ITTC Quality System Manual
Recommended Procedures and Guidelines

Procedure

Statistical Validation of Extrapolation Methods for Time Domain Numerical Simulation of Ship Motions

7.5	Process Control
7.5-02	Testing and Extrapolation Methods
7.5-02-01	General
7.5-02-01-11	Statistical Validation of Extrapolation Methods for Time Domain Numerical Simulation of Ship Motions

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Table of Contents

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1. SCOPE OF PROCEDURE

1.1 Objective

The present procedure has been developed in support of direct stability assessment within second generation IMO intact stability criteria, introduced by the Interim Guidelines in MSC.1/Circ.1627 (IMO 2020) – cited further just as the "Interim Guidelines".

The purpose of the procedure is to formulate a process for the validation of statistical extrapolation methods for time domain numerical simulation of ship motions and loads.

The validation of a statistical extrapolation aims at demonstrating that the extrapolated value is in reasonable statistical agreement with the result of the direct counting procedure, if such volume of data would be available. Requirements for validation of extrapolation procedures are formulated in section 3.5.6 of the Interim Guidelines.

Additionally, this procedure may be applicable to validation of extrapolation methods outside of the scope of the second generation IMO (2023) intact stability criteria, including but not limited to other ship motions processes or other failure definitions.

Application of this procedure is not limited to extrapolation methods are described in ITTC Recommended Procedure 7.5-02-07-04.6 "Extrapolation for Direct Stability Assessment in Waves" (ITTC 2024a).

1.2 Limitations

The present procedure outlines the validation of the statistical extrapolation methods but does not address the validation of the numerical simulation tool. The procedure does not contain description of any extrapolation methods.

2. DEFINITION AND REQUIREMENTS

The statistical extrapolation predicts random, extreme, rare events from a set of smaller, more recurring events based on the statistical properties of a smaller data set. The objective of the extrapolation is to predict the probability of events that are too rare to be captured/quantified from model tests or numerical simulations of reasonable duration.

Validation is based on the Specific Intended Uses (SIU) of the extrapolation. The SIUs serve to limit the scope of the validation to a reasonable and useful domain. The SIUs also define the operational and environmental conditions and type of response and statistics, where the simulation is applicable.

For the validation of an extrapolation method to predict extreme, rare motion values, the SIU can be to determine the upper boundary of the confidence interval of the mean crossing rate at a specified comparison level on specified exposure time for a given motion, speed, heading and environmental conditions.

For dynamic stability failures, the probability is derived from time domain simulations, based on Poisson assumption that relates time and probability, i.e., based on the event rate λ, where the probability of at least one stability failure during exposure time T is expressed as:

$$p(T) = 1 - e^{-\lambda T} \quad (1)$$

Two important aspects should be considered here. First, stability failure is defined, which should be associated to the exceedance of a certain level (crossing level) of a ship motion process. The Interim Guidelines (section 3.2.1) defines the failure as exceedance of roll angle of 40 degrees or exceedance of lateral acceleration of 9.81 m/s^2.

Second, the exposure time or duration, which should be long enough (in theory, infinite) to observe and reliably estimate the probability of failure. The value corresponding to infinite time is defined as the "true" value. The "true" value is required to validate the statistical extrapolation method. The large-volume dataset to produce this "true" value is further referred as "validation dataset".

Since both experimental data and high-fidelity simulations with very long durations for the statistical characterization of extreme rare events are impractical, a simulation tool of reduced complexity, but capable of correctly representing the physics of the phenomenon is required.

To verify that such reduced complexity simulation tool correctly represents a physics of stability failure, a qualitative validation of this tool may be performed. Requirements for qualitative validation are formulated in section 3.4.2 of the Interim Guidelines and further explained in section 3.4.2 and in Section 2 of Appendix 4 to the Explanatory Notes to the Interim Guidelines, MSC.1/Circ.1652 (IMO 2023), cited further just as "Explanatory Notes".

To obtain an estimate of the crossing rate from the validation dataset, a direct counting procedure is applied, described in the ITTC Recommended Procedure 7.5-02-01-10 "Estimation of Frequency of Random Events" (ITTC 2024).

A subset from the the validation dataset is extracted following data requirement for a particular extrapolation method to be validated. This subset is further referred as "extrapolation dataset".

A number of extrapolation datasets is required in order to account properly for natural statistical variability and test confidence interval of extrapolated estimate. Interim Guidelines requires 50 extrapolation datasets.

