Measurements of IR propagation in the marine boundary layer during the September 2011 SQUIRREL trial

Lars Trygve Heen, Arthur D. van Rheenen, Eirik Glimsdal

Lars Trygve Heen, Arthur D. van Rheenen, Eirik Glimsdal, "Measurements of IR propagation in the marine boundary layer during the September 2011 SQUIRREL trial," Proc. SPIE 8535, Optics in Atmospheric Propagation and Adaptive Systems XV, 853506 (17 December 2012); doi: 10.1117/12.981644

Event: SPIE Remote Sensing, 2012, Edinburgh, United Kingdom

Measurements of IR propagation in the marine boundary layer during the September 2011 SQUIRREL trial

Lars Trygve Heen*, Arthur D van Rheenen, Erik Brendhagen
Norwegian Defence Research Establishment (FFI), PO Box 25, N-2027 Kjeller, Norway

ABSTRACT

A multinational field trial (SQUIRREL) was performed at the Eckernförder Bucht, in the Baltic Sea, during September 2011 to study infrared ship signature and atmospheric propagation effects close to the sea surface in a cool environment. In this paper mid-wave infrared camera recordings of ship-mounted sources are analyzed. The camera was positioned about 6 m above mean sea level. Several meteorology stations - mounted on land, on a pier and on a buoy - were used to characterize the propagation environment, while sensor heights were logged continuously. Both sub- and superrefractive conditions were studied. Measurements are compared to results from an earlier field trial performed at Chesapeake Bay, in 2006, during warm and humid atmospheric conditions. The ship-mounted sources - two calibrated blackbody sources at 200 °C and 100 °C - were used to study contrast intensity and intensity fluctuations as a function of distance. The distance to the apparent horizon is also determined. Measurement results are compared to results from the IR Boundary Layer Effects Model (IRBLEM[§]), and good agreement is found.

[§]IRBLEM is proprietary to the Department for National Defence of Canada as represented by DRDC-Valcartier.

Keywords: Marine boundary layer, atmospheric optics, infrared, propagation, refraction, turbulence

1. INTRODUCTION

The part of the atmosphere closest to the sea surface, often referred to as the marine boundary layer, typically stretches from 0 m to about 50 m above sea level. In the marine boundary layer, large gradients in the vertical temperature and humidity profiles occur quite frequently, leading to several interesting propagation effects. In the visual and infrared (IR) regions of the electromagnetic spectrum, the propagation effects are dominated by the temperature profile, unlike in the radar region where the absolute humidity profile dominates. Thus, in the visual and infrared parts of the spectrum, one important parameter is the air-sea temperature difference (ASTD). The sign of the ASTD (for most instances) determines the sign of the curvature for rays propagating near the sea surface. Positive ASTD leads to rays being refracted towards the sea surface, a condition normally referred to as superrefraction, while negative ASTD leads to rays being refracted away from the sea surface, normally referred to as subrefraction.

The amount of turbulence is also influenced by the value of the ASTD parameter. The lowest degree of turbulence is accomplished (at least in theory) for near neutral conditions, or ASTD ≈ 0. The turbulence increases when the absolute value of the ASTD increases.

2. MEASUREMENT SETUP

A multinational measurement campaign (SQUIRREL) was performed at Eckernförder Bucht, near Kiel (Germany), in a corner of the Baltic Sea where Germany borders on Denmark, September 11 - September 23, 2011. Measurement teams from 13 nations, some with several teams, participated in the campaign. One goal of the campaign was to obtain infrared ship modeling validation measurements in cool conditions, while another was to perform infrared propagation measurements in the marine boundary layer under such conditions. Several measurement teams participated in each part of the trial. In addition to these IR experiments, measurements involving radar where performed at the same location, during the same period of time. The following sections give a brief summary of the measurement setup.

*For correspondence: lars-trygve.heen@ffi.no

Optics in Atmospheric Propagation and Adaptive Systems XV, edited by Karin Stein, John Gonglewski,
Proc. of SPIE Vol. 8535, 853506 · © 2012 SPIE · CCC code: 0277-786/12/$18 · doi: 10.1117/12.981644

2.1. Geographical aspects

Measurements were performed from a German Naval facility Laboratory field site located at Surendorf, on the south shore of the Baltic Sea. For propagation measurements, two black-body sources were mounted on the German research ship Mittelgrund. Mittelgrund started its runs ca 3 km from the shore, where the measurement teams were located, and sailed at a speed of 10 - 11 kts in a straight line away from the shore. After an hour the ship turned around, made sure the black bodies were radiating towards the shore, and sailed back towards shore.

