ISSN 2939-1725 (Print)
ISSN 2939-1733 (Online)

BOOK OF EXTENDED ABSTRACTS

16th Baška GNSS Conference: Technologies, Techniques and Applications Across PNT

and

The 3rd Workshop on Smart, Blue and Green Maritime Technologies

Under the High Auspicies of

Baška, Krk Island, Croatia

14 – 18 May 2023

16th Baška GNSS Conference:
Technologies, Techniques and Applications Across PNT
and
The **3rd** Workshop on Smart, Blue and Green Maritime Technologies

BOOK OF EXTENDED ABSTRACTS

16th Baška GNSS Conference: Technologies, Techniques and Applications Across PNT
and
The 3rd Workshop on Smart, Blue and Green Maritime Technologies

BOOK OF EXTENDED ABSTRACTS

ISSN 2939-1725 (Print) | ISSN 2939-1733 (Online)

Published by

University of Rijeka, Faculty of Maritime Studies, Rijeka, Croatia

For the Publisher

Assoc Prof Ana Perić Hadžić, PhD, Dean, University of Rijeka, Faculty of Maritime Studies, Rijeka, Croatia

Publisher's address

University of Rijeka, Faculty of Maritime Studies, Studentska 2, 51000 Rijeka, Croatia
Phone: +385 (0)51 338 411, Fax: +385 (0)51 336 755; URL: http://www.pfri.uniri.hr/
E-mail: dekanat@pfri.uniri.hr, GNSS_SBGMT@pfri.uniri.hr

Publishing Associates

Cynthia Robinson, OBE, FRIN, President, The Royal Institute of Navigation, London, UK

John Pottle, FRIN, Director, The Royal Institute of Navigation, London, UK

Editors

Assoc Prof David Brčić, PhD, University of Rijeka, Faculty of Maritime Studies, Rijeka, Croatia

Assoc Prof Marko Valčić, PhD, University of Zadar, Maritime Department, Zadar, Croatia

Prof Emer Serdjo Kos, PhD, FRIN, University of Rijeka, Faculty of Maritime Studies, Rijeka, Croatia

Prof Jana Kegalj, University of Rijeka, Faculty of Maritime Studies, Rijeka, Croatia

Proofreading

Jana Kegalj, univ. spec. philol., University of Rijeka, Faculty of Maritime Studies, Rijeka, Croatia

Photo credits

Front page: *The tide,* David Brčić

Text design

Tempora, Rijeka

Print

AKD d.o.o. Zagreb

Published in 2023

The publication of this book was supported by the University of Rijeka under the project *uniri-tehnic 18-66: Research of environmental impact on the operation of satellite navigation system in maritime navigation*, Rijeka, Croatia.

16th Baška GNSS Conference: Technologies, Techniques and Applications Across PNT

and

The **3**rd Workshop on Smart, Blue and Green Maritime Technologies

Under the High Auspicies of

BOOK OF EXTENDED ABSTRACTS

University of Zadar

Baška, Krk Island, Croatia

14 – 18 May 2023

ORGANISERS

Royal Institute of Navigation, London, United Kingdom; **University of Rijeka, Faculty of Maritime Studies**, Rijeka, Croatia; **University of Rijeka, Faculty of Engineering**, Rijeka, Croatia; **University of Zadar, Maritime Department**, Zagreb, Croatia; **University of Zagreb, Faculty of Transport and Traffic Sciences**, Zagreb, Croatia

MEDIA COVERAGE

Navigation News (London, UK), **Burza Nautike** (Rijeka, Croatia), **My Coordinates** (Delhi, India)

TECHNICAL CO-SPONSORS

University of Applied Sciences Hrvatsko Zagorje, Krapina, Croatia

INTERNATIONAL PROGRAM AND ORGANISING COMMITTEE

Conference chair:

John R Pottle, Director, The Royal Institute of Navigation, London, UK

Conference co-chairs:

David Brčić, University of Rijeka, Faculty of Maritime Studies, Rijeka, Croatia; **Hrvoje Gold**, University of Zagreb, Faculty of Transportation and Traffic Sciences, Zagreb, Croatia; **Serdjo Kos**, University of Rijeka, Faculty of Maritime Studies, Rijeka, Croatia; **Jasna Prpić-Oršić**, University of Rijeka, Faculty of Engineering, Rijeka, Croatia (and Chair of Smart, Blue & Green Maritime Technology Workshop); **Marko Valčić**, University of Zadar, Maritime Department, Zadar, Croatia

Programme chairs:

Marko Valčić, University of Zadar, Maritime Department, Zadar, Croatia; **David Brčić**, University of Rijeka, Faculty of Maritime Studies, Rijeka, Croatia

International Organising Committee Members:

Clare Stead, Communications & Events Manager, The Royal Institute of Navigation, London, United Kingdom; **Danijel Šugar**, University of Zagreb, Faculty of Geodesy, Zagreb, Croatia; **Franc Dimc**, University of Ljubljana, Faculty of Maritime Studies and Transport, Portorož, Slovenia; **George Shaw**, General Lighthouse Authority, London, United Kingdom; **Josip Vuković**, University of Zagreb, Faculty of Electrical Engineering and Computing, Zagreb, Croatia; **Luka Grbić**, University of Zadar, Maritime Department, Zadar, Croatia; **Mario Muštra**, University of Zagreb, Faculty of Transportation and Traffic Sciences, Zagreb, Croatia; **Nikola Lopac**, University of Rijeka, Faculty of Maritime Studies, Rijeka, Croatia; **Mariusz Specht**, Gdynia Maritime University, Gdynia, Poland; **Nenad Sikirica**, Krapina University of Applied Sciences, Krapina, Croatia; **Neven Grubišić**, University of Rijeka, Faculty of Maritime Studies, Rijeka, Croatia; **Srđan Žuškin**, University of Rijeka, Faculty of Maritime Studies, Rijeka, Croatia; **Tomislav Josip Mlinarić**, University of Zagreb, Faculty of Transport and Traffic Sciences, Zagreb, Croatia; **Tomislav Kos**, University of Zagreb, Faculty of Electrical Engineering and Computing, Zagreb, Croatia