For dynamic stability assessment, a condition is defined as a unique combination of environmental parameters (ex: sea states), the ship speed and heading, and its motions. A validation comparison should be made for each condition of interest.

The validation consists of three (3) tiers of validation: tier 1 is performed on an individual extrapolation dataset, tier 2 works with series of the extrapolation datasets coming from the same condition and tier 3 covers several conditions.

3. PREPARATION FOR VALIDATION

Data preparation for validation of an extrapolation method requires the following steps. The validation is performed following the steps.

3.1 Qualitative validation of reduced-complexity simulation tool

To demonstrate that the reduced-order simulation is capable to reproduced basic physics of a stability failure phenomenon, a qualitative validation needs to be carried out as described in section 3.4.2 of the Interim Guidelines. The qualitative validation requirements are failuremode specific. Some of the qualitative validation requirements are further detailed in sections 2.1 through 2.4 of the Appendix 4 to the Explanatory notes.

3.2 Validation simulation campaign

The reduced-complexity simulation tool generates the validation dataset, i.e., a large simulation dataset with a statistically sufficient number of stability failures. The validation dataset should cover several conditions combining ship speeds, relative wave headings, and sea states.

The sea states and speeds are to represent typical conditions of operations. Caution should be exercised while selecting of the conditions for generation of the validation dataset, as some of them may not produce sufficient number of failures. Sample size of known validation datasets, generated for statistical validation, could be on the order of millions of full-scale hours (Campbell et al. 2023, Weems et al. 2023).

"True" values of crossing rate are estimated with one of the methods described in ITTC Recommended procedure 7.5-02-01-10 "Estimation of Frequency of Random Events" (ITTC 2024).

3.3 Estimation if extrapolated values

The extrapolation datasets are extracted from validation dataset. Volume of sample for validation dataset is defined by data requirements of the extrapolation method to be validated. The Interim Guidelines suggests 50 extrapolation datasets for each condition. More extrapolation datasets may be used for exploratory purposes.

Revision 01 of the ITTC Recommended Procedure 7.5-02-07-04.6 "Extrapolation for Direct Stability Assessment in Waves" (ITTC 2024a) describes application of three extrapolation methods: Split-time/MPM, EPOT and Extrapolation-over wave height. Carrying out necessary calculations produced 50 (or more) extrapolated estimates, grouped per relative wave heading, forward speed and sea state.

4. ACCEPTANCE CRITERIA

4.1 Tier 1 Validation: Single Extrapolation

The base for comparison is an estimate of the crossing rate from direct observation. Per ITTC Recommended procedure 7.5-02-01-10 "Estimation of Frequency of Random Events" (ITTC 2024), this estimate come with a confidence interval, expressing its uncertainty: $\left[\lambda_{low}^{T};\lambda_{up}^{T}\right]$. This estimate serves as a "true" value. The values in brackets represent the lower and upper values of the confidence interval, the superscript T stand for the "true" value.

Per ITTC Recommended Procedure 7.5-02-07-04.6 "Extrapolation for Direct Stability Assessment in Waves" (ITTC, 2024a), an estimate extrapolated from a single extrapolation dataset also comes with confidence interval: $\left[\lambda_{low}^{E};\lambda_{up}^{E}\right]$. The values in brackets represent the lower and upper values of the confidence interval, the superscript E stands for the extrapolated estimate.

If these confidence intervals overlap, a probability that these estimates are equal is finite, i.e. is not infinitely small. Then, following standard logic of testing of hypothesis, the observed difference between the estimates can be explained by random reasons, and the estimates may be considered equal in a statistical sense. The result of tier 1 validation is expressed as:

$$C_1 = \begin{cases} 1 & \left[\lambda_{low}^{E};\lambda_{up}^{E}\right] \cap \left[\lambda_{low}^{T};\lambda_{up}^{T}\right] \neq \emptyset \\ 0 & \left[\lambda_{low}^{E};\lambda_{up}^{E}\right] \cap \left[\lambda_{low}^{T};\lambda_{up}^{T}\right] = \emptyset \end{cases} \quad (2)$$

where $C_1 = 1$ is means success and $C_1 = 0$ means failure, see also Figure 1.