Figure 1 summarizes the most important geographical aspects of the measurement area. North is up in the figure. A meteorological buoy was positioned near the measurement path, at a distance of about 6 km.

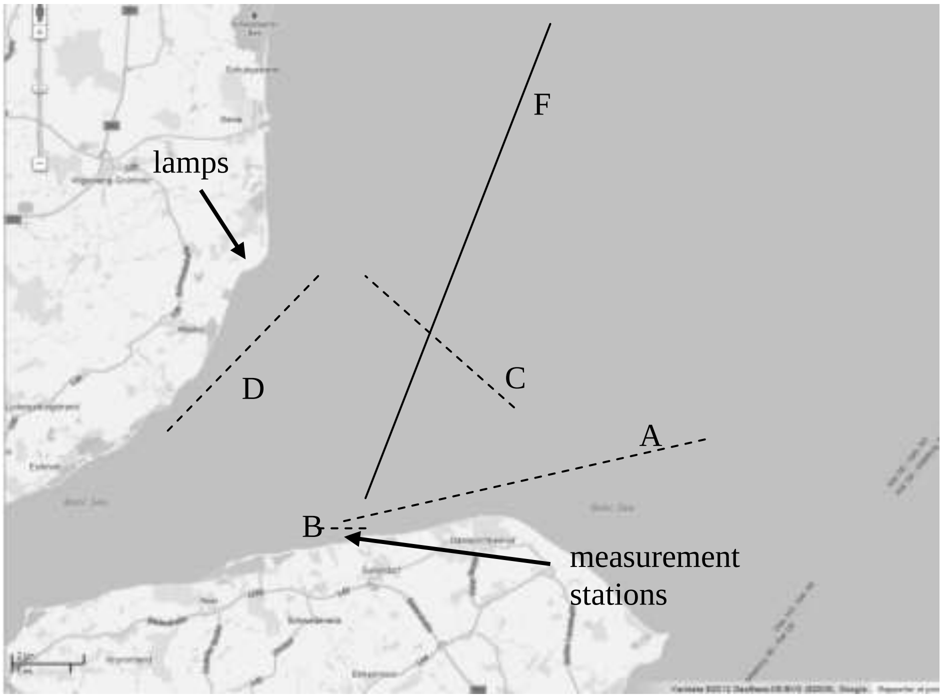

Figure 1. Map of the measurement area. The lines show the run geometries for different aspects of the trial: the solid line (F) denotes the path sailed by the Mittelgrund during propagation runs.

2.2. Sources

Two temperature-controlled blackbody sources with an effective diameter of 0.23 m radiating at 100 ^{o}C and 200 ^{o}C were mounted on the German research vessel Mittelgrund. The sources were mounted on horizontal booms, extending about 4 m from the vessels side, one at port (200 ^{o}C) and one at starboard (100 ^{o}C), at a height of about 4.9 m above the water line. After sailing out for an hour the vessel had covered about 20 km, at which point it turned around and started on the inward leg.

2.3. MWIR Camera

A Cedip Emerald focal plane array (FPA) infrared camera, sensitive in the 3 - 5 µm wave band, was the main sensor used during the Mittelgrund propagation experiments, see Figure 2. Some camera parameters can be found in Table 1. The height of the optical axes of the cameras was 6 m above sea level on average. The tidal variation during the propagation runs was about 0.2 m.

Figure 2. The Cedip MWIR camera used during the trial. The other, larger instrument in the image is a high-resolution radiometric FTIR instrument.

Table 1. Important camera characteristics

Spectral range	3 - 5 μm
Focal length	250 mm
Array size	640 x 512
Field of View (FOV)	$3.9^{o} \times 2.9^{o}$
Instantaneous FOV (IFOV)	100 μrad x 100 μrad

2.4. Sensor motion control

The camera was mounted on a tripod. Since Mittelgrund sailed along a straight line whose direction was very close to the length axis of the measurement container, it was not necessary to move the camera at all, and still keep the vessel and its blackbodies in view during its complete track. After the vessel completed its outbound leg, a calibration of the camera was undertaken with the help of two blackbodies. Upon completion of the calibration, the camera was aimed in the same direction as the ship heading, waiting until the vessel became discernible again.

