Validation of ShipIR (v3.2): methodology and results

David A. Vaitekunas[a,1]
[a]W.R. Davis Engineering Limited, 1260 Old Innes Road, Ottawa, Ontario, Canada K1B 3V3

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ABSTRACT

The naval ship infrared signature model and naval threat countermeasure simulator (ShipIR/NTCS) developed by W.R. Davis Engineering Ltd has undergone extensive validation since its adoption as a NATO-standard, and has been accredited by the US Navy for Live Fire Test and Evaluation of the DDG class warship, Preliminary Design of the DD(X) destroyer, and Contract Design and Live Fire Test and Evaluation of DD(X). Validation has played a key role in the model development by assessing current accuracy, identifying key areas of improvement, and tracking achievements made by each new release. This paper describes some of the recent improvements in full-ship infrared (IR) signature measurement and model prediction based on the measurements and predictions of an unclassified Canadian research vessel (CFAV Quest). The results show how some of the more recent trial parameters: radiosonde input, ship surface optical properties, atmosphere-scattered solar irradiation, and large-scale Reynolds Number; have affected our model predictions and accuracy.

Keywords: infrared signature, thermal model, background irradiation, background radiance, path scattering, optical properties, validation

1. INTRODUCTION

ShipIR/NTCS is a comprehensive software package for predicting the infrared signature of naval ships in their maritime background, as shown in Figure 1. The software includes a generic imaging seeker model and IR flare countermeasure deployment model to simulate the engagement between a ship, its flare tactic and an infrared-guided missile. ShipIR and NTCS were developed by W.R. Davis Engineering for the Canadian Department of National Defence. The ship signature component of the model (ShipIR) consists of several sub-models, including an infrared sky radiance and atmosphere propagation model (based on MODTRAN4) and a complex sea reflectance model based on the work of Mermelstein (1994) and Shaw and Churnside (1997). The platform model is constructed from an AutoCAD™ 3D surface model, forming the basis of a 3D heat transfer and in-band surface radiance model, that handles both diffuse and specular components of the bi-directional reflectance distribution function (BRDF). A plume trajectory and IR emission model predicts infrared signatures of diesel engine and gas turbine exhaust systems. The model has been under development since 1990, with the first version delivered to Defence Research Development Canada (DRDC) Valcartier in June 1992. Sub-models of the plume, flare decoy and missile engagement were added in 1994 to form the basis of ShipIR/NTCS (v2.0). The acronym NTCS (Naval Threat Countermeasure Simulator) refers to the IR engagement capabilities of the model.

After a careful review of ship IR models from the US and other NATO countries, the NATO Research Study Group (RSG-5) adopted ShipIR as a NATO-standard in 1995. In 1996, the US Naval Research Laboratory (US-NRL) adopted ShipIR as a signature prediction tool for all their ship signature and electronic warfare (EW) studies. With funding

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[1] davidv@davis-eng.com; http://www.davis-eng.com; phone 1 613 748 5500; fax 1 613 748 3972

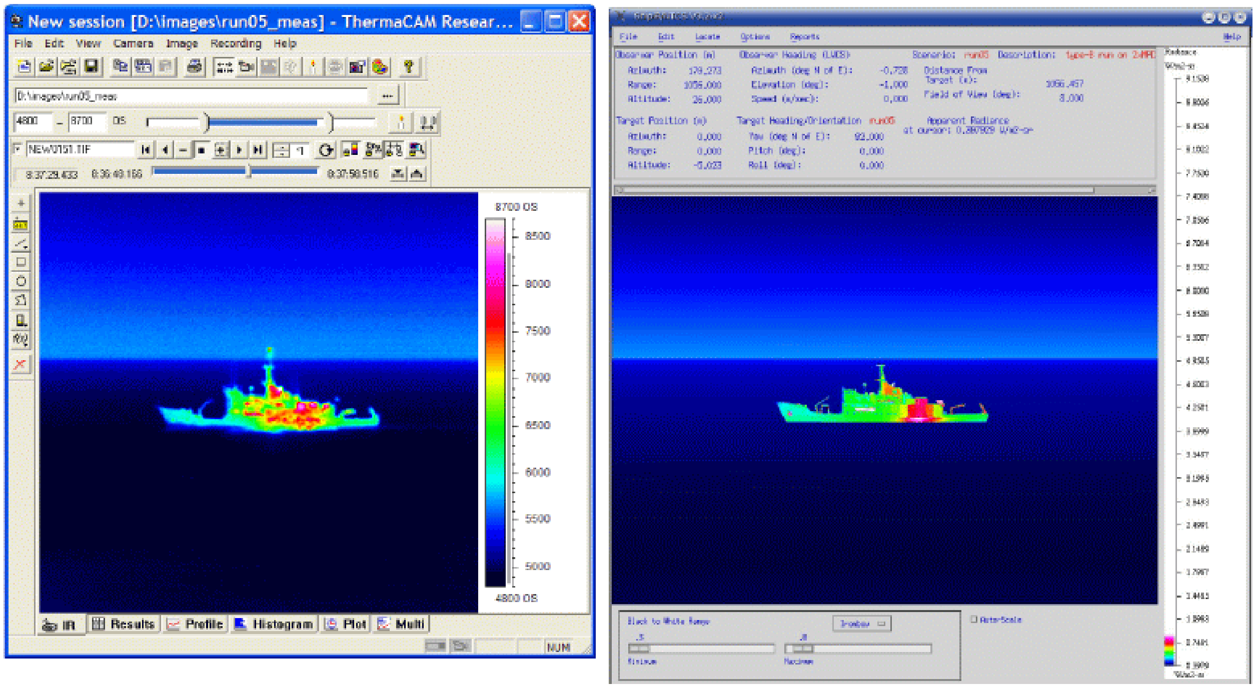

Figure 1: FLIR camera image of Quest taken during Q276 on left, with simulated output from ShipIR/NTCS (v3.2) on right.

from the US Office of Naval Research (ONR) and NAVSEA, Davis and the US-NRL have continued to improve and validate ShipIR to meet specific requirements of the US Navy, and interface with the US-NRL CRUISE_MISSILES seeker simulation software. The ShipIR/CRUISE_MISSILES package (Taczak et al., 2002) was first accredited by the US Navy in May 2001 for the DDG-51 Live Fire Test and Evaluation (LFT&E) program. ShipIR has since been accredited by NAVSEA for both Preliminary Design and Contract Design of the US DD(X) destroyer, and for the LFT&E of DD(X) . The model continues to be developed and improved with funding from both Davis and NAVSEA. DRDC (Atlantic) is also contributing to its further development with the planning and execution of joint signature trials involving the CFAV Quest, an unclassified DND research vessel. The software has been available commercially since 1995 and has over 40 site installations worldwide, including Northrop Grumman (Newport News, Ship Systems), Lockheed-Martin (Naval Electronics and Surveillance Systems, Sippican), Bath Iron Works, Blohm and Voss (Germany), Navantia (Spain), Fincantieri and Galileo Avionica (Italy), DCN (France), Celcius (Sweden) and numerous government organizations.

