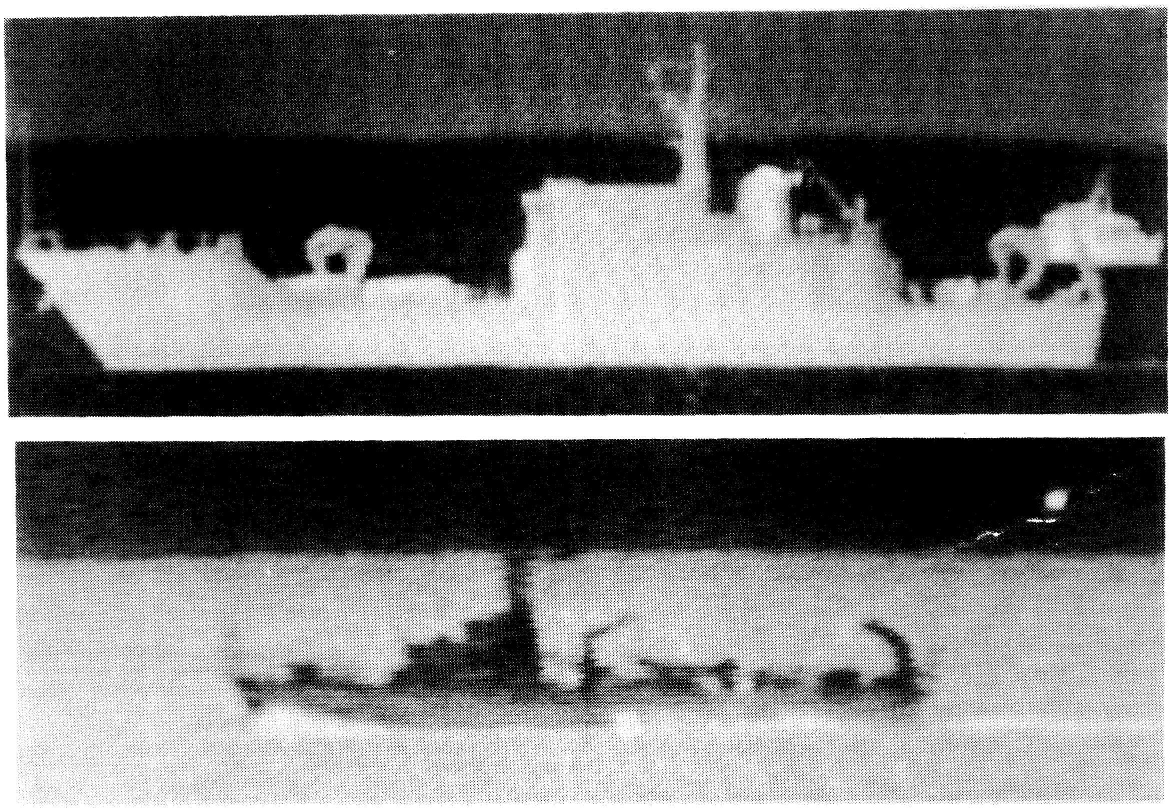


Fig. 1. IR imagery of ship in Livorno during SIVEX trials, showing contrast inversion from one day to next day due to drop in air temperature.

Furthermore the standard sensor package on board is inadequate to provide the required data for any prediction model. The former IR ship-contrast model, based upon heat transfer equations[2] needs accurate air temperature and -speed like the IR sea-sky background model.[3] In many occasions therefore thermocouple-sensors were mounted on board in order to provide the data with the required accuracy.

During the SIVEX trials a radiometric sensor package has been installed on board of the experimental ship Rosetti.[4] Data have been used to calculate the radiant contrast of the ship, to be compared with radiometric measurements from shore-based and airborne sensors. In this case the background radiometric data were obtained from a calibrated shore based sensor.[5] It was found that the discrepancy between predicted- and measured polar diagram of the IR contrast was too big due to background errors.