2.5. Meteorology

Care was taken to accurately characterize the meteorological conditions. Several buoys were deployed, including an FFI buoy, see Figure 3. This buoy was equipped with PT100 sensors combined with relative humidity sensors at four heights up to 4 m above sea level, and also incorporated a sea temperature probe. The position of the trial buoys are also shown in Figure 1.

A pressure sensor mounted at a fixed depth at the pier allowed accurate recordings of water level as a function of time.

3. PROCEDURE

During the Mittelgrund propagation runs with blackbody sources (point source detection runs), the source signal was studied as a function of distance in mid-wave IR. In this way, signal transmission as a function of propagation distance was obtained.

Throughout, the contrast signal is used whenever signal strength is applicable. The contrast signal was obtained by defining a target box around the source (the target box was only as large as needed to enclose the source signal) and a background box of equal height next to the target box, and subtracting the average values in the latter box from the average in the former on a frame by frame basis, taking the size of the target box into account,

$$C = M_{tgt}\left(S_{avg} - B_{avg}\right) \qquad (1)$$

where C is the contrast signal, M_{tgt} is the number of pixels in the target box, S_{avg} is the average signal of the target box and B_{avg} is the average signal in the background box. For these runs, the background was the sky above the horizon at the same elevation as the source.

Figure 3. The FFI buoy at sea during the SQUIRREL trial.

The multi-purpose vessel Mittelgrund was equipped with two temperature controlled blackbodies with a diameter of 0.23 m. The temperature of the sources was held constant at 100 and 200 ^{o}C during runs. The position of the boat was measured with a GPS-unit, and thus, the measured signal strength as a function of distance can be correlated with Planck curves for the blackbody transmitted through an IRBLEM or MODTRAN model atmosphere. This comparison will not depend heavily on sea water temperature, as mainly the atmospheric amplification factor - the refractance - depends on the details of the ray curvatures.

The contributions to the measured contrast C can be deduced from the following equation,

$$C = \frac{\Omega_S}{\Omega_{IFOV}} K \int \left[N_{BB}\left(T, \sigma\right) - N_{BB}\left(T_{atm}, \sigma\right) \right] r_s\left(\sigma\right) \tau_{eff}\left(\sigma\right) d\sigma \qquad (2)$$

where $\Omega_S = A_k/R^2$ is the solid angle of the source, A_k is the source area, R is the distance, Ω_{IFOV} is the solid angle seen by one detector element, K is the camera constant (LSB/W/cm^{2}sr) incorporating several factors. $N_{BB}(T, \sigma)$ and $N_{BB}(T_{atm}, \sigma)$ are the spectral radiant intensity of the blackbody source and the atmosphere very close to the horizon, respectively, $r_s(\sigma)$ is the relative response of the camera, $\tau_{\mathrm{eff}}(\sigma)$ is the modeled spectral transmission of the atmosphere, possibly including a refractance contribution, and σ is the wave number. It should be noted that Equation (2) holds for the case that the solid angle of the source Ω_S is less than that seen by a single detector element Ω_{IFOV}, i. e. that all radiation emitted by the source is received by a single pixel. Real cameras are not perfect and as a result some radiation will be received by adjoining pixels. This has to be accounted for in the analysis. A spectral resolution of 5 cm^{-1} is obtained from IRBLEM. The contrast values are typically obtained by averaging over 100 frames.

4. RESULTS

Propagation results from the SQUIRREL trial will be presented. Where applicable, these results are compared with results from the SAPPHIRE trial in hot and humid conditions in Chesapeake Bay [1]. Several different aspects of propagation in the marine boundary layer were addressed during the SQUIRREL trials, here only a few will be covered.

4.1. Maximum range and source signal as a function of range

Recordings of the German multi-purpose vessel Mittelgrund with two mounted black bodies were made on four separate days as the ship made both outbound and inbound runs. Mostly, these runs took place during the night and early morning hours: 14 runs in total. Figure 4 shows examples of recordings made when the Mittelgrund was at 2.3 km, left-hand image, and 10.2 km, right-hand image, while on an outbound run. The black bodies extend out from the hull. The stack and exhaust are clearly visible as well as some of the running lights. At the longer distance some refraction effects are visible for the hottest black body (port side).