1.1 Evolution in IR modelling

Over the years, a number of significant upgrades have contributed to an overall improvement in model accuracy. A large amount of commonality exists between the various components of the model which can facilitate and complicate the model validation process. For example, the in-band sea surface and target surface radiance models share many of the same input parameters: they are both assumed thermally opaque and require a similar process to predict background reflections, self-emission, and source propagation through the atmosphere. Similarly, a commonality exists between the in-band and thermal models: MODTRAN sun, sky and atmosphere predictions for a user-defined sensor band (e.g., 3–5μm, 8–12μm) are expanded to cover the entire thermal and optical spectrum (0.2–250 μm) to predict the net radiative heat exchange between surfaces on the platform. This commonality and inter-coupling between various sub-models of ShipIR has resulted in a highly sophisticated and tightly integrated approach to modelling platform thermal/IR signatures. The following paragraphs briefly describe each model upgrade and its impact on model accuracy.

One of the first important upgrades to ShipIR (v2.6, 1999) involved the extension of its multi-bounce diffuse radiosity model, used to predict both temperature and in-band surface radiance, to include single-bounce specular reflections from the thermal background and/or solar-glint sources; and the option to perform these multi-bounce (iterative) calculations at each sub-band wave number (termed full-spectral analysis). The thermal model was also further improved to include separate convection heat transfer correlations for tangential-flow and separated-flow, based on ship geometry, relative wind speed and direction. The solar-scattering options of MODTRAN were extended to the thermal and in-band sky radiance predictions in ShipIR (v2.8, 2000) to approximate the indirect solar irradiation of both the sea and platform surfaces based on a lumped-parameter approach. The interface between ShipIR and MODTRAN was also upgraded to MODTRAN4 (mod4v1r1), and the target thermal radiation model segregated into two mutually exclusive solar (0.2–4.2μm) and thermal (4.2–250μm) sub-bands to rigorously conserve the solar and thermal radiation through its multi-bounce reflection – a required feature for modelling low solar absorptive (LSA) paints.

In NTCS (v3.0, 2002), the constituent gas emission models used to simulate the spectral emission of CO_2, CO, H_2O, and soot were adjusted based on comparisons with Handbook data (Ludwig et al., 1973) and actual plume measurements of a GE LM2500 (Fraedrich, 2001). User inputs to the plume model were changed to a dry-air analysis, so that actual stack exit conditions could be re-calculated by the model for each scenario background (relative humidity and air temperature). The sea radiance model was also upgraded to further distinguish between single and multi-bounce specular reflections of direct-sun (solar-glint), single and multi-bounce non-glint reflections of thermal sea/sky emissions and single/multi-bounce non-glint reflections of path-scattered solar radiance. This allowed the solar and thermal components of background irradiation to be further conserved throughout the multi-bounce process within the background and target thermal models, a pre-cursor to the latest version of the model (directional irradiation). The MODTRAN interface was further upgraded to permit user-input of cloud altitude, thickness, and extinction for all cloud types in MODTRAN4 (Berk, 1995), a required feature for matching ShipIR model predictions with trial measurements of solar irradiance in overcast conditions. This version of the model also initiated the migration of the software from its native SGI-IRIX system to the Intel-based Linux and MS-Windows systems.

The next major enhancement to ShipIR (v3.1, 2004) extended the multi-bounce diffuse / single-bounce BRDF model of v2.6 to multi-bounce specular and bi-directional surface modelling. The multi-bounce option forces the model to ray-trace the reflection of each specular surface element to determine whether its source is indeed the background or another surface on the same platform. The new bi-directional option specifies whether the source radiance of a multi-bounce surface-to-surface reflection will be based on a nominal (pseudo-diffuse) or bi-directional calculation (2^{nd}-order effect). The end result is a full implementation of the radiance equation. Other important refinements included increased sky-grid resolution near the horizon, upgrades to the sea reflectance model to include the effects of air-sea temperature difference on sea roughness (Shaw and Churnside, 1997) and 2^{nd}-order surface hiding (Smith, 1967). An application programming interface (API) was also added to provide users with direct access to the selected models and routines within ShipIR/NTCS, including sea radiance clutter predictions associated with the Mermelstein (1994) sea model which are now being used by the US-NRL CRUISE_MISSILES program (Fraedrich et al., 2004). The wind convection model was also upgraded to define three separate flow-regimes: stagnation, tangential and separated flows.

The focus of the latest round of model upgrades (v3.2, 2005) was the platform thermal model. A mass transfer process was added to detect and predict the rate of atmospheric condensation and associated heating of the platform when surface temperatures drop below dew-point. The new model uses an analogy between convective heat and mass transfer to predict the ability of the surrounding air to deliver the condensate as part of an overall energy balance. The sky, sea and target irradiance models were also upgraded to implement a fully two-dimensional mapping of path-scattered solar radiance of the sea and platform surfaces, replacing the previous lumped-parameter approximations of ShipIR (v2.8). The empirical wind convection model was also upgraded based on the work of Fraedrich and Rundquist (2004) to account for the very large length scales and Reynolds number ($10^6<Re<10^9$) associated with naval ships. The Linux version was also enhanced to include an off-screen rendering feature using the Mesa 3D[2] library, allowing users to run multiple instances of ShipIR on a single platform (display) to take advantage of multi-threading and Linux clustering, while extending the OpenGL IR image precision from 12-bits up to 23-bits.