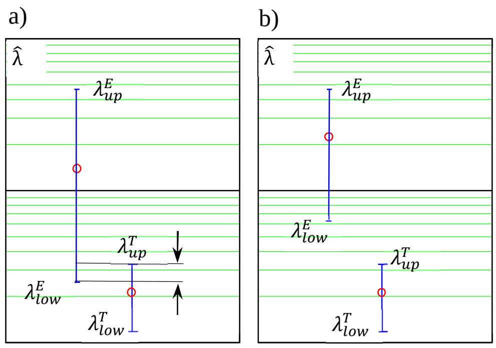

Figure 1: Tier 1 validation (a) success (b) failure

4.2 Tier 2 Validation: Single Condition

Multiple extrapolation datasets computed for the same environmental / loading conditions, speed, and heading are for tier 2 validation.

The acceptance criterion for the level 2 is an average of the tier 1 results also referred as a “passing rate”:

$$C_2 = \frac{1}{N_{EX}} \sum_{i=1}^{N_{EX}} C_{1i} \quad (3)$$

where N_{EX} is a number of extrapolation datasets. The Interim Guidelines suggests 50 extrapolation datasets (paragraph 3.5.6.5).

Adjudication on the tier 2 validation accounts for natural variability of extrapolated estimates i.e. testing how correctly confidence interval is constructed. Smith (2019) considered each tier 1 validation as a Bernoulli trial and proposed the boundaries for acceptance of C_2 to be computed through binomial quantiles as:

$$B_{2up,low} = \frac{1}{N_{EX}} Q_B\left(0.5(1 \pm P_\beta), N_{EX}, P_\beta\right) \quad (4)$$

where P_β is an accepted confidence interval. A typical value of the confidence probability is 0.95 and is also suggested by the Interim Guidelines (paragraph 3.5.6.4).

For the $N_{EX} = 50$ and $P_\beta = 0.95$, the tier 2 acceptance interval is:

$$B_{2up,low} = [0.88; 1.0] \quad (5)$$

The value of 0.88 as a standard for passing rate is mentioned in the paragraph 3.5.6.7 of the Interim Guidelines. The number of extrapolation datasets $N_{EX} = 50$ is to low for any limitation of upper boundary. Increasing number of the extrapolation datasets imposes an upper limit for the passing rate, e.g. Weems et al. (2023).

Figure 2 illustrates a successful tier 2 validation. While significant variation of the extrapolated values is observed, the true value was “captured” 45 times out of 50 making the passing rate 0.9. Figure 3 demonstrates how a failure of tier 2 validation may look. With the passing rate only 0.68, the mean values of extrapolated estimates are all located on one side of the “true” value, suggesting overestimation of crossing rate by an extrapolation method for this condition.

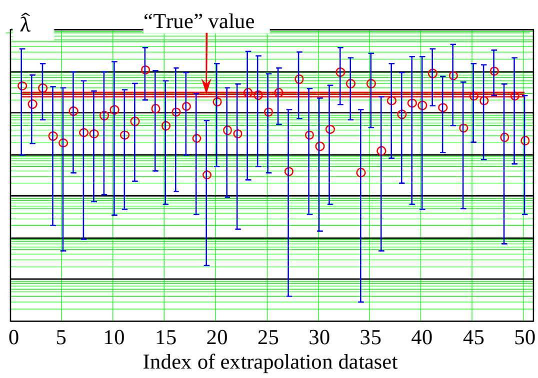

Figure 2: Tier 2 Validation: Success. Passing rate 0.9, with the tier 1 failures on datasets 19, 27, 30, 34 and 36.

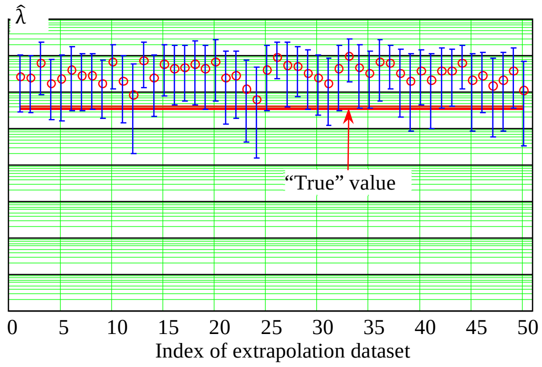

Figure 3; Tier 2 Validation: Failure. Passing rate 0.68.

4.3 Tier 3 Validation: Multiple Conditions

Interim Guidelines suggest that validation has to be performed for a number of ship speeds, relative wave heading, and sea states (paragraph 3.5.6.6).

The objective of Tier 3 validation is not only to accept or reject an extrapolation method for a particular specific intended use but also find limitations where considered extrapolation method can be applied.

