FINAL REPORT

1 General Information

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Cooperation partners:	-
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2 Summary

Die Entwicklung von Vorhersagen zeitnah bevorstehender extremer Meereswellen ist ein wichtiges Ziel für Schifffahrt und Meerestechnik. Die zu Projektbeginn vorliegenden Vorhersagemethoden bildeten den Seegang bestenfalls der folgenden Minute zufriedenstellend ab. Ursächlich hierfür waren Schwierigkeiten bei der Berücksichtigung amplitudenabhängiger Dispersionseffekte im Modell, bei gleichzeitiger Echtzeitfähigkeit des Simulationsverfahrens. Die Vorhersage von Seegang als chaotisches System ist zudem sehr empfindlich gegenüber Fehlern, Ungenauigkeiten und Unsicherheiten in den Messdaten von Anfangsbedingungen, die anschließend in die Vorhersageverfahren eingehen. Wellenphysikalische Studien legen nahe, dass Vorhersagen bis zu etwa 10 Minuten, je nach Seegangszustand auch deutlich darüber hinaus, möglich sein sollten. Um hinreichend genauer Vorhersagen für einen derartigen Zeitraum darzustellen, sind jedoch zwei Hindernisse zu bewältigen. Zunächst müssen die Verfahren zur Identifikation des Anfangsseegangs aus den Messdaten verbessert werden. Dann ist der Rechenzeitbedarf für die Prognosen so zu minimieren, dass die Vorhersagen tatsächlich rechtzeitig vorliegen, idealerweise in nahezu Echtzeit bereits kurz nach Vorliegen der Messdaten. Im vorliegenden Projekt wurden drei Themenbereiche verbunden, um dieses Ziel zu erreichen: (i) Nichtlineare Wellenphysik, (ii) numerische Wellenfeldsimulation, und (iii) datenbasierte Verfahren des maschinellen Lernens und der künstlichen Intelligenz. Die Vision des Projekts bestand in einer geeigneten Kombination und Gewichtung von Verfahren der drei Domänen, sodass Vorhersagezeiten von fünf bis zehn Minuten, bei einem hinreichend kleinen Amplituden- und Phasenfehler möglich sind. Die gesteckten Ziele wurden erreicht. Einerseits gelang es, diskretisierungsbasierte Lösungsverfahren der physikbasierten Bewegungsgleichungen nichtlinearer Meereswellen auf so auf die verfügbaren Daten anzupassen, dass die Berechnungsgeschwindigkeiten um mehr als eine Größenordnung gesteigert werden konnten. Andererseits wurde in einem parallelen Untersuchungsstrang gezeigt, wie physikgestützte Verfahren des maschinellen Lernens, als einer Untergruppe von Verfahren der künstlichen Intelligenz, für die Erfassung und Vorausberechnung realistischer Seegangszustände verwendet werden können. Die so entwickelten Berechnungsverfahren erfassen neben üblichen Seegängen auch die manchmal als Monsterwellen bezeichneten extremen Wellenzustände. Wir erwarten, dass die entwickelten Methoden Ausgangspunkt für weitere Arbeiten der numerischen Wellenberechnung sein werden und Niederschlag in einer Reihe von Anwendungsfeldern finden. Beispielsweise bei der Schiffsführung, der Routenplanung, dem Bau und Betrieb von Offshore-Anlagen wie Windkraftwerken, Meeresenergieanlagen, aber auch bei Rettungsoperationen wie Hubschrauberlandungen auf Schiffen in schwerer See.