The next release of ShipIR (v3.3) includes a new textured sea/sky radiance model for modelling partial (broken) cloud, a full-spectral viewing and analysis feature, and the option to simulate multiple altitudes in the same scenario. As

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[2] http://mesa3d.org: home page of the Mesa 3D Graphics Library.

shown in Figure 2, the upgrades described in this sub-section have all been part of a systematic approach to IR model development where validation is key to identifying sources of model errors and/or deficiencies. Solutions are proposed and implemented through new releases, and then tested to determine the net effect on accuracy. This incremental approach to model development focuses our attention on the dominant source of error, and the resultant residual errors provide useful input for the next round of model improvements. The next section will show a similar evolutionary process in the planning and execution of IR signature measurement trials.

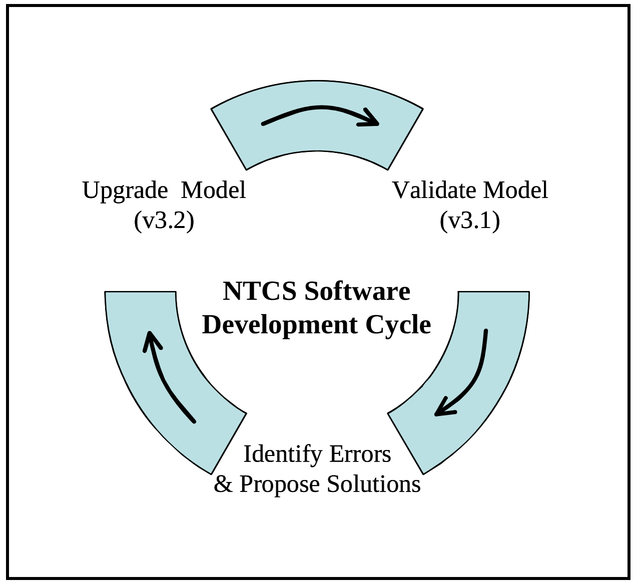

Figure 2: ShipIR Development Cycle.

1.2 Evolution in trial measurement

This section describes some of the full-ship and panel signature measurements used over the previous decade to validate ShipIR and further illustrates how trial measurements have followed a similar evolution as a result of model validation. This description is by no means complete since it does not include any US or other NATO member trials that have contributed to the validation and accreditation of ShipIR. A large amount of infrared ship signature data has been collected over the years to support various naval operational requirements such as decoy effectiveness, threat analysis and the pursuit of stealth technology. However, much of this data had limited use for model validation since it lacked the detailed meteorological, ship operational and ship surface optical measurements required for input to ShipIR. Once new trial data has been collected, its suitability for model validation must first be verified. Fraedrich and Goldberg (2000) and Fraedrich and Gover (2001) have developed a methodology for assessing the overall uncertainty between a measurement and model, based on the propagation of uncertainty in model inputs, to ascertain the usefulness of IR measurement data. They defined the following three components of statistical error between a model and measurement (U_R):

$$U_{\mathrm{R}}^2 = U_{\mathrm{M}}^2 + U_{\mathrm{P}}^2 + U_{\mathrm{T}}^2 \qquad \textbf{(1)}$$

U_M is the measurement error in the output variable, U_P is the propagation error associated with uncertainties in the model inputs, and U_T is the true model error sought through the validation process. For a complex model like ShipIR, it is not feasible to define the mathematical relation between U_P and the uncertainty in each input variable (U_I) , therefore, a sensitivity analysis is used to assess the change in model output (U_P) as a function of changes in each input variable. Given the cost and complexity of performing such sensitivity analyses, they are often used as a post-validation tool when the error diagnostics indicate that a particular data set or group of measurements do not conform with the other replicates, or simply as a check when there is no apparent correlation between the residual error and the primary input variables affecting the output.

Our first attempt to validate the model occurred in 1994 when the NATO Research Study Group (RSG-5) distributed the data from a 1992 US-NRL panel test. These results were presented to NATO for comparison and discussion on the state-of-the-art in ship IR modelling. The methods and results used to compare ShipIR (v1.0) against these measurements layed the ground work for the model input sensitivity analysis used in future validation experiments. Our second effort to validate the model came when existing DRDC IR sea trial data for the Canadian Patrol Frigate (CPF) and Tribal Class Update and Modernization Program (TRUMP) ship programs were compared against ShipIR models of both ships. Although the measurements were sufficient to demonstrate an overall reduction in ship signature, when compared to previous Canadian Navy ships, they lacked the information and detail necessary to formulate observations about the validity or accuracy of the ShipIR model. The conclusion was to recommend a standard method of IR data collection and signature analysis to promote better IR measurement and model validation practices. These included automatic and redundant recording of all meteorological input parameters, repeated on-site calibration of IR cameras, and careful analysis of model input variables during the ½-hour leading up to each IR measurement.

The lessons learned from these earlier trials were put into practice in two subsequent model validation experiments: the 1998 US-NRL panel test and the 1997 NATO SWG/4[3] measurement. Although significant improvements were made in the data collection and model input process for these two experiments, a number of measurement runs had to be rejected on the basis of thermal non-equilibrium. In the 1998 panel test, a maximum threshold in surface temperature gradient (|dT/dt|<0.15 ºC/min) was used to isolate the thermal equilibrium runs. During the CPF measurement, installation and logging of ship surface temperature sensors was not feasible, therefore ship GPS data and ShipIR predictions were used to eliminate measurement runs or ship aspects where large recorded changes in ship heading were shown to have a significant effect on predicted signature. The plan has been to first validate the ShipIR model for steady-state conditions, and then proceed to develop and validate a full-transient model.