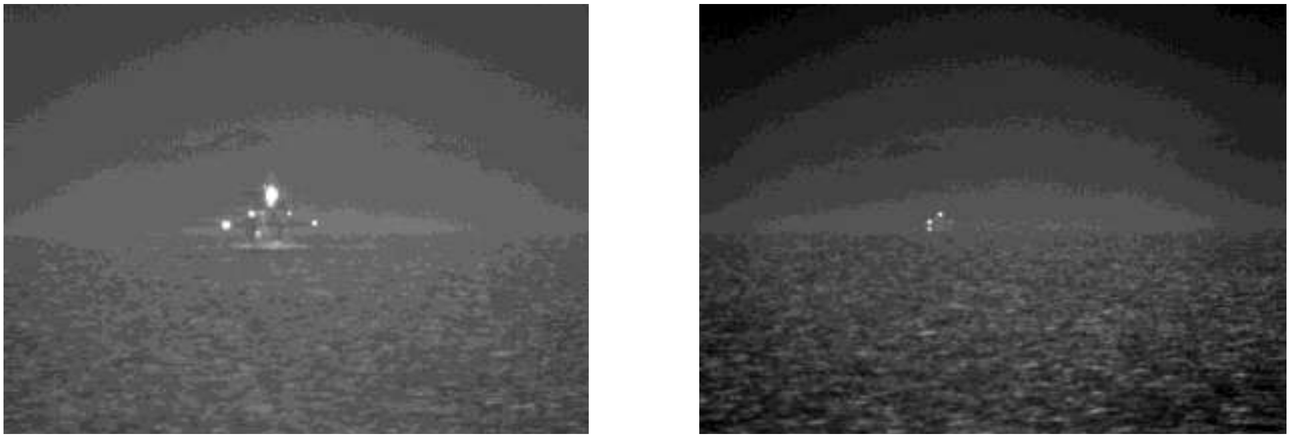

Figure 4. Examples of MWIR recordings made of the Mittelgrund on an outbound run. The black bodies extend from the hull, the hottest on port side and the coolest on starboard. In the left-hand image the ship is at 2.3 km from the camera, whereas it is at 10.2 km in the right-hand image.

Due to the large amount of data gathered from focal plane arrays at high frame rate, high frame rate continuous recordings of the boat were not practical. In order to study turbulence effects as well, short high frame rate recordings were thus taken at about 1 km intervals.

Meteorological data from the Norwegian buoy was used for this analysis. Five air temperature sensors of the same type were located at different heights up to 4 m above sea level. One sea temperature sensor measuring the sea temperature at about 0.25 m depth was also incorporated on the buoy. The sensors were calibrated against each other before the trial. The measured distances and contrast signals have been compared with calculations using IRBLEM version 5.3. The simulated contrast signal is found through the use of Equation (2). Meteorological input to IRBLEM is given in Table 2.

Table 2. Meteorological data used in the analysis.

Run	Date	Time (Z)	RH(%)	T*air*(◦C)	T*sea*(◦ C)	ASTD(◦ C)	Height (m)
Run 1	11.09	14.00-14.40	68	19.9	15.9	+4.0	5.98
Run 2	12.09	02.00-03.00	90	15.6	15.7	-0.1	5.85
Run 3	12.09	03.10-04.00	91	15.5	15.7	-0.2	5.86
Run 4	12.09	04.00-04.50	90	15.4	15.7	-0.3	5.91
Run 5	12.09	05.00-05.45	90	15.3	15.7	-0.4	5.94
Run 6	12.09	05.45-06.30	90	15.3	15.6	-0.3	5.97
Run 7	12.09	07.00-07.45	86	15.6	15.5	+0.1	6.05
Run 8	19.09	02.00-03.00	87	10.7	14.1	-3.4	6.04
Run 9	19.09	04.00-04.35	90	10.1	13.9	-3.8	6.09
Run 10	19.09	04.45-05.30	91	9.9	13.9	-4.0	6.09
Run 11	19.09	06.25-07.00	90	10.3	13.8	-3.5	6.05
Run 12	20.09	07.10-08.00	87	12.5	13.8	-1.3	6.19
Run 13	20.09	08.15-09.00	86	13.3	13.7	-0.4	6.10
Run 14	20.09	09.05-10.10	84	13.8	13.7	+0.1	6.09