It was therefore decided to set up another experiment, based upon a more complete package of sensors, including a background sensor, measuring sea and sky background from the ship itself. This experiment was carried out on board of a Netherlands ship, making an exercise for about 2 months in various geographic locations. The set-up and results of this experiment will be described in the following chapters.

2. SHIP IR CONTRAST PHENOMENA

IR contrast complexity, as mentioned in the introduction is due to a number of physical phenomena:

. solar heating, determined by solar absorbivity
. internal heating sources
. wind cooling, determined by convective heat transfer
. cold sky cooling, determined by apparent sky temperature
. sea surface reflection of cold sky/cloud background
. sunglint at the sea surface
. selective radiation from exhaust gases
. sea clutter pattern
. spectral response curve of sensor
. spatial resolution of sensor
. range and aspect angle (azimuth and elevation).

These phenomena are in general difficult to model due to the complex ship geometry. The resulting models are complex and require a large amount of completing time. Therefore simplification of the geometry of the ship and provision of input data from special on board sensors is a logical step.

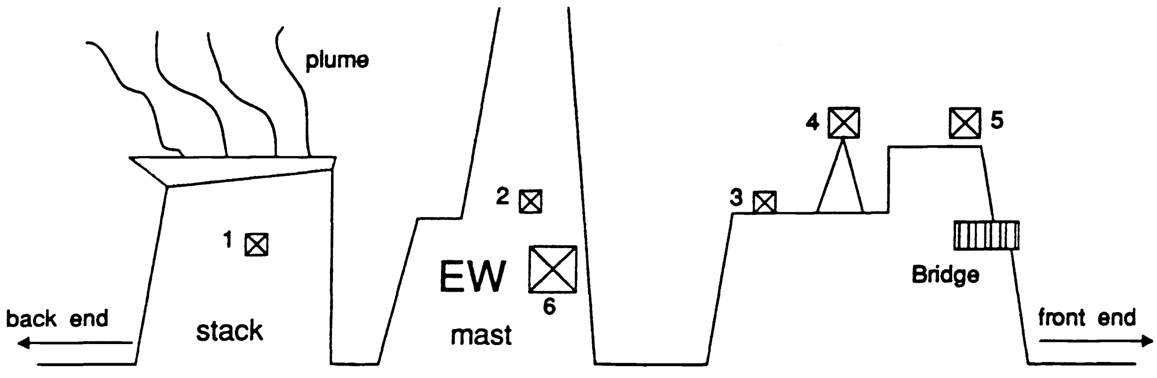
Solar effects can be tremendous, especially for top decks, which general have greater absorbivities. Cold sky cooling starts already before sunset but is countered by water condens and wind effects. Exhaust gas emission peaks in CO_2 emission regions around 4,2 μm and mostly extinguishes at ranges 3-5 km. The most difficult phenomena are the sea surface reflection. The difficulty arises as the sea state values are unreliable and do not determine the reflection properties precisely. Furthermore sea reflection concerns the sky background up to elevations of 45° or more. Therefore special attention has been spent to this topic. The other phenomena are somewhat easier to model.

3. ON BOARD SENSOR PACKAGE

Two questions arise upon the sensor package: which type of sensors and where to put them. The second question is mostly determined by the geometry of the ship. In the case of the Royel Netherlands Navy, we have only a few types of ships, one of the most frequent occurring is the Standard Frigate. Knowing a lot on the IR imagery of this ship, we found that only a limited number of positions were really relevant. These places are indicated in fig. 2.