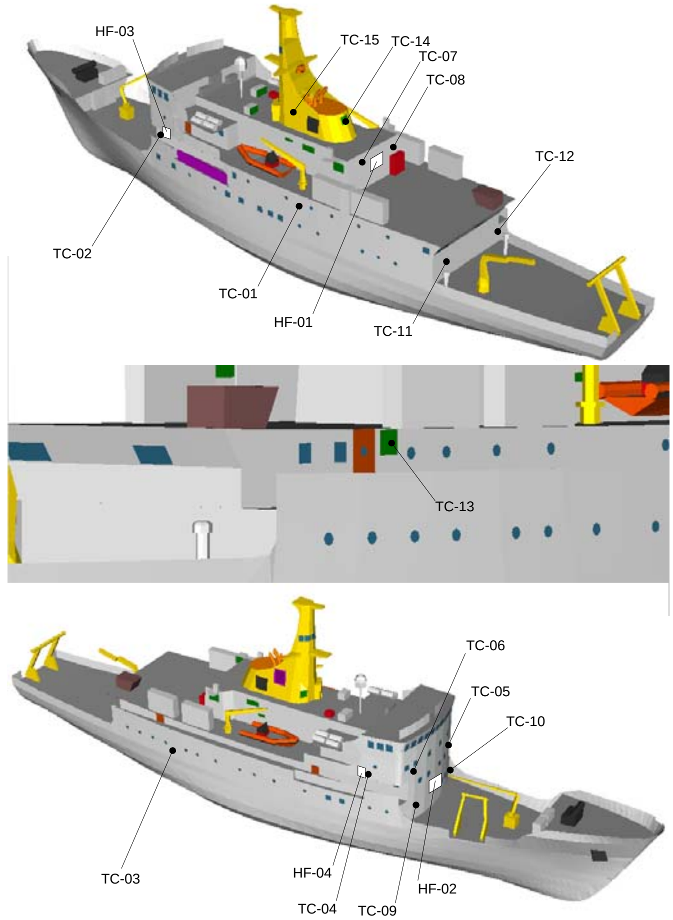

Figure 3: Thermocouple locations during Q280.

In 2001, the NATO Task Group on ship signatures (TG-16) organized the NATO Ship Infrared Model Validation Experiment (SIMVEX), which was held in Canada using the Canadian Forces Auxiliary Vessel (CFAV Quest). The Quest was outfitted and modelled to provide an unclassified data set for the NATO group to work with. Both the ShipIR geometry and thermal/IR models were prepared in advance of the trial, and temporary instrumentation and sensors were installed on Quest to record all the ShipIR inputs as well as a number of sub-model outputs (e.g., solar irradiance, surface temperature). A standard set of measurement runs were configured to provide sufficient time to reach thermal equilibrium while still providing adequate domain coverage (i.e., solar-heated, solar-shadowed, night conditions). The original NATO SIMVEX Quest trial (Q262) and model validation exercise has now been repeated a number of times, under both similar (Q276) and different (Q280) weather conditions. The remaining sections will describe these various Quest trials and the methodology used to validate ShipIR.

2. TRIAL DESCRIPTION

The CFAV Quest shown in Figure 3 is a multi-purpose scientific research vessel, measuring 76m (length) by 12.6m (beam) by 4.8m (draft) with a total displacement of 2130–2200 tonnes. Its main propulsion system is diesel electric with two 10 cylinder Fairbanks-Morse 38D8 diesel engines (2240 kW) driving two GE electric motors. Quest also has an auxiliary propulsion/power configuration utilising a 750kw Solar Saturn gas turbine driving two 500 kW generators in tandem – providing either AC ship service or auxiliary DC propulsion power. The maximum ship speed on the two main propulsion diesels is 15 kts. Most of the hull and superstructure are painted white, while the funnel and main mast are painted yellow. Outfitted as an acoustic signature measurement vessel, the Quest has a well-insulated and ventilated thermal acoustic chamber for both its main propulsion and ship AC power systems. Hot-air from the acoustic chamber (hood) is vented upwards through the main funnel in the centre of the ship, and exhausted through vents located on the external funnel (e.g., TC-14 shown in Figure 3). Because the external portion of the funnel is uninsulated, a user-defined thermal boundary condition

[3] Special Working Group 4 (SWG/4) on Electronic Warfare.

(TBC) model had to be input to ShipIR. It has since been determined that these internal sources of heat transmission have a limited impact on the total predicted and measured IR signature (W/sr).

The IR signature measurements of the background and ship were taken from shore at the Canadian Forces NESTRA facility located near Cow Bay, Nova Scotia, just outside Halifax. This location is ideal for RCS and IR ranging because of its proximity to the Maritime Forces Atlantic (MARLANT) in Halifax Harbour and the unobstructed views of the Atlantic ocean to the South, South East and East. As part of pre-trial planning for NATO SIMVEX, four basic IR runs were proposed for full-ship measurement within a 1 km range of the shoreline:

- Type A: 10 km ship trajectory heading W (270°) with the starboard side measured at 1 km to the S (180°),
- Type B: 10 km ship trajectory heading N (0°) with the port side measured at 1 km to the E (90°),
- Type C: 10 km ship trajectory heading NNE (32°) with the port side measured at 1 km to the SSE (122°),
- Type D: 10 km ship trajectory heading SSW (212°) with the starboard side measured at 1 km to the SSE (122°).

Type A through C runs were designed specifically for daytime thermal equilibrium. Ship material thickness, specific heat, thermal conductivity and convective heat transfer rates were analysed to estimate an approximate thermal time constant of 30 minutes – the time required to sail 9 km at 10 kts. A quick reversal of the Type C run at night was used to provide an additional Type D run, where the thermal equilibrium is less sensitive to heading. Type D runs executed on the way to start a Type A or C run were also used to validate the thermal model.

Table 1: Parameter ranges for CFAV Quest trials.

Parameter	Actual Range			Desired Range†
	Q262	Q276	Q280	
Dates	14–20 Sep (2001)	25 Aug (2003)	16–18 Feb (2004)	N.A.
T_{sea} (°C)	17 to 18	16	0.0 to 0.1	+7 to +34
T_{air} - T_{sea} (°C)	-4 to 2	-2 to 4	-13 to -3	-9 to +5
solar irradiance (W/m^2)	3 to 720	2 to 870	30 to 510	N.A.
sky irradiance (W/m^2)	N.A.	290 to 365	170 to 290	N.A.
cloud cover	0/8 (15) 8/8 (1)	0/8 (5) broken (4)	broken (6) 0/8 (6) 8/8 (8)	0/8 and 8/8
wind speed (m/s)	5 to 11	4 to 10	2 to 12	1 to 15
humidity (%)	35 to 83	28 to 63	41 to 75	15 to 98
solar absorptance	0.21 (white) 0.63 (yellow)	0.21 (white) 0.54 (yellow)		0.2 to 0.95
thermal emissivity	0.94 (white) 0.93 (yellow)	0.93 (white) 0.96 (yellow)		0.2 to 0.95
3–5 µm HDR (average)	0.23 (white) 0.17 (yellow)	0.09 (white) 0.08 (yellow)		0.05 to 0.80
8–12 µm HDR (average)	0.06 (white) 0.06 (yellow)	0.03 (white) 0.04 (yellow)		0.05 to 0.80