Local Organising Committee:

Ivan Sulovsky, University of Rijeka, Faculty of Engineering, Rijeka, Croatia; **Ivan Vilić**, University of Rijeka, Faculty of Maritime Studies, Rijeka, Croatia; **Jana Kegalj**, University of Rijeka, Faculty of Maritime Studies, Rijeka, Croatia; **Luca Maras**, Valamar Hotels and Resorts, Poreč, Croatia; **Marijana Balas**, University of Rijeka, Faculty of Engineering, Rijeka, Croatia; **Marko Strabić**, University of Rijeka, Faculty of Maritime Studies, Rijeka, Croatia; **Maro Car**, University of Dubrovnik, Maritime Department, Rijeka, Croatia; **Tomislav Krljan**, University of Rijeka, Faculty of Maritime Studies, Rijeka, Croatia

Reviewers:

Franc Dimc, University of Ljubljana, Faculty of Maritime Studies and Transport, Portorož, Slovenia; **Hrvoje Gold**, University of Zagreb, Faculty of Transportation and Traffic Sciences, Zagreb, Croatia; **Jasna Prpić-Oršić**, University of Rijeka, Faculty of Engineering, Rijeka, Croatia; **Josip Orović**, University of Zadar, Maritime Department, Zadar, Croatia; **Joško Parunov**, University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Zagreb, Croatia; **Luca Braidotti**, University of Trieste, Department of Engineering and Architecture, Trieste, Italy; **Mario Bakota**, University of Split, Faculty of Maritime Studies, Split, Croatia; **Mario Muštra**, University of Zagreb, Faculty of Transportation and Traffic Sciences, Zagreb, Croatia; **Mariusz Specht**, Gdynia Maritime University, Gdynia, Poland; **Mate Barić**, University of Zadar, Maritime Department, Zadar, Croatia; **Nexhat Kapidani**, Administration for Maritime Safety and Port Management, Bar, Montenegro; **Nikola Lopac**, University of Rijeka, Faculty of Maritime Studies, Rijeka, Croatia; **Sanjin Valčić**, University of Rijeka, Faculty of Maritime Studies, Rijeka, Croatia; **Serdjo Kos**, University of Rijeka, Faculty of Maritime Studies, Rijeka, Croatia; **Tomislav Kos**, University of Zagreb, Faculty of Electrical Engineering and Computing, Zagreb, Croatia

CONTENTS

KEYNOTE LECTURES

EXTENDED ABSTRACTS

PREFACE TO THE 16th/3rd EDITION

Dear colleagues, dear friends,

This year I had the honour of writing you a few introductory words. First of all, I cannot tell you enough how happy I am to see you live again, or rather offline. It has not been easy to get through this strange time. We have been dealing with a global pandemic caused by the coronavirus, which has really disrupted a lot of things, including many conferences and meetings around the world. Unfortunately, some of them have either closed down altogether or the organisers have decided to go online only. Apart from the fact that the development of technology nowadays does not allow us to communicate easily through various applications, which we all had the pleasure to get to know, we are still convinced that nothing can replace direct contact, discussions, making contacts, establishing new ones and/or deepening existing ones, all in the most classical way – live and on site. Given the above reasons and constraints, we also struggled with various hybrid approaches during the pandemic, but at no point did we think of postponing the conference. Just as it was not easy for others, it was not easy for us either, but that is why we are even happier and prouder to welcome you this year at the 16th Baška GNSS Conference and the 3rd Workshop on Smart, Blue and Green Maritime Technologies in a row.

If we look back a few years, the Baška conference was traditionally primarily focused on GNSS and related technologies and applications. In the meantime, we have expanded it with the Workshop on Smart, Blue and Green Maritime Technologies, with which we actually wanted not only to attract a larger number of interested researchers, but also to additionally emphasise the connection between satellite navigation systems and all other maritime fields, especially in the context of guidance, navigation and control of modern vessels. Nowadays, we can truly say that we are witnessing an incredibly rapid development of technologies based primarily on artificial intelligence, but also on other advanced computational solutions, which in turn is directly reflected in the possibilities of autonomous systems and autonomous vessels in general. The synergy of satellite navigation technologies, inertial navigation, classical and intelligent sensors, ship hydrodynamics, energy systems and propulsion, digitalisation, automation, robotics, artificial intelligence, security, etc. has never been more in the spotlight than in recent times, and will continue to be so in the coming period. In this context, we want to ensure that our conference remains a lever for holding constructive discussions in the aforementioned areas in the future.

None of this would have been possible without the synergy of all of us, i.e. everyone who contributed in some way – keynote speakers, authors and co-authors of papers, presenters of papers and posters, reviewers, members of the International Programme Committee and the Organising Committee. A heartfelt thank you to them all. A big thank you also goes to our institutions, i.e. the co-organisers of the event, for their active support and help, both in terms of organisation and logistics as well as in financially. I believe that the difficult times are now slowly behind us and that we will meet and socialize in even greater numbers at the next conference, to which I cordially and openly invite you. Be well and take care.