Example of such analysis can be found in Campbell et al. (2023), where partial Tier 3 validation for EPOT method for multiple extrapolation targets is described (single sea state and speed only). The EPOT is one of the extrapolation method, described in ITTC Recommended Procedure 7.5-02-07-04.6 "Extrapolation for Direct Stability Assessment in Waves" (ITTC 2024a), as well as in the Interim Guidelines (paragraph 3.5.5.4.1) and the Explanatory Notes (Section 5.4 of Appendix 4). The EPOT, method with Pareto tail, may be not applicable to oblique sea heading where nonlinearity of roll has been sufficiently manifested i.e. roll motions are too small. This kind of conclusion is expected from the Tier 3 validation effort.

Natural variability of extrapolated estimate, caused by statistical uncertainty, is not the only imperfection of extrapolation methods. As these methods are intended for nonlinear dynamical systems under random excitation, inevitably, other assumptions are made.

The impact of these assumption may be seen as a relatively small deviation from the boundaries (5). To account for impact these assumptions, an empirical assumption allowance is introduced. Based on results of Campbell et al. (2023) its value is set to 0.05.

Figure 4 illustrates tier 3 adjudication, where the results of tier 2 validation are plotted against relative wave heading. Different speeds are identified with different shapes, while sea states are identified with color. Some of the tier 2 points have fallen below the theoretical low boundary of 0.88, as their deviation was within the approximation allowance. These are still considered as "successful". The point at 135 degrees heading at Speed 1 and Sea state 1 has fallen significantly below the lower boundary is recognized as failure. Based on this notional example, the extrapolation method could be validated for stern-quartering and beam seas. i.e. from 15 to 90 degrees, but not oblique seas

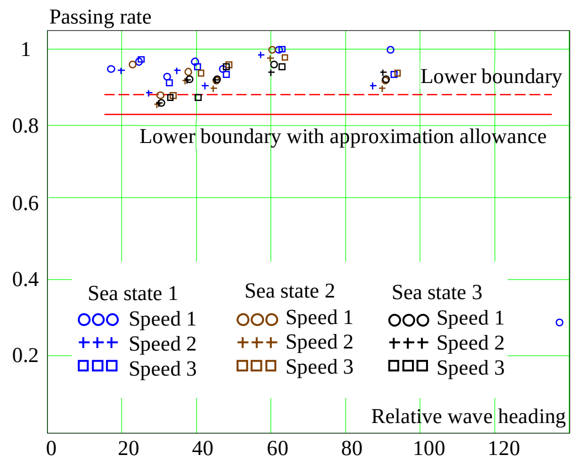

Figure 4: Notional tier 3 validation

5. LIST OF SYMBOLS

B_2 Acceptable boundaries for the second-tier validation criterion
C_1 First-tier validation criterion
C_2 Second-tier validation criterion
N_{EX} Number of extrapolated datasets
P_β Confidence probability
p Probability
Q_B Quantile of binomial distribution
T Time of exposure
λ Rate of stability failures
λ^E Extrapolated rate of stability failures
λ^T "True" rate of stability failures
$\square_{up}$ Upper boundary of confidence interval
$\square_{low}$ Lower boundary of confidence interval

6. REFERENCES

Bishop, R. C., W. Belknap, C. Turner, B. Simon & J. H. Kim (2005) Parametric Investigation on the Influence of GM, Roll damping, and Above-Water Form on the Roll Response of Model 5613, Hydromechanics Department Report NSWCCD-50-TR-2005/027, Naval Surface Warfare Center Carderock Division, West Bethesda, Maryland, USA.

Bretschneider, C. L. (1959) "Wave Variability and Wave Spectra for Wind-Generated Gravity Waves," U. S. Army Beach Erosion Board, Technical Memorandum 118, Washington, DC, USA.

Campbell, B., K. Weems, V. Belenky, V. Pipiras, & T. Sapsis (2023) "Envelope Peaks over Threshold (EPOT) Application and Verification," Chapter 16 of *Contemporary Ideas on Ship Stability – From Dynamics to Criteria*, Spyrou, K., V. Belenky, T. Katayama, I. Bačkalov & A. Francescutto, eds., Springer, ISBN 978-3-031-16328-9, pp. 265-289.

IMO MSC.1/Circ.1627 "Interim Guidelines on the Second Generation Intact Stability Criteria", London, UK, December, 2020.

IMO, MSC.1/Circ.1652 "Explanatory notes to the interim guidelines on the second generation intact stability criteria", London, UK, April, 2023.