The signals from the ship-mounted black-bodies, as measured with a mid-wave IR camera, as a function of range are compared with IRBLEM results in Figures 5–7. The figure shows integrated signal contrast as a function of distance. These results can be converted to contrast radiance (W/cm^2 sr) by dividing through by *K* in Equation 2. The gain factor *K* is obtained from calibration recordings made of a separate set of two black bodies at temperatures at and slightly above air temperature, held right in front of the camera.

The measured signal corresponds well with the modeling results in most cases. The measured signal naturally fluctuates somewhat from measurement point to measurement point.

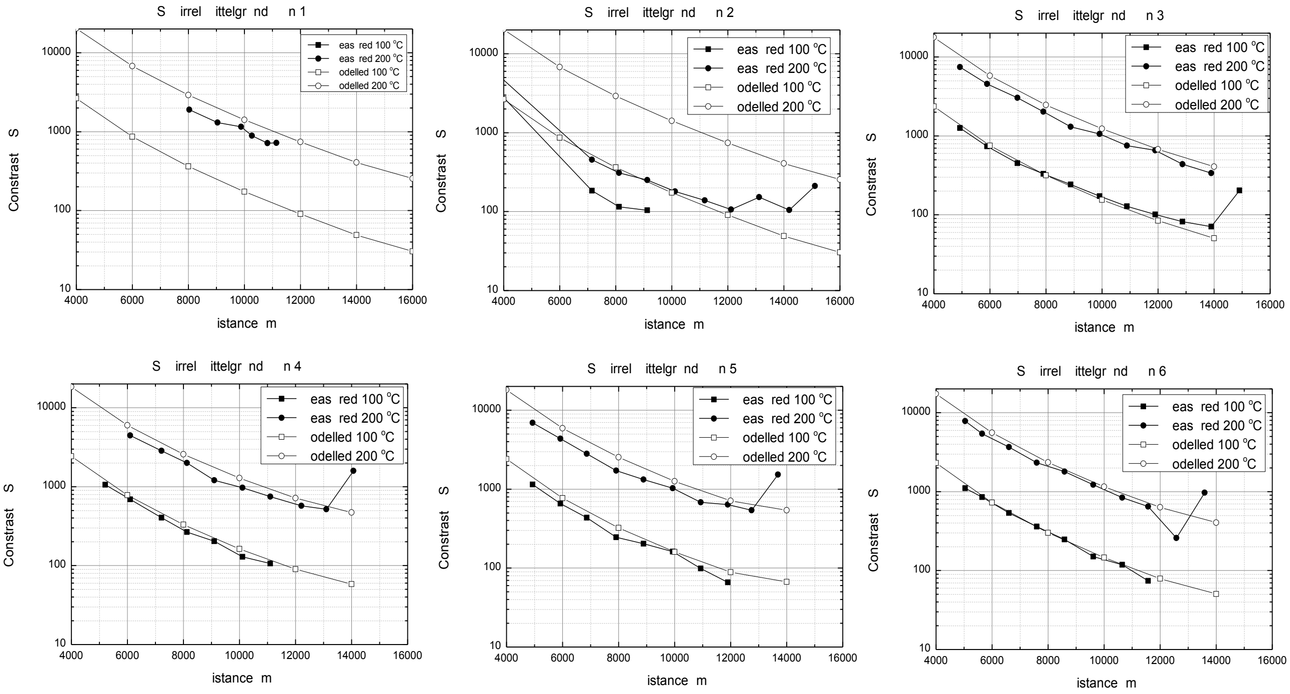

Figure 5. Measured and modeled source signals as a function of distance in the mid-wave IR band for run 1 through 6. The solid symbols are measurement results, circles for the 200 ^{o}C source and squares for the 100 ^{o}C source. The open symbols represent the modeling results.