On behalf of the International Programme and Organising Committee,
Marko Valčić

KEYNOTE LECTURES

University of Zadar

INTERNATIONAL EFFORTS TOWARDS GNSS MODERNISATION

Terry Moore

University of Nottingham

Abstract. *The four Global Navigation Satellite Systems (GNSS) have all reached a level of operational maturity and are all undergoing a slow process of modernisation as older satellites are replaced with new generations of spacecraft, and additional signals and new services are introduced. In addition, many national and international agencies around the world are striving to address the known vulnerabilities of GNSS and other PNT technologies to provide robust and resilient PNT services in various application domains. This presentation will discuss the planned (and possible) developments in the provision of core GNSS services and present a number of international initiatives aimed at ensuring a more robust and resilient PNT.*

University of Zadar

A-PNT AND THE EU PNT ECOSYSTEM: PNT ALTERNATIVES

Łukasz K Bonenberg

European Commision DG JRC

Abstract. *The European Commission's Joint Research Centre (JRC) recently completed an eight-month test campaign evaluating mature PNT services that can support or complement GNSS PNT services (so-called A-PNT). The seven technologies tested were*

- *Time transfer using White Rabbit and over computer networks;*
- *Time transfer Over The Air;*
- *Positioning using Pseudolites and LEO.*

This presentation will discuss how the findings from this test campaign fit into the current objectives of EU PNT and contribute to guaranteed, secure and resilient PNT services. It also outlines a current medium-term vision for the EU PNT ecosystem, covering in particular the main trends in terms of new constellations and signals, improvements in hardware and processing algorithms, and an increase in radio-frequency interference and global connectivity. This vision of the PNT ecosystem is supported by other activities mandated by the 2016 Space Strategy for Europe, including the European Radionavigation Plan (ERNP) 2023, published in March this year.

This assessment is important not only for EU Critical Infrastructure or dedicated PNT applications but also for overall economic growth as PNT and GNSS underpin a wide range of both commercial and critical activities in Europe and globally. Initial discussions and presentations from the Demo Day can be found at **https://joint-research-centre.ec.europa.eu/scientific-activities-z/critical-infrastructure-protection/alternative-pnt_en**.

TESTING TIMES – ASSURING PNT PERFORMANCE AND RESILIENCE

Stuart Smith

Spirent PLC

Abstract. *The world is becoming increasingly complex, and Position Navigation and Timing is no exception. One could consider this complexity as being driven by three essential things:*

- *An increasing reliance on PNT systems over a broadening range of applications*
- *An increasing number and variety of threats and challenges*
- *An increasing number of technologies and techniques for providing PNT services*

In these testing times, we need to make the time to test properly so that our PNT systems are resilient, reliable and efficient.

This keynote looks at how this is done, and how it is evolving.

REALISING REALISM IN GNSS TEST & ASSURANCE

Stuart Smith

Spirent PLC

Abstract. *Robust testing is essential to ensure that GNSS and PNT devices, systems and services perform as expected and with high resilience in their intended application when exposed to a variety of conditions. Different methodologies for testing need to be adopted at different stages of the development, integration and verification of the product/solution development life cycle. In many cases, it is either impractical, not valid or not cost-effective to perform extensive testing in the real operating environment. Therefore, test tools must be able to add enough realism to the laboratory test to ensure a smooth transition between development and deployment. This paper discusses how realism is incorporated into a robust PNT test methodology and the techniques used to realise this in laboratory-based simulation and emulation tools. It includes examples of evaluation of techniques to demonstrate correlation with real-world performance.*

University of Zadar

SHIP PERFORMANCE WITH A HYDRODYNAMIC PERSPECTIVE

Odd Magnus Faltinsen

Centre for Autonomous Marine Operations and Systems (AMOS)
Norwegian University of Science and Technology, Trondheim

Abstract. *Hydrodynamic aspects of semi-displacement and high-speed vessels are discussed. One topic is the effect of ocean waves on CO2 emissions from ships. Criteria for voluntary speed reduction in waves are an important source of error. Manoeuvring simulators and autonomous ships need time-efficient methods that account for ocean waves. Satisfactory time-efficient manoeuvring predictions for slender ships at moderate speed, infinite water depth, finite wave frequency of encounter and moderate wave steepness are discussed using a two-time scale method. The influence of ocean waves on manoeuvring in following waves with possible surf riding and broaching needs further investigation. The effects of water depth, mud, ship-to-ship interactions and channels were discussed. There are a variety of challenging physical problems for high-speed vessels. Cavitation limits the vessel speed to about 50 knots. As the speed of high-speed vessels increases, dynamic instabilities become more important. Green water on deck is discussed. Slamming can involve many complicated hydrodynamic details, but considering water impact in terms of structural response and hydroelasticity can simplify the problem.*

University of Zadar

AUTONOMY AND SUSTAINABILITY: IMO UPDATE

James Taylor

IAIN's IMO delegate

Abstract. *The oceans are the lungs of planet Earth. We must take care of them.*

Sustainability – IMO's watchword is "Safer ships in cleaner seas." It could also be "Cleaner ships in safer seas." Safe from damage, from pollution and from loss of biodiversity. The shipping industry is a global and highly commercial enterprise, seeking economic advantage wherever it can. This can run counter to pressures on the environmental. We have seen more efficient shipping, with, thanks to IMO, reductions in the polluting sulphur content of marine fuels, and stricter controls on discharges. But much depends on effective monitoring and port state control, the policing of our seas and ships and those who operate them.

The UN agreement to delineate maritime protected areas, covering about 30% of the world's oceans, is only the first step. Enforcement also still needs to be agreed.

Autonomy – MASS – is still a long way off, as are the exotic, non-fossil fuels needed to achieve "cleaner ships". The control and monitoring of unmanned ships remains legally complex and unresolved. How will autonomous vessels interact safely with manned vessels?

Can effective management of marine space, the allocation of certain areas to certain types of vessels or occupations or tonnages or cargoes or propulsion systems bring about effective autonomy and sustainability and protect our oceans?