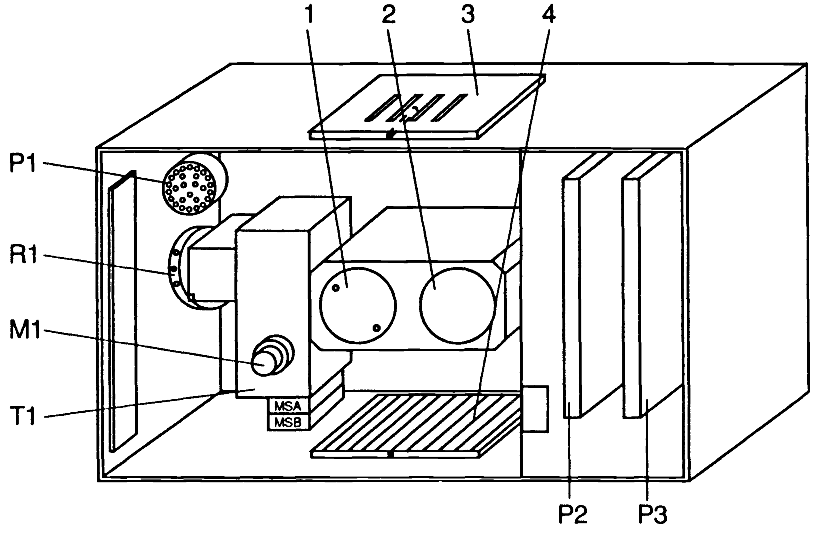
The types of sensors are in general the following:

. thermocouples or thermistors
. radiometric sensors in selected spectral band (8-14 μm) wide field of view, close range, high sensitivity
. double radiometer, observing port and starboard side sea- and sky background radiance (see fig. 3.)
. weather station, including solarimeter, pyrgeometer
. global positioning system (GPS).



1 = port and SB thermocouple; 2 = port and SB radiometer and thermocouple, 3 = deck radiometer and thermocouple, 4 = double radiometer, 5 = weather station + GPS antenna, 6 = "radarhut" with 2 PC's and data acquisition.

Fig. 2 Locations of sensors on board



1 Port sensor
2 SB sensor
3 Reference plate 1
4 Reference plate 2

P1 26 pole plug
P2 Signal processing
P3 Motor control

M1 Motor
T1 Tacho
R1 Potentiometer

Fig. 3 Schematic view of double radiometer

The double radiometer was especially developed and uses 1 mm diameter thermopile detectors with 60 mm diameter receiving parabolic mirrors. The unit contains internal calibration using blackbodies with Pt. resistors. The field of view of this radiometer of about 1° is sufficient to resolve the background dips above and below the horizon. The spectral band of this radiometer is 8-14 μm at this moment but might be switched to both the 3-5 and 8-14 μu bands in the future if required . All data are taken by a data acquisition PC. The processed data are transferred to a second PC, running the IRTDA with the different models.

4. RANGE MODELS

The detection range R_D of a point source is generally determined by the formula:

$$R_D = \sqrt{\frac{\Delta W_0 * \tau(R_D)}{K * NEI}} \qquad (1)$$

in which ΔW_0 is the radiant intensity contrast in W/ster, $\tau(R_D)$ the atmospheric transmission over the detection range R_D, NEI the noise equivalent irradiance in W/m^2 and K the signal to noise ratio for a certain detection probability. For simplicity the values of τ as a function of range are either plotted in tables, given the weather data at a certain time, or even more simple in certain spectral bands a simple extinction coefficient can be taken. The next step is to search for that value of the function I_0:

$$I_0 = \frac{R^2 * K * NEI}{\Delta W_0} \qquad (2)$$

that equals $\tau(R_D)$ by varying R.

As most of the time the ship is not a point source, but larger than the value $R\Delta\varphi$, where $\Delta\varphi$ is the instantaneous field of view in one dimension, the formulae (1) and (2) have to be modified. Two cases will be considered here (assuming the ship having a block shape).

1) $R\Delta\varphi$ larger than the height h of the ship but smaller than the length of the ship. I_0 is changing into I_1:

$$I_1 = \frac{R * K * NEI}{\Delta W_1 * \Delta\varphi * h} \qquad (3)$$

in which ΔW_1 is the radiance difference for the ship's wall and the background (in W/m^2 ster). We note that I_1 is only linearly increasing with R, whereas in formula (2) I_0 increased with the square of R.

2) $R\Delta\varphi$ is smaller than the height h of the ship. I_0 is changing into I_2:

$$I_2 = \frac{K * NEI}{\Delta W_1 * (\Delta\varphi)^2} \qquad (4)$$

assumed that the instantaneous field of view $\Delta\varphi$ has square dimensions. The value of I_2 is independent of the range, so R_D follows simply from $\tau(R_D)$ equally I_2.