Achieving short-term predictions of rogue waves on the ocean is widely considered an important objective for offshore operations and shipping. At the start of the project, none of the available approaches and methods published or used could be considered satisfying. Prediction times were on the order of a minute or less. Probably the most important reason for this was the inability to integrate the wave amplitude dependent dispersion effects properly into a computating and simulation environment that is numerically efficient enough to have real-time capability. The present state-of-the-art was thus far below what was needed. Two key obstacles were to be overcome: First, from the available wave-state measurement data, initial or initial-boundary conditions had to be identified for the subsequent prediction process. Second, the prediction processes themselves needed to reach a substantially higher quality and numerical efficiency, if real-time capability was intended. Three research fields were to be connected for progress: (i) understanding the physics of rogue ocean waves, (ii) predicting the short-term occurrence of rogue ocean waves by numerical simulation, and (iii) employing data driven methods from artificial intelligence and machine learning in the context of rogue ocean waves. In the project we succeeded to integrate the three fields of knowledge and methods to develop novel hybrid approaches. The project aimed at studying optimised combinations of all three fields mentioned to push the boundary of how one can achieve predictions closer to the theoretically possible horizon of predictability. The objectives have been reached. By combinations of wave physics, advanced numerical simulation, and data driven methods novel algorithms and approaches have been developed which allow an improvement of the achievable prediction horizon by at least one order or magnitude. This implies a sufficient accuracy in terms of amplitude and phase error of the prediction within the desired time frame. The achievement is based on mainly two streams of work. First, methods based on physical evolution equations were approached by traditional discretization based numerical schemes in combination with methods to deal with sparse data, as it results from typical wave observation techniques, like marine radars or buoys. Second, physics-informed methods of machine learning were developed to efficiently tackle the nonlinear wave evolution problem of surface gravity waves. Both approaches now enable viable predictions of ocean waves, including the rare and extreme ocean rogue waves. We expect that the new methods will serve as starting points for even more advanced ocean wave prediction tools, and we expect the methods to find wide applicability in many fields of offshore and maritime engineering, like sea-keeping, ship routing, early warning to evacuate dangerous zones on ships or platforms, construction of offshore wind plants or ocean wave energy harvesters.

3 Progress Report

- Background and objectives of the project

The project dealt with the excitability of large and extreme ocean waves, often designated as rogue waves. Rogue ocean waves are important in many senses in maritime engineering and naval architecture. In terms of design, structures and ships have to withstand the rare encounters. In terms of operation, structures have to be able to deal with the very large but rare wave encounters, and ships might prefer routes without very large waves. To better understand the physics of rogue waves, and to potentially also predict them a few minutes ahead of their occurrence is thus an important subject.

In the first phase of the project, the objectives were mostly on the physics and phenomenological side: the excitability of rogue ocean waves on non-regular background, i.e in natural sea states, was studied. Both milder and stronger irregularity was treated. In parallel, potentially novel sea state characteristics were to be studied and identified. In the second phase of the project, four objectives were defined. First, to develop viable data assimilation and wave field reconstruction methods. Second, to advance the wave field identification achieved in phase one of the project. Third, to develop combined data and physics based approaches to simulate and predict realistic wave states. And fourth, to identify precursors of rogue waves or ways to identify them ahead of their actual occurrence.

- Description of the project-specific results and findings.

A primary objective of the first phase of the project was to improve the understanding of the randomness of sea states and to better understand how, why, and when rogue waves of the Peregrine type can be excited or generated. For that purpose studies on time-series analysis and stochastic model reconstruction have been conducted. Measured ocean wave data from the North Sea and from the Japanese sea, with and without rogue waves, were available. After progress on multi-scale embedding and phase space reconstruction had already been achieved around the start time of the project (Hadjihosseini et al. 2014), further progress on the embedding were accomplished by including the surface elevation increments and the absolute surface elevations into the phase space reconstruction process as independent variables. It turned out that Markov properties could be confirmed from the so derived models, and Fokker-Planck type stochastic differential equations could be derived that captured the full single-point and multi-point statistics of the stochastic process corresponding to the natural, irregular sea state. From that description distribution functions for increments over varying scales, but also for peak wave heights could be calculated (Hadjihos-

seini et al. 2016). All the work was carried out in close collaboration with the team of Prof Peinke in Oldenburg.