HUMAN FACTORS ROLE ON AUTONOMOUS SHIPS (MASS)

Aly Elsayed

The Nautical Institute

Abstract. *Human factors play a pivotal role in the design, operation and maintenance of MASS (Maritime Autonomous Surface Ships). Proper consideration of human factors can ensure that these ships operate safely, efficiently and effectively, bringing significant benefits to the maritime industry and humanity. The main objective is to ensure a level of safety at least equivalent to that of a conventional ship in terms of human and ship safety. This paper aims to establish a critical safety aspect regarding the role, responsibility and location of the master and crew during MASS operations as a precautionary principle until all associated risks are clearly quantified. Every effort must be made to ensure the safety of life on board and of other vessels and the surrounding environment, and the need for appropriate caution is no less important because this is a precautionary and proactive measure. On the contrary, the safety of life at sea must not be compromised, either in the experimental phase or in normal operation.*

University of Zadar

EXTENDED ABSTRACTS

University of Zadar

SPATIAL ARRANGEMENT OF GNSS SATELLITES AND ACHIEVED ACCURACY OF THE USER'S POSITION

Mario Bakota[1*], Serdjo Kos[2], Lea Vojković[1], David Brčić[2]

Abstract. *Determining the user's position using Global Navigation Satellite System (GNSS) data depends on the presence of errors in the satellite part of the system, random errors, errors in the system environment, and user errors. If we systematically neglect and do not apply the error reduction algorithms and process the available input position records of the observed GNSS satellites identically, the differences in position accuracy can be attributed to the effect of the geometric position of the satellite expressed by the GDOP (Geometric Dilution Of Precision) coefficient. At the same time, the number of visible satellites is observed considering the applied elevation mask. The results indicate that the differences in the geometric positioning of the satellites and the orbits lead to a non-uniform accuracy of the user's position, which depends on the latitude of the user's position. The key parameter is the elevation mask, whereby increasing the number of visible satellites does not contribute to increased accuracy.*

Keywords: *elevation mask; error correction algorithms; GDOP; GNSS; satellite orbits*

[1] Faculty of Maritime Studies, University of Split, Ruđera Boškovića 37, 21000 Split, Croatia

[2] Faculty of Maritime Studies, University of Rijeka, Studentska 2, 51000 Rijeka, Croatia

Corresponding author: Mario Bakota (mbakota@pfst.hr)

1. INTRODUCTION

This paper presents the results of an investigation into the influence of the spatial arrangement of three GNSS systems on the accuracy of the positions obtained. The research covers satellite navigation systems GPS (Global Positioning System), GLONASS (Global Navigation Satellite System) and Galileo. In addition to the technical characteristics of each system, the conducted research is based on their spatial geometry, which is determined by the altitude and the number of orbits, which differ from system to system. The data include 11 GNSS stations [1] at different locations, the basic parameters being the accuracy of the user's position achieved, the value of the elevation mask and the number of visible satellites. The results obtained confirm that the number of visible satellites itself does not contribute to increased position accuracy. Moreover, in this context the latitude is the most important geographical element for the accuracy of the user's position.

2. METHODOLOGY

The conducted research includes positional data from GNSS stations geographically distributed from 64.7° S (Palmer Station – Antarctica) to 78.9° N (Ny-Aalesund, Svalbard-Norway), as shown in **Table 1**. As the basic requirement for selected stations was data availability, the time frame for the research is 2020 for nine stations and 2021 and 2022 for one station. Since the objective was to determine the accuracy based on the raw signal, the number of visible satellites of a given GNSS system at different elevation mask angles, ionospheric and tropospheric correction algorithms, and Earth Tide correction were not used. The deviations were calculated within the ECEF (Earth Centered, Earth Fixed) coordinate system.

Table 1. Input data of GNSS stations (made by authors according to [1]).

Location of the GNSS station	Latitude [°]	Longitude [°]
Palmer Station – Antarctica	64.7 S	64.0 W
Sydney – Australia	33.7 S	151.2 W
Cordoba – Argentina	31.5 S	64.5 W
Papua New Guinea	2.4 S	147.4 E
Virgin Islands – USA	17.7 N	64.6 W
Tenerife – Spain	28.3 N	16.5 E
Mersin – Türkiye	36.5 N	34.3 E
Kunzak – Czech Republic	49.1 N	15.2 E
Badary – Russia	51.7 N	102.2 E
Sodankyla – Finland	67.4 N	26.4 E
Ny-Alesund, Svalbard-Norway	78.8 N	11.9 E

The accuracy of each user's position was determined separately for elevation mask values of 3° and 10° [2], whereby the number of visible satellites was also observed in addition to the deviation [3].

3. RESULTS AND DISCUSSION

The aim of the study was to determine whether a larger number of visible satellites simultaneously leads to a more accurate user position at different latitudes. The spatial arrangement of the satellite systems varies and has the following basic characteristics: the inclination of the GLONASS system over the equator is the largest of the observed systems and is 64.8° [4], which theoretically allows the most accurate positioning in the polar regions. The obtained results for an elevation mask of 3° are shown in **Figure 1**.