Complications appear if we consider port and starboard side from an elevation and both have different radiance contrasts. The formula are basically the same but more cases have to be considered separately.

More complication arises in case we consider the ship as being not a homogeneous block of height h and length l, but more complex in shape, containing a hot stack with a plume of spectrally selective gas-emission. In the extreme case one has to convolve the 2 dimensional point spread function over this complex 2 dimensional shape, taking into account the horizontal and vertical aspect angles.

In stead of entering this complexing, it is preferable to look to the required accuracy of the value of the range. In most cases 10% accuracy may be sufficient. This means that we can accept some simplifications. In our case the ship is approached by a block of rectangular shape and a point source, located at a certain distance above the center of the block and a certain radiant intensity. At short ranges the plume may dominate, but for this source a different extinction coefficient is assumed. Ranges are calculated following the lines as indicated in formulae (2), (3) and (4) but with more cases in geometry.

5. RESULTS OF EXPERIMENTS

First the spectral response of the radiometers has to be introduced. The detectors have a flat response between 3 and 14 micrometer. The applied filtertransmission is given in fig. 4.

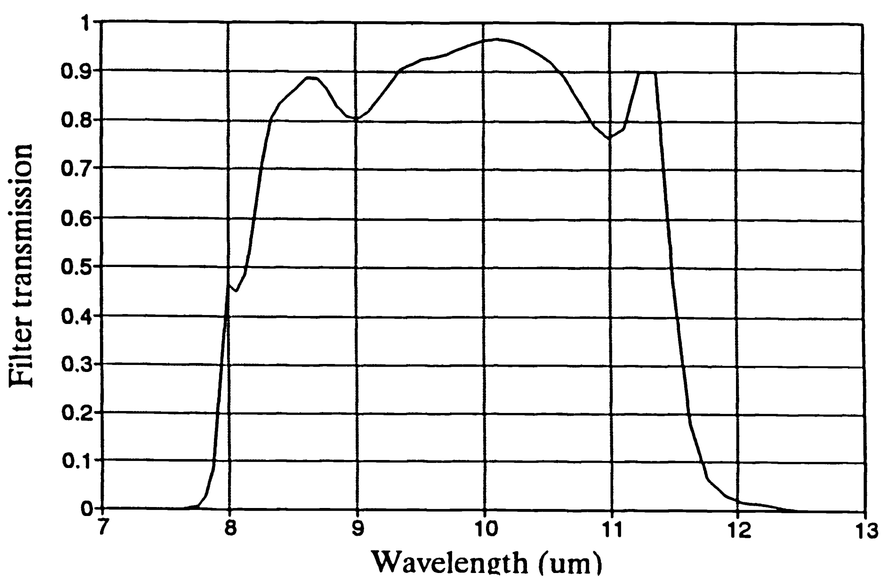


Fig. 4 Filter transmission for radiometers.

The 8-11,5 μm band corresponds to the spectral bands of modern 10 μm imagers. It is however a question how accurate the 3-5 μm band radiance can be predicted from the measured 10 μm band radiance, if surface emissivity and background radiances are given.

In our case the transfer from 10 μm radiance to apparent temperature, to real temperature and back to 3-5 μm radiance has been made with accuracies better than that required for the 10% error bar accepted for range.

An example of radiometric recording of the port-side, starboard-side and deck radiometers is given in fig. 5.