†based on U.S. Navy requirements (Vaitekunas and Fraedrich, 1999)

The range of climatic and other operational data recorded during each Quest trial have been tabulated as per Table 1 along with a desired parameter range from the US-NRL (Vaitekunas and Fraedrich, 1999). The Q276 trial served as a replicate of the original NATO SIMVEX trial (Q262). The Q280 trial held in February 2004 provided a unique opportunity to measure under extreme air/sea temperature conditions. Although ShipIR does not yet handle the input of partial cloud conditions, signature and temperature data were collected during both Q276 and Q280 to assess the IR signature prediction error associated with broken-sky conditions. Two separate optical measurements of the Quest white and yellow paints were performed: one by the NATO Group during Q262 and another by Surface Optics between the Q276 and Q280 trials. The two measurements show a remarkable difference in total hemispherical directional reflectance (HDR) for the 3–5µm band, which will be further analysed in the sub-section on contrast signature. A pyrgeometer was introduced during Q276 and Q280, to add thermal sky irradiance measurements to the existing solar pyranometer readings taken during the NATO-SIMVEX trial, allowing both the down-welling solar and thermal sky irradiance predictions of ShipIR to be validated based on a hemispherical volume integration of the MODTRAN sky radiance results in each of the two thermal model bands (0–4.2µm, 4.2–250µm), respectively. In addition to climatic data measurements on shore and ship, self-adhesive thermocouples and self-logging iButton® temperature sensors were attached at several locations on Quest, as illustrated by Figure 3, to record surface temperature versus time. A total of between 40 and 50 temperature sensors were used in 20 to 40 different locations to provide redundancy and allow these two sensor types to be compared. Each of 15 external thermocouples used during Q280 was paired with a redundant iButton to measure the average and standard deviation between each sensor pair, providing an independent assessment of the uncertainty associated with surface temperature measurement in the field.

3. METHODOLOGY AND RESULTS

The methodology used to validate ShipIR consists of systematically testing each sub-model by comparing as many intermediate outputs or physical quantities as possible in an effort to better understand the current accuracy limits of the model. For Quest trials, the following output variables were measured and compared with ShipIR:

- down-welling solar and thermal sky irradiance,
- ship surface temperature,
- in-band sea/sky radiance,
- total contrast intensity.

The sub-sections to follow describe the measurement, analysis and results for each sub-model output. Comparison with previous versions of the model are also used to highlight the accuracy improvements and identify some residual sources of error in IR measurement and modelling.

3.1 Scenario inputs

Before running the model, various data logs from the weather stations (ship and shore) and ship data acquisition systems are compiled and processed to define an average and time variance for each model input, as shown in Table 2. In our case, the average ship heading and speed, relative wind speed and direction were obtained from a permanent non-acoustic data acquisition system (NADAS) onboard the Quest. Since external convection is modelled using relative wind speed and direction, and because there are large scale fluctuations in both ship and shore measurements of absolute wind speed and direction, the absolute wind condition input to the model was calculated using the average ship speed and heading, and average relative wind speed and direction, so that the net relative wind conditions of the simulation would be identical to those measured. The variance computed for each input variable is a useful statistic when trying to determine which of two instruments to use during model validation, or to establish the sensitivity of the model to unsteady input conditions. In this example, the largest variance was found in the relative wind speed (9.3%) and ambient air temperature (12%). The remaining variances are all less than 2%, well within the measurement accuracy of each sensor. The start and end times were obtained from the analysis of ship GPS data: two end points forming a straight-line along the constant trajectory of each run (A, B, C, D). The time histories from each thermocouple and iButton location were also analysed between these two end-points to find the closest measurement to the end-point and test for thermal equilibrium ($|dT/dt|<0.15$ ºC/min). When automating the analysis of time history data, care should be taken not to interpolate the data past the end-point, since the ship will tend to manouevre quickly after each run to avoid the shoreline and cause a large transient in some of the sensor readings, which when interpolated over a large sampling

Table 2: Scenario inputs for run01 (Q276).

Run ID:	1			
Trajectory:	B			
Propulsion system:	2×MPDE			
Date:	2003-08-25			
Start Time:	14:39:00			
End Time:	15:07:00			
Duration:	00:28:00			
Solar Azimuth (deg)†	142–152			
Solar Elevation (deg):	49.6–52.3			
Measured Input Parameters	**Quest**		**shore**	
	Mean	σ	**Mean**	σ
Ship Heading (deg)†:	359	3		
Ship Speed (kt):	10.5	0.1		
Ship Speed (m/s):	5.40	0.05		
Rel. Wind Speed (m/s):	12.9	1.2		
Rel. Wind Direction (deg)†:	318	7		
Current Wind Speed (m/s):	9.6		6.2	1.5
Current Wind Direction (deg):	295		N.A.	
24-Hour Wind Speed (m/s):			4.6	1.3
Ambient Temperature (°C):	10.8	1.3	16.7	0.2
Relative Humidity (%):	45	4	43	3
Dew Point (°C):			4.1	1.0
Solar Irradiance (W/m^2):	intermittent		816	12
Thermal Sky Irradiance (W/m^2):	296	1		

†Angles clockwise (CW) from North (absolute) or bow (relative).

period (e.g., 3–4 minute interval for the iButtons) can result in large errors or bias in the model validation.

3.2 Background irradiance

Figures 4 and 5 show the predicted and measured solar and thermal sky irradiance under clear and overcast conditions during each Quest trial. Both instruments are calibrated to output an equivalent total irradiance which corresponds to a wave-band integral of the MODTRAN results from 0.2–250μm. As previously stated, a pyrgeometer was not used during the NATO SIMVEX trial (Q262). The mean and standard deviation between the model and measurement for all the Quest runs are shown in Table 3. Although the model tends to under-predict the solar irradiance (μ=-38 W/m^2), the standard error (2σ) is well within the measurement accuracy of both instruments (+/-5% full-scale). In the case of broken-sky night runs of Q276 in Figure 5, these were modelled using a clear-sky which would tend to under-predict the true sky irradiance; these data points were not included in the above statistics.