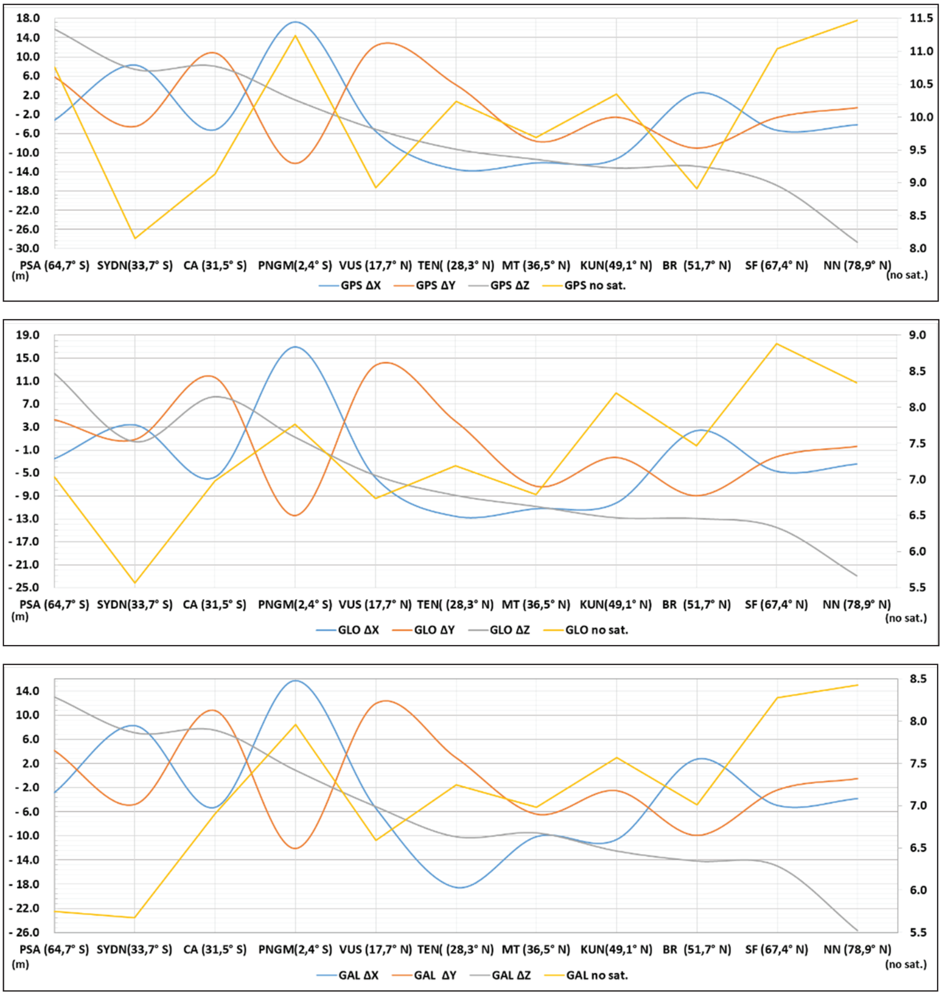


Figure 1. Achieved deviation values and the number of visible satellites for the GPS (top), GLONASS (middle) and Galileo (bottom) system for 3° elevation mask.

The satellite elevation value for Galileo is 56° and for GPS 55° [**5**]. Another significant difference is in the number of orbits of each system (four for GPS and three for GLONASS and Galileo) and in the altitude of the orbits (20,200 km for GPS, 19,100 km for GLONASS and 23,200 km for Galileo [**4**, **5**]). The results obtained for elevation mask of 10° are shown in **Figure 2**.

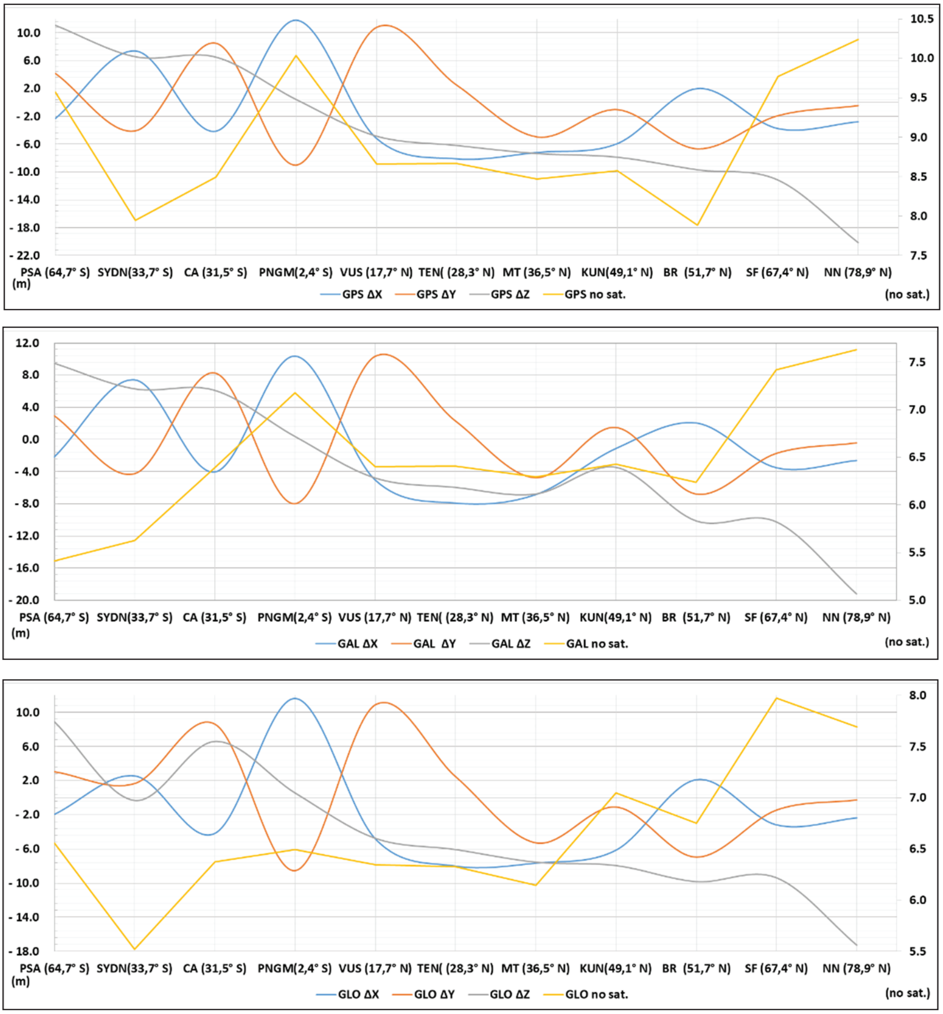


Figure 2. Achieved deviation values and the number of visible satellites for the GPS (top), GLONASS (middle) and Galileo (bottom) system for 10° elevation mask.

The values shown in **Figures 1** and **2** show that a larger number of visible satellites does not automatically increase the accuracy of the user's position. The assumption that GLONASS achieves a higher degree of accuracy above the polar regions was confirmed, while in other areas the GPS and Galileo system achieved better results. At an elevation mask angle of 3° a larger number of visible satellites was observed for all systems (on average one visible satellite more), but at an elevation mask angle of 10° significantly more accurate results were obtained.

This suggests that the spatial arrangement of the visible satellites, i.e. the value of the GDOP coefficient, and not their total number, is crucial for the position accuracy [6]. The figures show that the deviations along the individual coordinate axes are not uniform and exhibit independent dynamics of movement.