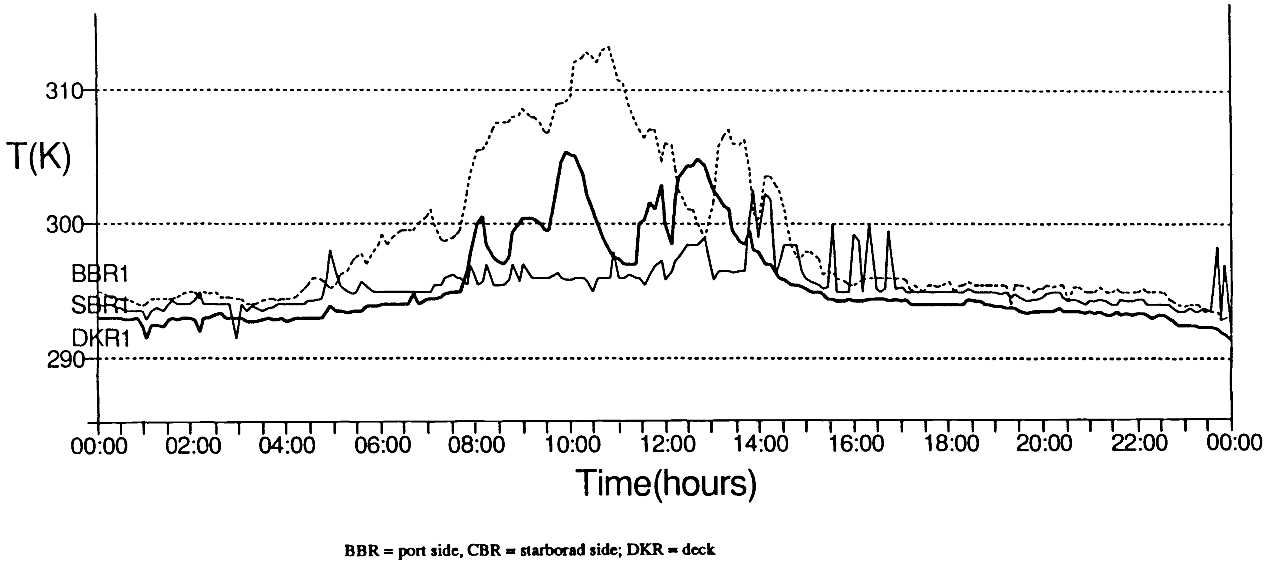


Fig. 5 Radiometer data for 08/10-1992.

The ship was cruising at a latitude of about 34° North and 30° East in the Mediterranean Sea. The air temperature was about 22°C in day time. The ship was cruising West, determined from the GPS system, with a speed of about 10 kts. Portside is heated to a maximum of 18°C above air temperature. The deck does not reach that temperature; starboard-side stays cool.

Data from the double radiometer are shown in fig. 6.

The curves show a strong decrease of apparent temperature for negative elevation angles (above the horizon). At the horizon an emission peak occurs due to atmospheric radiance. Both port- and starboardside come close to the air temperature of 293 K. For positive elevation angles sea reflection of cold clear sky occurs at early morning. The dip in apparent temperature is of the order of 4°C. Unfortunately the windspeed meter was broken at that time, so now sea state information was available. However the dip of 4°C suggest a low sea state.

An example of a polar diagram with range as function of aspectangle, obtained through the formulae and methodology given in the previous paragraph is given in figure 7 for a non-specific ship with a length of 130 m, widt 10 m and height 10 m. Plume and stack are included. Atmospheric extinction coefficient were calculated through Lowtran: 0,06 km^{-1} in the 3,4-4,1 μm band and 0,15 km^{-1} in the 8-12 μm band for 0° elevation angle. For this angle it is assumed that the sensor sees the ship on the horizon. The NEI resp. K values were assumed to be 10^{-8} W/m^2 resp. 10 for both spectral bands. For higher elevations the extinction coefficient decreases; for 5° a factor 1,5. The instantaneous field of view of the sensor is 5 mrad. Starboard side detection range exceeds well the portside range due to the solar heating effect. Range values correspond well with the values, found by real sensors in these types of scenarios.