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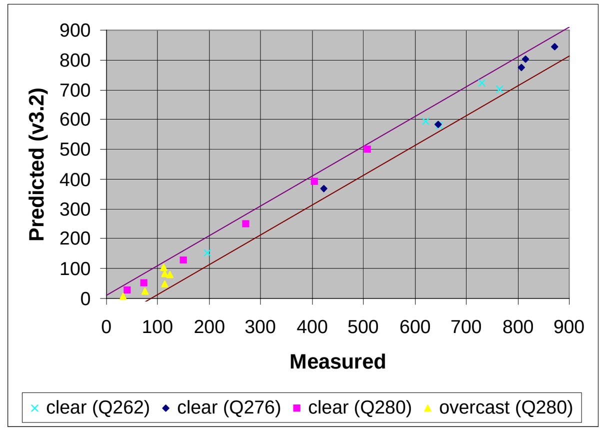

Figure 4: Down-welling solar irradiance (W/m^2).

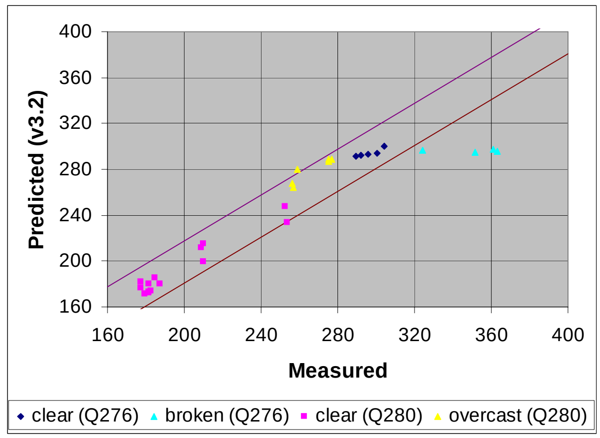

Figure 5: Down-welling thermal sky irradiance (W/m^2).

Table 3: Mean and standard deviation in background irradiance.

	Differences		max. reading
	mean μ	variance 2σ	
Solar Irradiance (W/m^2)	-38	42	900
Thermal Irradiance (W/m^2)	-1	18	400

3.3 Surface temperature

Two different surface temperature sensors were used on Quest. A limited number of self-adhesive fast-response T-type thermocouples (T/C) were installed to store detailed time histories with a sampling period of 15 seconds, while self-logging iButton sensors were used to complement each T/C and provide a greater number of sample locations without having to wire each sensor to a central data logger. The only disadvantage of iButtons is the need to download the data during the trial and the relatively large sampling period required to reduce the number of downloads during a trial: each iButton has a 1024 KB buffer which translates into 4–5 days of time history data using a 4 min sampling period. One of the objectives of the Q280 trial was to statistically compare the steady-state measurements from all T/C and iButton pairs. The results shown in Table 4 provide operational evidence that these two sensors and the methods used to mount them on the ship produce steady-state readings that are within the accuracy of each sensor. A T-type T/C has a rated accuracy of +/- 1°C over these range of temperatures. The next objective is to compare the predicted and measured ship surface temperatures. Table 5 shows the mean and standard error in surface temperature for each set of clear and overcast, day and night runs of the Quest using ShipIR (v3.2). Although on average, the model does tend to under-predict the day and night surface temperatures, the mean offset is well within the standard error (2σ) of the model; it is therefore impossible to ascertain whether this is a true model error. However, the standard error does increase with daytime solar irradiance when comparing the clear-day (Aug = 3.8/3.9°C, Feb = 3.2°C), overcast (Feb = 2.4°C) and night (2°C), indicating that residual temperature errors are most likely the result of model or measurement error in direct or indirect solar and thermal irradiation. Table 6 illustrates the improvements in thermal modelling over the last three versions, based on the NATO SIMVEX trial results. A greater than 50% reduction in standard temperature error has resulted from the latest round of upgrades in ShipIR (v3.2). These can be attributed to the

Table 4: Mean and standard deviation between T/C and iButton readings.

mean (μ):	-0.68 °C
variance (2σ):	0.96 °C
No. of points:	212

new high-Reynolds convection model and directional solar irradiation model, and represent a significant milestone in the pursuit of high-accuracy signature models.

3.4 Background radiance

Any platform IR signature is defined as the contrast between the average radiant intensity of the platform and its background. Therefore any attempt to validate a platform signature model must also validate the background radiance model to determine whether the errors in contrast signature result from ship surface radiance, background radiance, or both. As illustrated by Figure 1, the background radiance is predominantly a function of elevation angle or vertical position in the image. The decrease in sky radiance at higher positions in the image is a result of shorter emission paths through a progressively cooler atmosphere. Decreases in sea radiance at lower positions in the image are the result of high sea reflectance, roughness and higher angles of reflection into cooler parts of the sky. The maximum thermal emission from the background is typically at the horizon where the ambient temperature is at its highest along an infinite path length. The situation is somewhat more complicated at shorter wavelengths (3–5μm) where path solar-scattering can change the radiance in both azimuth and elevation.

In addition to qualitative comparisons between measured and predicted background images (see Figure 1), the average radiance across each row of the image can also be analysed, as shown in Figures 6 through 8 for various trial conditions and measurement bands. Figure 6 shows the impact of different radiosonde data (air temperature, relative humidity versus altitude) collected from two nearby weather balloons (Yarmouth and Sable Island) at 12 hour intervals. None of the four radiosondes are able to reproduce the measured 8–12μm profile, however after careful manipulation of one of these radiosonde files, we were able to match up the sky radiance profiles (see user-defined of Figure 6). Figure 7 shows the effect of recent improvements to the sea model, where the effects of 2nd-order slope-shadowing near the horizon were added in ShipIR (v3.1), and the directional irradiance model in ShipIR (v3.2). These effects are less apparent in the 3–5μm band, where the MODTRAN predicted path-scattered solar radiance appears to be the dominant source of error (see Figure 8).