4. CONCLUSION

The research results show that the geometric arrangement of the satellites is a basic prerequisite for the uniform quality of the received radio navigation signals, and thus for a more precise determination of the user's position. Each of the GNSS systems mentioned has different orbital characteristics that provide different results depending on the value of the elevation mask and the user's latitude. Common to all systems is that a larger number of visible satellites at lower elevation angles degrades the accuracy of the user's position, while at higher elevation angles the accuracy is improved despite the smaller number of visible satellites.

Acknowledgments: This work was fully supported by the University of Rijeka under the project uniri-tehnic 18-66: *Research of environmental impacts on satellite navigation systems*.

REFERENCES

[1] EUREF Permanent GNSS Network. Available at: http://www.epncb.oma.be/index.php, accessed on 16 November 2022.

[2] RTKLIB. (2013). An Open Source Program Package for GNSS Positioning. Tokyo. Takasu, T. Available at: http://www.rtklib.com/, accessed 18 July 2022.

[3] Shuqiang, X., and Yuanxi. Y. (2016). Understanding GDOP minimization in GNSS Positioning: Infinite Solutions, Finite Solutions and No Solution. *Advances in Space Research*. 59. doi: 10.1016/j.asr.2016.10.019.

[4] ICD GLONASS CDMA. Информационно-Аналитический Центр Контроля ГЛОНАСС и GPS. Available at: https://www.glonass-iac.ru/, accessed on 16 January 2023.

[5] Sanz Subirana J., Juan Zornoza, J. M. and Hernandez-Pajares, M. (2013). GNSS Data Processing Book. Paris: European Space Agency. Available from: http://gage.upc.edu/gnss_book, accessed 18 December 2022.

[6] Kabir, M. H., Lee, S. and Shin, W. (2022). Performance Evaluation of GNSS Positioning with Geometric Dilution of Precision. *ICTC 2022, 13th International Conference on Information and Communication Technology Convergence* Jeju Island, Korea, Republic of, 2022, pp. 910–912, doi: 10.1109/ICTC55196.2022.9953014.

ON GPS L1 POSITIONING ERRORS' PREDICTION POSSIBILITIES USING GROUND TRUTH DATA: PRELIMINARY RESULTS AND FEASIBILITY VERIFICATION

David Brčić*, Tomislav Krljan, Serdjo Kos, Sanjin Valčić

Abstract. *This research represents the preliminary phase of the investigation of positioning error prediction possibilities based on ground truth data from GNSS reference stations. The preliminary results confirmed known facts, namely the similarities in positioning deviations, i.e. that satellite positioning performing equally or similarly in the relatively small area. The motivation for this research is to build a comprehensive satellite positioning environment with known influencing factors and satellite positioning performance. The aim is to develop a methodology for definition of distance limits within which positioning deviations can be applied to surrounding areas. To this end, several machine learning algorithms have been introduced. The contributions of this work relate to further efforts and research towards boundarization of valid corrections in terms of distance.*

Keywords: *error prediction; global positioning system; ground truth data; machine learning; positioning deviations; satellite positioning; statistical modelling*

University of Rijeka, Faculty of Maritime Studies, 51000 Rijeka, Croatia
Corresponding author: David Brčić (david.brcic@pfri.uniri.hr)

1. INTRODUCTION AND BACKGROUND

The provision and advanced technologies of Global Navigation Satellite System (GNSS) Positioning, Navigation and Timing (PNT) services nowadays overcome the classical, single frequency positioning [11]. However, the latter remains strong can provide insights into the conditions prevailing in a given area, in addition to positioning and other basic services. In the proposed study, GPS L1 positioning was analysed using data from several stations of the Italian networks RING (Rete Integrata Nazionale GNSS) [3] and International GNSS Service (IGS) [4] and the CORS network of the National Geodetic Survey (NGS) [5]. The previous related works [1, 10, 12] were concerned with analysing positioning solutions in a larger area and finding regularities and similarities between specific locations in terms of spatial association. This study aims to investigate the extent to which (distance) a positioning (coordinate, spatial) deviation can be considered the same or at least similar when considering nearer and more distant locations (i.e. the respective data). The tendency was not to replace known differential services and corresponding further developments [6], but to define and specify the coverage radii more precisely.

2. DATA AND METHODS

Ground truth data from six GNSS stations (**Table 1**) covering mainland Italy were collected for three consecutive years (2015 to 2017).

Table 1. Features of employed RING and IGS reference stations. Based on [3, 4].

STATION ID	WGS84 APPROXIMATE POSITION		
	X	Y	Z
CAOC (RING), Abruzzo	4595853.6038	1102044.6402	4270101.7918
RNI2 (RING), Rionero Sannitico	4624969.9322	1166237.9925	4221760.6251
BZRG (IGS), Bolzano	4312657.7721	864634.4065	4603844.2281
GROT (RING), Grottaminarda	4650260.9360	1251243.2080	4168852.1010
CAFI (RING), Castiglion Fiorentino	4546379.3761	963562.6668	4354582.3788
PADO (IGS), Padua	4388882.2748	924567.2031	4519588.5230

The CAOC station was selected as the reference station for the study. The reasons were the most stable deviation values, minimum mean and minimum standard deviation calculated from the median coordinates, and its location in the centre of the study area (**Figure 1**).