ITTC (2024) "Estimation of Frequency of Random Events" ITTC Recommended Procedure 7.5-02-07-10, Revision 00, 30th Int'l. Towing Tank Conf.

ITTC (2024a) "Extrapolation for Direct Stability Assessment in Waves" ITTC Recommended Procedure 7.5-02-07-04.6, Revision 01, 30th Int'l. Towing Tank Conf.

Smith, T. C. (2019) "Validation Approach for Statistical Extrapolation", Chapter 34 of *Contemporary Ideas on Ship Stability. Risk of Capsizing*, Belenky, V., K. Spyrou, F. van Walree, M. A. S Neves & N. Umeda, eds., Springer, ISBN 978-3-030-00514-6, pp. 573-589.

Weems, K., V. Belenky & K. Spyrou (2018) "Numerical Simulations for Validating Models of Extreme Ship Motions in Irregular Waves," *Proc. 32nd Symp. Naval Hydrodynamics*, Hamburg, Germany.

Weems, K., & V. Belenky (2023) "Reduced-order Model for Ship Motions incorporating a Volume-based Calculation of Body-nonlinear Hydrostatic and Froude-Krylov Forces," *Ocean Eng.*, Special Issue on Extreme Stochastic Dynamics Ships Vol. 289, 116214.

Weems, K., V. Belenky, B. Campbell, & V. Pipiras (2023) "Statistical Validation of the Split-Time Method with Volume-Based Numerical Simulation," Chapter 14 of *Contemporary Ideas on Ship Stability – From Dynamics to Criteria*, Spyrou, K., V. Belenky,

T. Katayama, I. Bačkalov & A. Francescutto, eds., Springer, ISBN 978-3-031-16328-9, pp. 225-243.

Weems, K., V. Pipiras & V. Belenky (2023a) "Multifidelity Fast Code for Direct Stability Assessment," *Proc. of 19th Int'l. Ship Stability Workshop*, Istanbul, Turkey, pp. 201-210.

Appendix A. EXAMPLE

Example of partial validation of EPOT extrapolation method is based on data from Campbell et al. (2023). The validation is partial as the scope is limited by a single sea state and speed.

A.1. Input Data

The example uses the data from ONR (U. S. Office of Naval Research) tumblehome topside configuration (Bishop et al. 2005). Principal dimensions and other general input data are placed in Table A1, while the lines are in Figure A1.

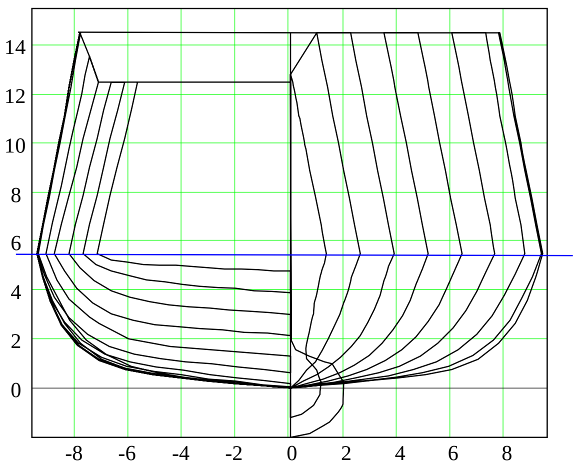

Figure A1: ONR tumblehome topside configuration

Table A1: Principal input data

Length BP, m	154
Breadth molded, m	18
Draft amidships, m	5.5
KG, m	7.5
Displacement, t	8675.6
GM, m	2.2
Speed, knot	6

A.2. Simulation Tool of Reduced Complexity

Fast volume-based simulation tool (Weems and Belenky 2023; Weems et al. 2023a) generated sample data. Simulation included 3 degrees of freedom: heave-roll-pitch. While these 3 degrees of freedom may be insufficient for direct assessment for all modes of failure under the Second Generation IMO Stability Criteria per MSC.1/Circ. 1627, this simplified simulation is capable of producing the data to serve as an example for validation of extrapolation.

While no formal qualitative validation data is available on this reduced-complexity simulation tool, some information on comparison with an advanced nonlinear simulation tool LAMP (Large Amplitude Motion Program) is available from Weems et al. (2018, 2023a).

A.3. Generation of Validation Dataset

Wave environment was represented by long-crested irregular waves generated with Bretschneider (1959) spectrum. The significant wave height was 9 m and modal period 15 s. The spectrum was discretized with 240 frequencies from 0.26 to 0.9 1/s. Duration of a record without self-repeating effect was 30 min.