In addition to the above trends in the sea/sky radiance versus angle, the average and standard deviation (σ) calculated for each sampled profile have also been compiled as per Table 7. The results show an RMS error between 0.10 W/m^2/sr and 0.40 W/m^2/sr in 8–12μm sky radiance depending on the seasonal conditions and radiosonde input selected. Similarly, the RMS error in the 3–5μm sky radiance varies from 0.002 to 0.004 W/m^2/sr for the clear summer runs, and up to 0.030 W/m^2/sr for the two winter runs. The RMS error in sea radiance ranges from 0.40 to 1.23 W/m^2/sr for the 8–12μm band, and from 0.0075 to 0.025 W/m^2/sr for the 3–5μm band, further indicating a direct correlation between sky and

Table 5: Mean and variance in predicted temperature of NTCS (v3.2) within each trial group.

Group	Difference (°C)		No. of points
	mean (μ)	variance (2σ)	
clear-day (Q262)	-1.80	3.76	257
clear-day (Q276)	-0.85	3.92	159
clear-day (Q280)	-2.28	3.20	99
overcast-day (Q280)	-1.45	2.44	142
clear-night (Q262)	-0.69	1.94	520
clear-night (Q280)	-1.10	2.06	152
broken-night (Q276)	-2.18	2.72	114

Table 6: Mean and standard errors in surface temperature for different versions of ShipIR.

Version	Difference (°C)		No. of points
	mean (μ)	variance (2σ)	
clear-day (Q262)			
ShipIR (v3.0b)	1.10	10.18	257
ShipIR (v3.1)	0.42	8.96	
ShipIR (v3.2)	-1.80	3.76	
clear-night (Q262)			
ShipIR (v3.0b)	-2.46	3.64	520
ShipIR (v3.1)	-2.32	3.20	
ShipIR (v3.2)	-0.69	1.94	

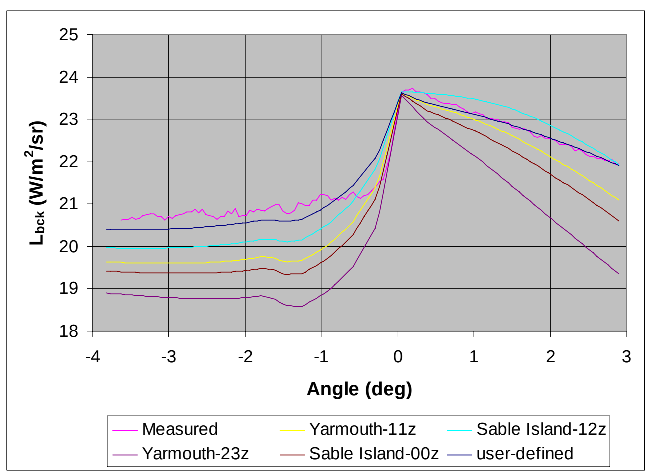

Figure 6: 8–12μm background radiance on clear summer day (Q262, run08) using different radiosondes.

sea model accuracy. Although large offset errors are present in all our 3–5μm background radiance comparisons, the RMS difference is very low and insensitive to atmosphere profile and seasonal air temperature, providing further evidence that residual errors in the 3–5μm band are attributable to MODTRAN over-predictions of path-scattering.

3.5 Contrast signature

The contrast signature obtained from different versions of ShipIR and the Quest model for the 3–5μm band of the Q276 trial are compared in Figure 9. The resultant mean and standard error are shown for each version and paint model in Table 8. Comparisons between ShipIR versions show a progressive reduction in error with the current accuracy somewhere between +/-40–60% for this particular data set and IR band. As per Table 1, a second set of paint measurements were taken by Surface Optics in 2004, and their comparison with NATO paint measurements from 2001 show a further reduction of almost 15% in contrast signature. Furthermore, the two paint property measurements put the two solar-illuminated runs from Q276 (run04, run05) on either side of the comparison line of Figure 9, providing another good example of how redundant data and sensitivity analysis can be used to isolate the model input error (U_P) from the true model error (U_T). Comparisons of the contrast signature for the 8–12μm band are still pending the results of a more recent trial (Q289) held in September 2005, where better 8–12μm image calibrations were obtained using a cold calibration source. This new data will be used to validate both ShipIR (v3.2) and the new partial cloud model developed in ShipIR (v3.3).

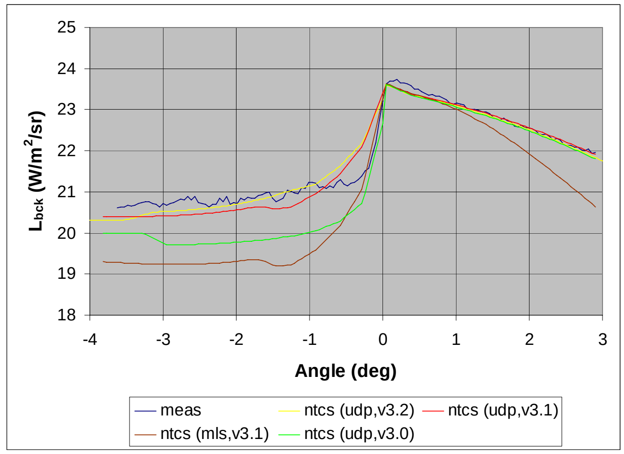

Figure 7: 8–12μm background radiance on clear day (Q262, run08) using different versions and a user-defined profile (udp).

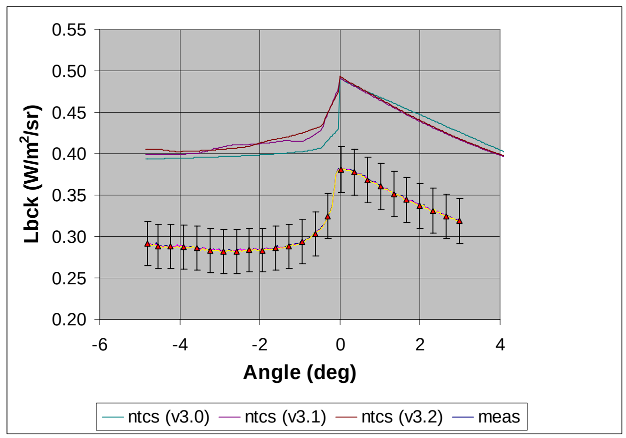

Figure 8: 3–5μm background radiance on clear day (Q276, run05) using a different versions and a standard atmosphere (mls).