From the statistical characterisation it became clear that three-dimensionality and phase-effects are of crucial importance in the generation of rogue waves. Another objective of the first past phase of the project on the excitability of Peregrine waves in complex sea states was to increase the understanding on broad-banded non-unidirectional nonlinear states, as an improved understanding of the interplay of nonlinearity and short-crestedness of large wave events was desired. For that purpose symmetry and transformation properties of the Nonlinear Schrödinger Equation (NLS) with respect to spatial rotations were identified and exploited. It was possible to derive analytically, and to generate experimentally, for the very first time short crested Peregrine breather waves on deep water. These completely novel, fully threedimensional complex Peregrine breather type waves might well be considered to be at the origin of rogue wave formation in broad-banded non-planar sea states, or in other words, to form the nonlinear prototypes of short-crested deep water ocean rogue waves. The results have been published in the Proceedings of the National Academy of the Sciences (PNAS), (Chabchoub et al. 2019), one of the globally highest-impact journals of the sciences.

Further work of exploiting the nonlinear rotational transformation resulted in identifying novel, previously unknown, solutions for threedimensional, nonlinear and time-dependent phase domain walls in deep water waves. With a view to the sensitivity of Peregrine rogue wave solutions to phase effects, the identification of truly nonlinear states linking plane waves differing by a phase shift seems promising towards further understanding of threedimensional and shortcrested effects. In detail, it turns out that nonlinear solutions of the two-dimensional defocussing NLS can be transformed to nonlinear solutions of the three-dimensional focussing NLS. The defocussing dark soliton solutions in two dimensions so have corresponding nonlinear non-stationary phase domain solutions in three dimensions. The results were published in the Physical Review Letters (PRL) (Tsitoura et al. 2018). When the phase shift is 180 degrees, the domain wall is aligned with the wave propagation direction and remains stationary. Smaller phase differences correspond to more inclined and laterally moving domain walls or domain boundaries.

After further clarification on the role and subtlety of three-dimensionality and phase effects, numerical studies were conducted. Especially after having seen that there is a short-crested Peregrine type rogue wave, it was to be studied numerically in a full three dimensional wave field. The high-order spectral method (HOS), basically a numerically efficient Euler solver for free surface flows, was adapted to the present problem. The first task consisted in identifying initial conditions from measurements. For that purpose a Krylov-subspace based model

order reduction was implemented to allow numerically efficient and accurate approximation for the wave field. Subsequently, nonlinear wave fields were time-marched (Köllisch et al. 2018). An error evaluation shows how a linear prediction quickly looses validity due to nonlinear dispersion effects. To give some characteristic numbers, a wave field of 2 x 2 km, evolving in physical time for 120 seconds, took about 6 seconds for the identification of initial conditions, and about 18 seconds for the simulation, with a nonlinear order of 4. So although the computer hardware was not very sophisticated, the results suggest that real-time prediction is achievable by further parallelization (using GPUs) and distributed computing. At the same time, when it comes to extreme waves (rogue waves), tests were conducted with Peregrine solutions. It clearly turned out that small details of the non-planar nature of the sea state play in important role, in accordance with our findings on three-dimensional analytical solutions, and that phenomena that affect the nonlinear dispersion will have a decisive role in determining whether a wave field does or does not tend to the emergence of an extreme wave like the Peregrine one.

Following this work towards numerical wave predictions, in (Klein et al. 2020) and (Wedler et al. 2022) progress was achieved towards more accurate simulations by improving the error measures used in comparing predicted results with actual ones. It had turned out that especially phase errors render predictions unusable. From a wave physics perspective this is closely linked to the nonlinearity, or amplitude dependency, of the underlying dispersion relations. On the one hand this makes nonlinear simulations necessary, on the other hand also the error measures comparing results need to reflect this. We introduced the so-called surface similarity parameter to the field. Although similar measures are well known in other fields of study, like in vibration analysis, where they are usually called modal assurance criteria, or in tribology and contact mechanics, they surprisingly do not seem to have been applied widely in ocean wave dynamics. At the heart of the method of the surface similarity parameter is considering amplitude and phase errors separately first, and then to combine them again. All our further studies have benefitted strongly from the new error measures.