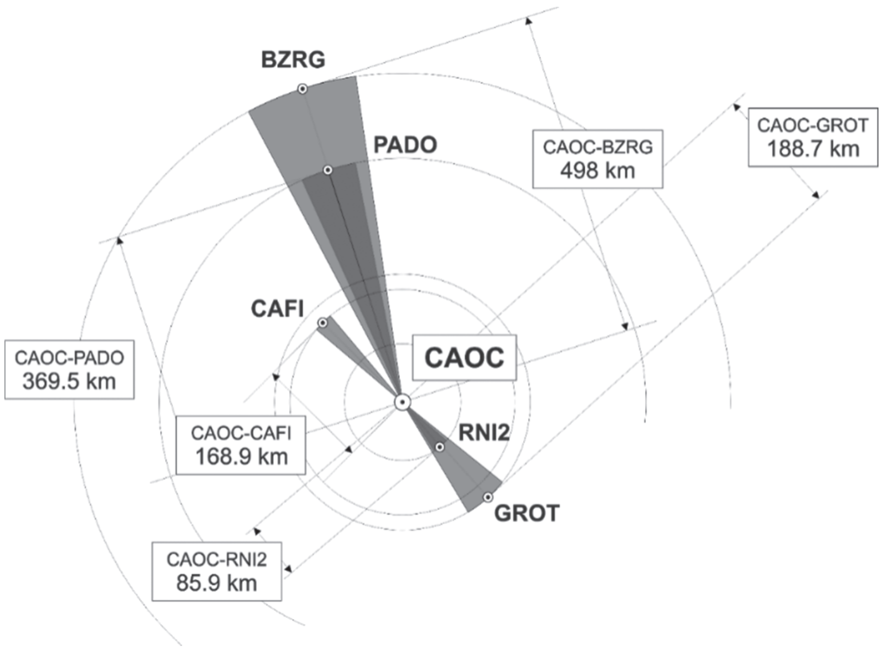


Figure 1. Mutual positions and distances between employed GNSS stations.

Various tools and methods were used during the research phases. The open source package *RTKLIB* [**9**] was used to create positioning solutions based on Receiver INdependent EXchange observation and navigation files (RINEX.o/n) [**2**]. Positioning deviations, statistical analyses and correlation matrices were calculated using the *R* programming language [**8**]. Several machine learning algorithms (ML) were considered for preliminary testing of the possibilities: Support Vector Regression (SVR), Random Forest Regression (RFR), Decision Trees Regression (DTR), Gradient Boosting Regression (GBR), K-Nearest Neighbours Regression (KNN), and Multylayer Perceptron Regression (MLP). The algorithms from the *Python* module *scikit-learn* [7] were used for modelling and evaluation. The datasets train-test ratio was 70:30. The data were normalized in the range of 0 to 1. The distribution of variables was randomised in both training and testing. In this way, the entire observed period was taken into account to compensate for seasonal, temporal, space weather and other influences.

3. RESULTS AND DISCUSSION

The correlation matrices for each of the coordinate axes between the data from all the stations used are shown in **Figure 2**. **Figure 3** gives an overview of the actual vs. predicted deviation values obtained with all the algorithms used.

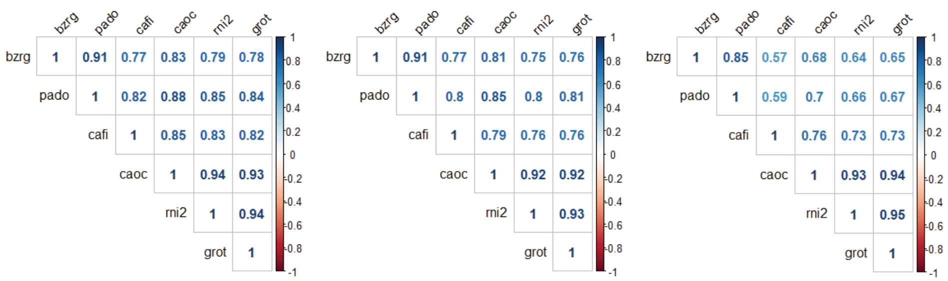


Figure 2. Correlation of latitude (left), longitude (centre) and height (right) deviations between elaborated GNSS reference stations' data.

The best metrics are obtained for the CAOC – RNI2 scenario, as the distance between the stations is the smallest (85.9 km). As expected, the predictions for the most distant station BZRG (498 km) were less successful.