Table 7: Statistical comparison of 3–5μm and 8–12μm background radiance profiles for a select number of trial runs.

Description	Sky radiance (W/m²/sr)		Sea radiance (W/m²/sr)	
	mean (μ)	std. dev. (σ)	mean (μ)	std. dev. (σ)
Q262 (run08), clear-day, 8–12μm				
ShipIR (v3.2, udp)	0	0.092	0.05	0.387
ShipIR (v3.1, udp)	0	0.079	-0.11	0.340
ShipIR (v3.0, udp)	-0.10	0.082	-0.89	0.226
ShipIR (v3.1, mls)	-0.46	0.372	-1.30	0.508
Q262 (run08), clear-day, 3–5μm				
ShipIR (v3.2, udp)	0.040	0.0040	0.069	0.0075
ShipIR (v3.1, udp)	0.070	0.0094	0.080	0.0126
ShipIR (v3.1, mls)	0.061	0.0077	0.079	0.0122

Description	Sky radiance (W/m²/sr)		Sea radiance (W/m²/sr)	
	mean (μ)	std. dev. (σ)	mean (μ)	std. dev. (σ)
Q276 (run05), clear-day, 3–5μm				
ShipIR (v3.2, mls)	0.103	0.0019	0.123	0.0073
ShipIR(v3.1, mls)	0.102	0.0025	0.121	0.0074
ShipIR (v3.0, mls)	0.107	0.0027	0.108	0.0096
Q280 (run11), clear-day, mlw				
8–12μm	0.76	0.189	-2.52	1.230
3–5μm	0.150	0.0268	0.130	0.0234
Q280 (run22), overcast, mlw				
8–12μm	2.65	0.18	1.98	0.03
3–5μm	0.203	0.0310	0.231	0.0266

4. Summary and conclusions

This paper has described the efforts to upgrade and validate ShipIR since its adoption as a NATO-standard almost a decade ago. Proper validation experiments have played a key role in model development by tailoring the measurement to specific areas of study or improvement, providing better understanding of the intermediate variables and sub-models and their effect on overall accuracy of IR signature prediction. The methods used by Fraedrich and Goldberg (2000) and Fraedrich and Gover (2001) have been applied to the various experiments on Quest to distinguish model input errors from true model errors. The Quest trial measurements and instrumentation have been described along with some standard techniques to compare the IR model with measured data.

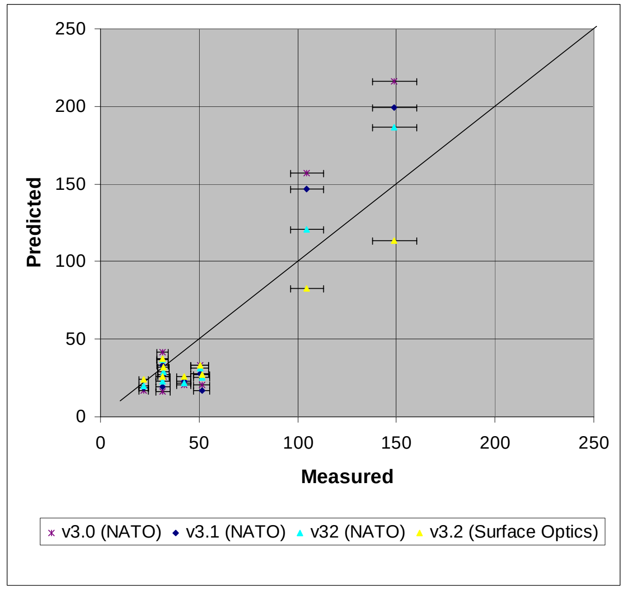

Figure 9: Predicted versus measured 3–5μm ship signature (W/sr) for Q276 using different versions of NTCS and Quest paint properties.

Table 8: Mean and variance (2σ) in predicted 3–5μm ship signature of Q276.

Version / Paint Property	Difference (%) mean (μ)	Difference (%) variance (2σ)	No. of points
v3.0 (NATO)	-12%	86%	9
v3.1 (NATO)	-16%	78%	
v3.2 (NATO)	-14%	58%	
v3.2 (Surface Optics)	-17%	44%	

Based on these results, the accuracy of ShipIR (v3.2) can be summarized as follows. The prediction of down-welling solar and thermal sky irradiance are within the accuracy of the measurements (+/-5% Full-Scale) for the current domain of the model (clear and overcast sky conditions). The absolute accuracy of ShipIR (v3.2) surface temperature prediction is +/-4°C for clear-day, +/-2.5°C for overcast-day and +/-2°C for night conditions. The accuracy of MODTRAN and ShipIR to predict in-band background radiance near the horizon is a function of IR band, atmosphere profile and seasonal weather conditions. The 8–12μm sea radiance is found to be strongly dependent on radiosonde input from the sky model and 2nd-order sea-slope shadowing near the horizon. The daytime 3–5μm background radiance predictions are strongly affected by the solar-scattering and less affected by radiosonde input and 2nd-order hiding. Despite relatively large offset differences in absolute background radiance, the standard deviation between the measured and predicted background profiles was found to be very low with values ranging from 0.4–1.3% in the 8–12μm band, and 0.15–4.0% in the 3–5μm band, reinforcing the notion that both the model and measurement are more accurate in contrast signature than absolute signature. The contrast signature results are limited to the 3–5μm band of the Q276 trial, but indicate an almost 50% reduction in residual error compared to ShipIR (v3.0), and highlight the particular susceptibility of the Quest measurements to variations in the 3–5μm reflectance of white paints.

A recent Quest trial (Q289) was executed in September 2005, and the NATO Task Group TG-51 has scheduled another NATO Quest trial in the Chesapeake Bay for June 2006. New instrumentation and measurement runs are being planned to isolate other sub-model variables (e.g., thermal and solar irradiance around the horizon) so that other possible sources of error in the sub-models can be evaluated. Higher ship speeds will be used to further test the new high-Reynolds convection model, and additional sea/sky radiance maps will be collected to validate the MODTRAN sky model, the sea mode, and the partial cloud model of ShipIR (v3.3).

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