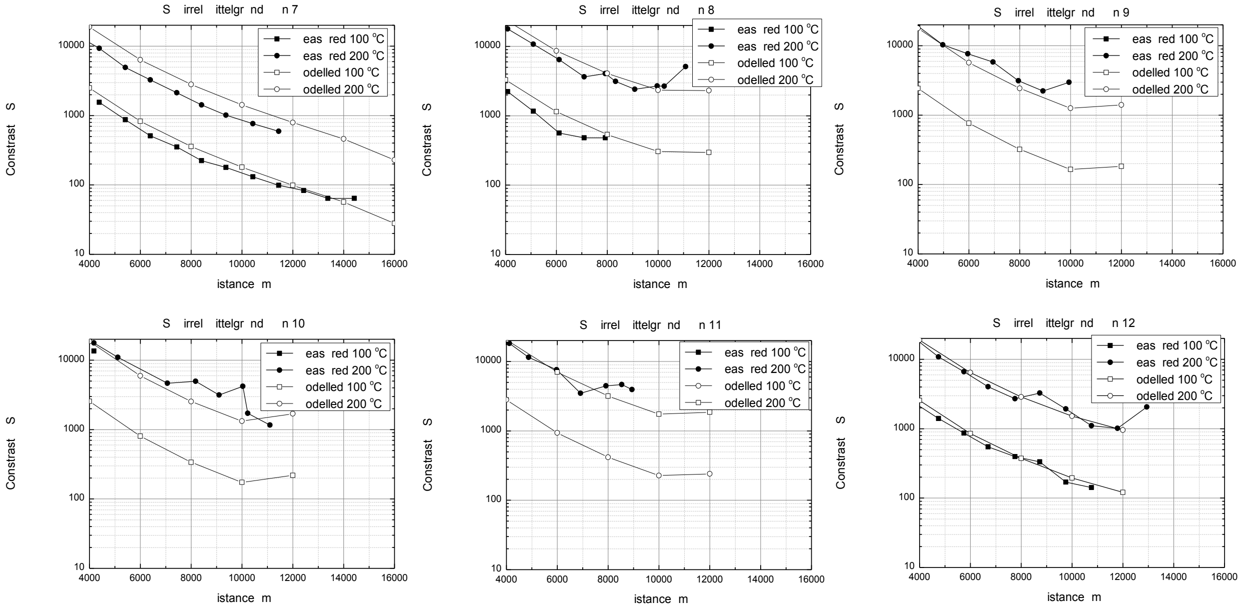

Figure 6. Measured and modeled source signals as a function of distance in the mid-wave IR band for run 7 through 12.

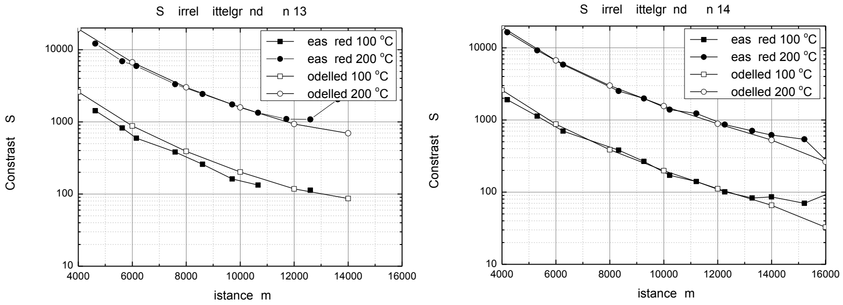

Figure 7. Measured and modeled source signals as a function of distance in the mid-wave IR band for run 13 and 14.

In some runs only the hot blackbody was operational. In run 2 there is a large discrepancy between measured values and model values. This is most likely caused by a problem with the source. Apart from run 1, where the data is somewhat scarce, there are only a few marginally superrefractive cases, while the rest are subrefractive.

The predicted signal contrast is generally representing the measurements quite well with no clear trends in the deviations. In contrast, during the SAPPHIRE trial [1], the predictions were always higher than the measurements. Results from the first six runs of this trial are reproduced in Figure 8, for comparison reasons.

In conclusion, for the observed conditions we find that we can use readily available meteorological data to obtain good agreement for mid-wave IR propagation to near the horizon. Estimates of IR performance should be sufficiently accurate in an operational sense at least under subrefractive conditions. Sub-band results may be more susceptible to details in the meteorological parameters than these broadband results. The ranges given in Figures 5–7 show that quite small signal to noise ratios are needed to observe a source that is being tracked. The ranges in these figures are limited by scintillation as the numbers given in the figures are based on observed contrast above the noise level in 100 consecutive frames.