Summary of validation simulation campaign is given in Table A2. Detail description and numerical results are available from Campbell et al (2023). Targets of 40 degrees are only available for heading angles from 30 to 60 degrees.

Table A2: Validation simulation campaign

Headings deg	Total time, h	Largest target
15	285,000	20
22.5	100,000	27.5
30	100,000	45
37.5	100,000	60
45	345,000	70
60	300,000	70
90	345,000	37.5
135	345,000	20

A.4. Extrapolation Datasets and Results

Fifty (50) extrapolation datasets were formed. Each extrapolation dataset consisted from 50 records, or 25 hours worth of data. Figures A2 through A5 provide results of extrapolations and the "true" value.

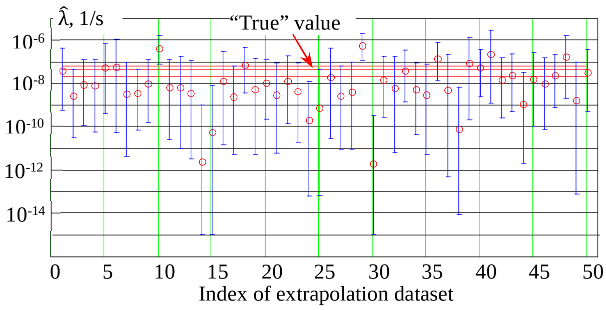

Figure A2: Heading 30 deg, passing rate 0.86

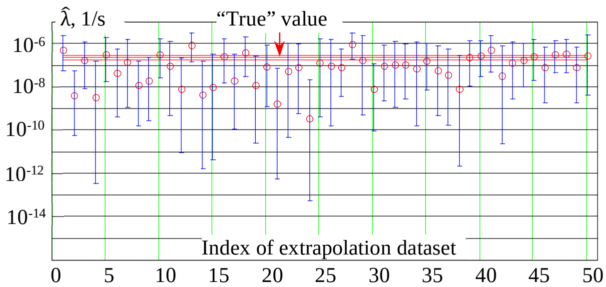

Figure A3: Heading 37.5 deg, passing rate 0.86

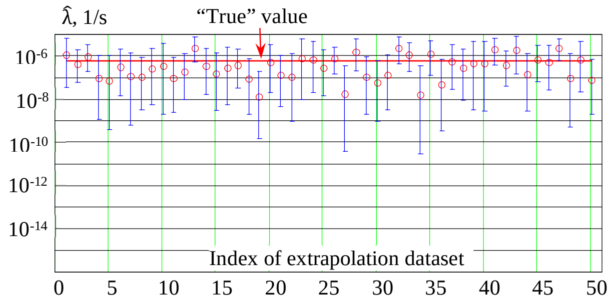

Figure A4: Heading 45 deg, passing rate 0.94

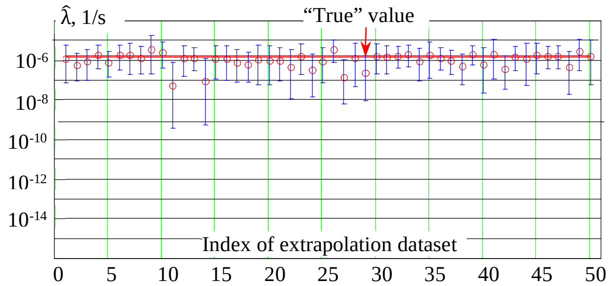

Figure A5: Heading 60 deg, passing rate 0.94

A.5. Validation of Extrapolation

Figures A2 through A5 contain results of Tier 1 and Tier 2 validation. Values of passing rated obtained from the Tier 2 validation plotted in Figure A6 against the heading angle. As the data only represent one speed and one sea state, the validation example is only partial. Nevertheless, the passing rate for considered for conditions are above the lower boundary with 5% approximation allowance.

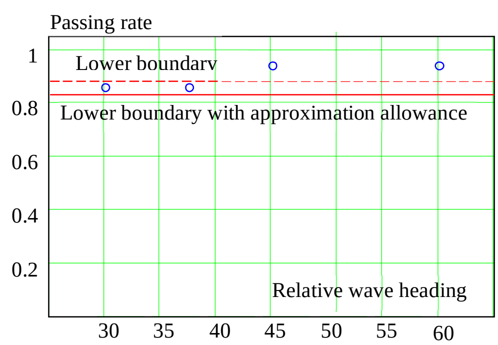

Figure A6: Partial tier 3 (multiple conditions) validation of EPOT for 40 degrees exceedance rate