Another substantial step forward was reached in the work of (Desmars et al. 2023). Here highly efficient interpolation methods to deal with sparse measurement data have been adapted to the problem: When marine radar data is used to identify the present sea state, it turns out that shadowing zones, where the radar has no access to, and measurement errors pose substantial difficulties to the approximation steps in wave state identification. Jointly with a fully nonlinear wave state modeling, the improved methods to take the sparse data into account have shown to strongly improve prediction potential. While these improvements turn out to apply in all wave states, they especially also work in the case of emerging rogue waves. It turned out that rogue waves can thus be predicted quite some time before they

actually rise to large levels. This finding in a sense answered the long-standing question if and how rogue waves can actually be identified ahead of time, and if and how they can be predicted. From an application perspective, to give some numbers on prediction horizons, it turned out that in irregular or natural sea states, predictions a few minutes before acutal occurrence are possible.

While work along the lines of (Desmars et al. 2023) continues, in parallel we also initiated work towards more data-based, machine-learning based methods. (Ehlers et al. 2023) opened a strand of research into predicting wave evolution by recurrent neural networks and encoder-decoder methods which have originally been derived from image analysis: here the ocean surface wave elevation is basically considered as a surface image. The training process includes the time-evolution of the wave field. The results are promising, however also show marked limitations, since there is no link to the underlying wave physics. It bacame clear that methods combining physics and data should be more powerful.

A first step toward hybrid methods was taken by identifying time-stepping algorithms directly from learning the data and the evolution (Stender et al. 2023). Another approach was tested by physics-informed neural networks (PINNs). They were first applied to the Nonlinear Schrödinger Wave Equation (Ehlers et al. 2024). The main motivation for this was to evaluate how Peregrine breather solutions could be modeled and simulated in the context of PINNs. The designed of an appropriate machine-learning network turned out non-trivial, but in the end we succeeded and were able to put down an efficient and effective implementation. From this, work continued towards wave models based on potential flow equations (Ehlers, Hoffmann et al. 2025). A viable PINN simulator was developed. While the approach basically works, it did not fulfil the efficiency requirements for real-time applications. For that reason, the approach was enhanced on the basis of Fourier-Neural-Operators (FNOs). The use of additional projections of the solution space onto a Fourier basis makes it possible to deal with more complicated higher-dimensional systems reasonably well, which comes out mostly in the training process: The developed FNO process allowed to train the neural networks much more accurately with the nonlinear wave evolution equations. For those a high order spectal method was used, and it seems that the spectral approach on the physics and equation side seems to match the spectral approach on the operator learning side very well.

With this we have come to the close of funding of the present project. Future work will deal with further improvement on the numerical efficiency, and with linking the phase-resolving work to phase-averaged wave modeling.

- Deviations from the original concept; findings that contradict the initial hypothesis

By and large the original concept of the project proposals have found excellent realization in the progress of the work and in the published results. At very early stages of the project we had somewhat larger expectations toward more highly abstracted concepts and measures to deal with the problem of excitability and occurrence of rogue waves. In the course of understanding the chaotic or turbulent nature of natural sea states better, also by the statistical analysis carried out, the focus of the study shifted more towards numerical and machine learning approaches. In a sense, the initial hypotheses needed to be modified somewhat, but the underlying vision was validated.

- Activities and approaches to quality-enhancing measures through which the validity or verifiability of your research findings was ensured

Much of the work is based on measurement data, which has been obtained at various national and international wave laboratories. Validation of simulation approaches and verification of software implementation has thus been ensured in team efforts. Moreover, the developed methods have all been published and are available for further validation, verification, and advancement by the research and application community.

- Description of the handling of research data generated in the project and the data infrastructures used

The research data accumulated in the project is handled according to the standard of our community. Wherever possible, data has been made available in the context of the publications.

- Implementation of scientific events, science communication measures

There has been a wide range of science communication to the public on the topic. Including coverage by television (Arte, ZDF), radio (Mare, NDR).