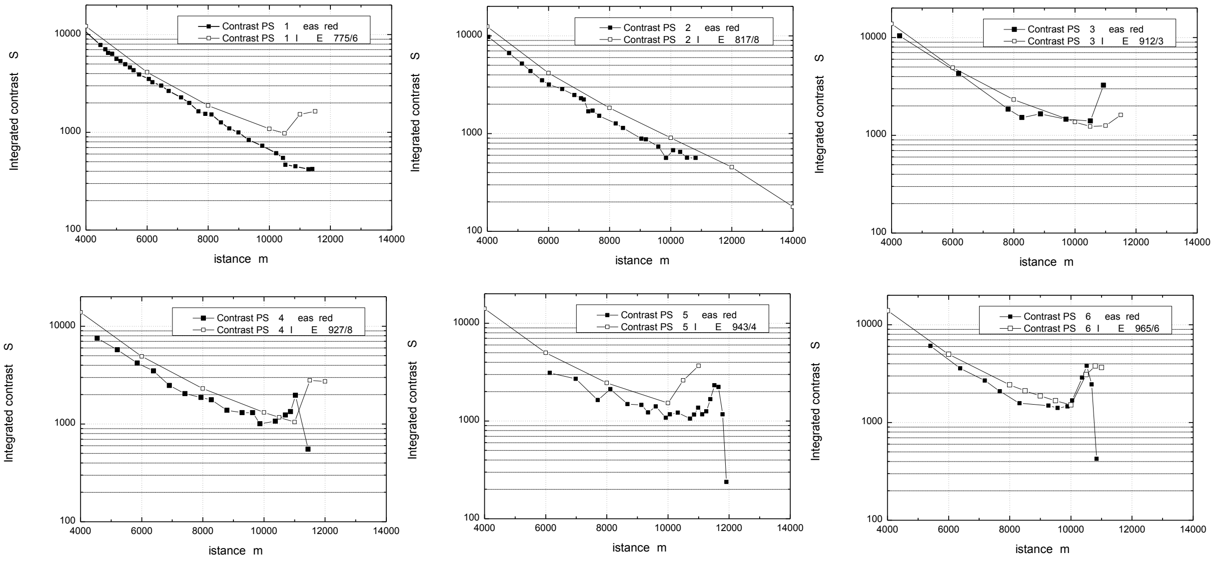

Figure 8. Measured and modeled source signals as a function of distance in the mid-wave IR band for runs 1 – 6 from the SAPPHIRE trial.

5. CONCLUSIONS

Measurements of transmission and refraction in the marine boundary layer have been performed during the September 2011 SQUIRREL trial, and have been compared with results from the modeling tool IRBLEM. Conditions were mostly near neutral or subrefractive during the SQUIRREL trial.

This fact and the large sensitivity of the results to minor variations in ASTD when ASTD is near zero, makes it imperative to have good meteorological data.

Transmission effects as a function of range have been studied in the mid-wave IR-band. Good agreement is found between measurements and model results of the signal from two blackbody sources at different temperature as a function of range. The maximum range seems to be slightly over-predicted.

The same analysis method and the same modeling tool was used in the analysis of SAPPHIRE data with hot and humid conditions [1]. Only MWIR data was analyzed in the current work, and one would therefore expect only a small effect of the change in humidity conditions. Results from these two trials are found to be quite similar, with good agreement between measurements and model predictions. However, during the SAPPHIRE trial, the predictions were consistently above the measured values. One reason for this may be inadequate aerosol modeling during the SAPPHIRE trial. In the SQUIRREL data, there is no such trend.

ACKNOWLEDGMENTS

The authors like to thank the other SQUIRREL participants, and the hosts represented in particular by Dr. Birgit Rasch.

REFERENCES

[1] Heen, L. T., Madsen, E. B., Steenfeldt-Foss, P., Wikan, K., Fonnum, H., van Rheenen, A. D., Brendhagen, E., and Almklov, B. “Measurements of IR propagation in the marine boundary layer in warm and humid atmospheric conditions,” Proc. SPIE 6747, 674706, 2007.