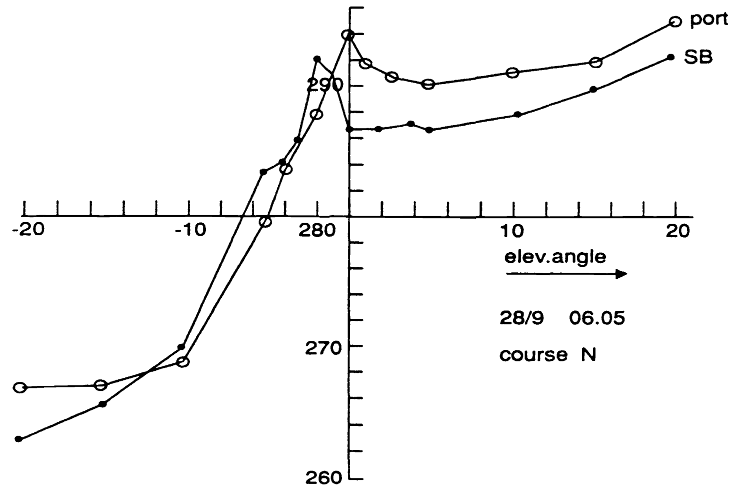


Fig. 6 Example of raw data from double radiometer on 28/9-1992.

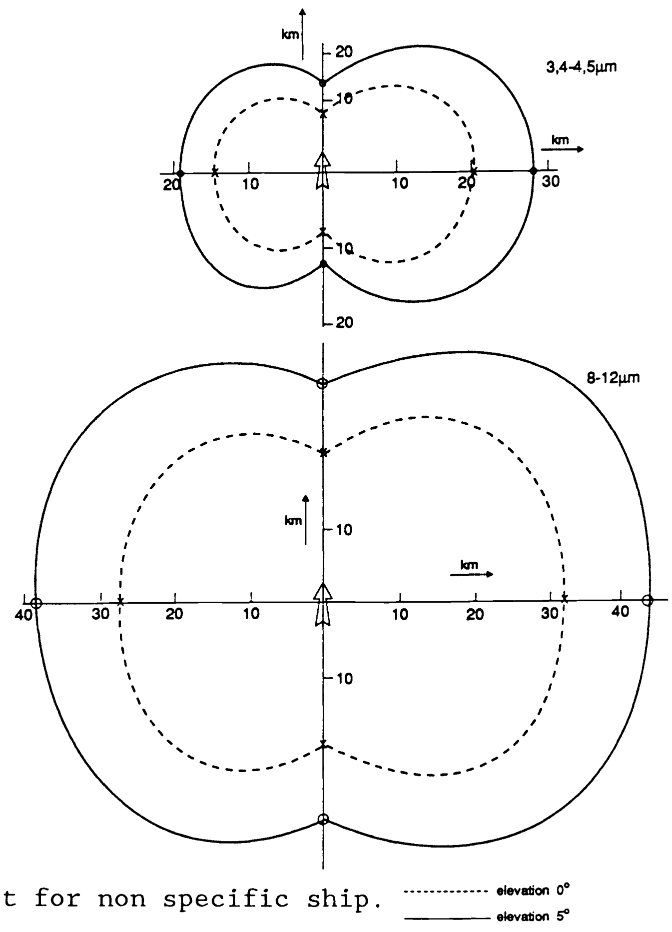


Fig. 7 Range plot for non specific ship.

6. DISCUSSION, CONCLUSION

The methodology for determining the ship's IR vulnerability described in this report, is based upon the following items:

. use of realistic background radiometric data
. use of radiometric- or thermocouple sensors
. use of special weather station
. use of simplified geometric model
. use of simplified atmospheric model.

It has been proved that the methodology provides the detection range data with sufficient accuracy for a large variety of situations. This is of importance as it is known that IR ship contrast is greatly variable.

Some improvements have to be made. Integration of ships data like engine power, position system, roll motion could improve the computations and simplify the sensor package. Introduction of a LIDAR sensor for atmospheric probing and a sea state meter for sea reflectivity might increase the accuracy, however also the cost.

It is finally recommended to further validate the methodology with experiments, where calculated ranges are directly compared to measured ranges. Such an opportunity is scheduled for autumn 1993 in the Netherlands with the so called MAPTIP trial, organized by NATO group AC/243 (Panel 4/RSG.8).

7. REFERENCES

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