4 Published Project Results

4.1 Category A – Articles in peer-reviewed journals, contributions to peer-reviewed conferences or to anthology volumes, and book publications

A.Hadjihosseini, M. Wächter, N.P. Hoffmann, J. Peinke, Capturing rogue waves by multi-point statistics. New Journal of Physics 18 (1), 013017, 2016.
doi 10.1088/1367-2630/18/1/013017

A.Hadjihoseini, P.G. Lind, N. Mori, N.P. Hoffmann, J. Peinke, Rogue waves and entropy consumption. Europhysics Letters 120(3), 30008, 2017.
doi 10.1209/0295-5075/120/30008

N. Köllisch, J. Behrendt, M. Klein, N. Hoffmann, Nonlinear real time prediction of ocean surface waves. Ocean Engineering 157, 387-400, 2018.
doi 10.1016/j.oceaneng.2018.03.048

F. Tsitoura, U. Gietz, A. Chabchoub, N. Hoffmann, Phase Domain Walls in Weakly Nonlinear Deep Water Surface Gravity Waves. Physical Review Letters 120 (22), 224102, 2018.
doi 10.1103/PhysRevLett.120.224102

A.Chabchoub, K. Mozumi, N. Hoffmann, A.V. Babanin, A. Toffoli, J.N. Steer, T.S. van den Bremer, N. Akhmediev, M. Onorato, T. Waseda, Directional soliton and breather beams. Proceedings of the National Academy of Sciences 116, 9759-9763, 2019.
doi 10.1073/pnas.1821970116

M. Klein, M. Dudek, G.F. Clauss, S. Ehlers, J. Behrendt, N. Hoffmann, M. Onorato, On the deterministic prediction of water waves. Fluids 5 (1), 9, 2020.
doi 10.3390/fluids5010009

M. Wedler, M. Stender, M. Klein, S. Ehlers, N. Hoffmann, Surface similarity parameter: A new machine learning loss metric for oscillatory spatio-temporal data. Neural networks 156, 123-134, 2022.
doi 10.1016/j.neunet.2022.09.023

N. Desmars, M. Hartmann, J. Behrendt, N. Hoffmann, M. Klein, Nonlinear deterministic reconstruction and prediction of remotely measured ocean surface waves. Journal of Fluid Mechanics 975, A8, 2023.
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S. Ehlers, M. Klein, A. Heinlein, M. Wedler, N. Desmars, N. Hoffmann, M. Stender, Machine learning for phase-resolved reconstruction of nonlinear ocean wave surface elevations from sparse remote sensing data. Ocean Engineering 288, 116059, 2023.
doi 10.1016/j.oceaneng.2023.116059

M. Stender, J. Ohlsen, H. Geisler, A. Chabchoub, N. Hoffmann, A. Schlaefer, Up-Net: a generic deep learning-based time stepper for parameterized spatio-temporal dynamics. Computational Mechanics 71 (6), 1227-1249, 2023.
doi 10.1007/s00466-023-02295-x

S. Ehlers, N.A. Wagner, A. Scherzl, M. Klein, N. Hoffmann, M. Stender, Data assimilation and parameter identification for water waves using the nonlinear Schrödinger equation and physics-informed neural networks. Fluids 9 (10), 231, 2024.
doi 10.3390/fluids9100231

S. Ehlers, N. Hoffmann, T. Tang, A.H. Callaghan, R. Cao, E.M. Padilla, Y. Fang, M. Stender, Physics-informed neural networks for phase-resolved data assimilation and prediction of nonlinear ocean waves. Physical Review Fluids 10 (9), 094901, 2025.
doi 10.1103/ytyy-pvys

S. Ehlers, M. Stender, N. Hoffmann, Bridging ocean wave physics and deep learning: Physics-informed neural operators for nonlinear wavefield reconstruction in real-time.
Physics of Fluids 37 (10), 2025.
doi 10.1063/5.0294655

4.2 Category B – Any other form of published results

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4.3 Patents (applied for and granted)

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