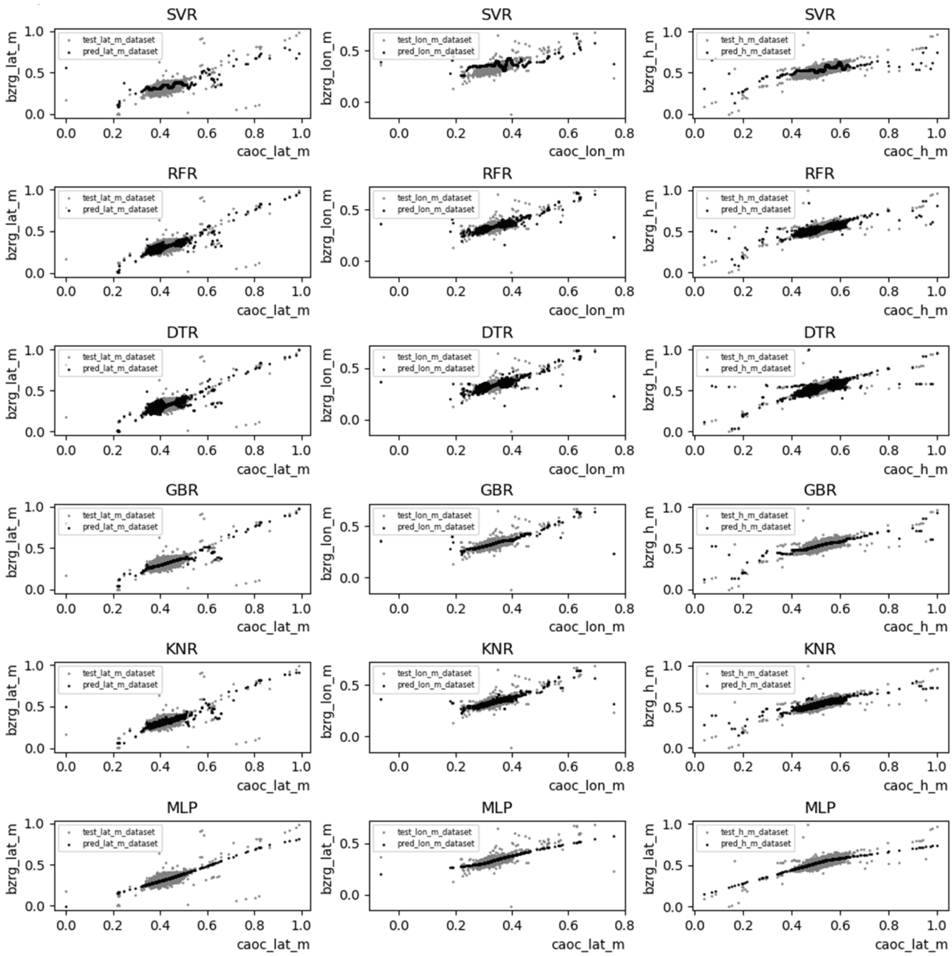


Figure 3. The rudimentary outcomes of selected ML modelling algorithms on example of CAOC/BZRG data. Predicted values of all three coordinate deviations are presented on *x*-axis.

Figure 4 shows the differences between the actual and predicted coordinate deviations using the example of the geographic latitude deviation modelling between CAOC and RNI2 (the closest scenario). The results show a strong correlation and good testing results.

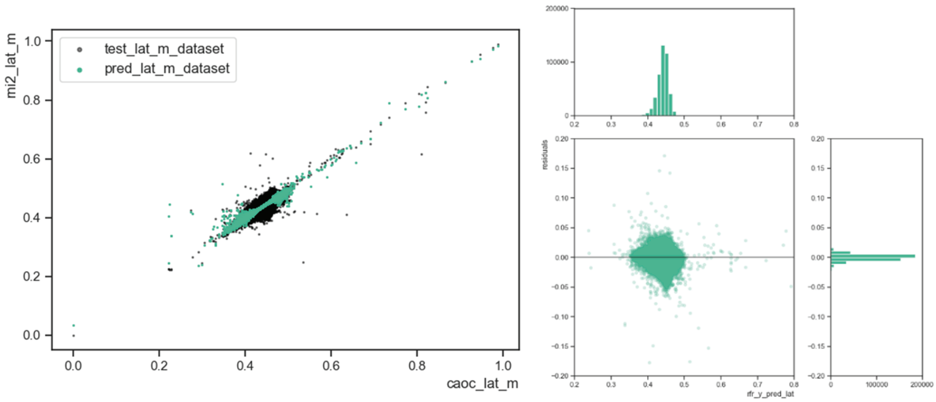


Figure 4. Example of Machine Learning Random Forest Regression and model testing: Test vs. Predicted dataset (left), and the residual plot of the RFR ML model (right) (the closest distance scenario – case CAOC/RNI2).

Table 2 presents the performance metrics of the RGR model for the longest and shortest distance scenario between the sites, using the CAOC station as a reference.

Table 2. RFR model performance metrics for the greatest and smallest distance scenarios.

MODELS	Latitude	Longitude	Height
METRICS	CAOC – BZRG		
R^2	0.648327	0.633777	0.388432
MAE	0.006923	0.004861	0.011530
MSE	9.889506e-05	4.681418e-05	0.000219
RMSE	0.009945	0.006842	0.014787

MODELS	Latitude	Longitude	Height
METRICS	CAOC – RNI2		
R^2	0.874623	0.827539	0.844707
MAE	0.003898	0.003007	0.004359
MSE	3.220706e-05	2.074952e-05	4.921514e-05
RMSE	0.005675	0.004555	0.007015

The results presented provide a starting point for further work: defining coverage radii for a given position deviation within a satisfactory predefined level. The tendency is to define almost exact regularities for the boundaries within positioning error, or to transfer the deviation present at a given location (in this case CAOC) to the surrounding area.

4. CONCLUSIONS AND FURTHER TENDENCIES

The models and presented and the corresponding results, although rudimentary, allow for further development. At this stage, only positioning deviations were considered, without the external influencing factors that could affect the results. In addition, the analyses presented dealt with deviations from specific coordinates. Further work will address, among other things, the prediction of total 3D positioning errors as a function of distance.

Acknowledgments: This study is fully supported by, and represents the part of the research project *Research of environmental impact on the operation of satellite navigation systems in maritime navigation*, funded by the University of Rijeka (Project ID: *uniri-tehnic 18-66*).

REFERENCES

[1] Brčić, D., Ćelić, J. & Valčić, S. (2020). Reconstruction of Geomagnetic Event as Observed in Northern Adriatic Region and Its Correlation with GPS Single-frequency Positioning Deviations. *International Journal of Marine Navigation and Safety of Sea Transportation (TransNav)*, *14*, pp. 349–357.

[2] Gurtner, W. & Estey, L. (2007). *RINEX: The Receiver Independent Exchange Format, V2.11*. Pasadena: IGS Central Bureau, p. 44.

[3] INGV RING Working Group. (2016). Rete Integrata Nazionale GNSS (RING). doi:10.13127/RING.

[4] International GNSS Service (IGS). (2014). GPS observables in RINEX format. Available at: ftp://igs.ign.fr/pub/igs/data/, accessed 4 April 2022.

[5] National Geodetic Survey. (2023). *Continuously Operating Reference Station (CORS) Navigation messages in RINEX format*. Available at: https://www.ngs.noaa.gov/CORS/standard1.shtml, accessed 20 January 2022.

[6] Nimvari, Z. E. & Mossavi, M. R. (2017). Accurate Prediction of Differential GPS Corrections using Fuzzy Cognitive Map. *ICSPIS 2017: 3rd Iranian Conference on Signal Processing and Intelligent Systems*, pp. 64–68. 20 – 21 December 2017, Shahrood, Iran. Shahrood: Shahrood University of Technology.

[7] Pedregosa et al. (2011). Scikit-learn: Machine Learning in Python. *Journal of Machine Learning Research*, 12, pp. 2825–2830.

[8] R Core Team. (2020). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. Available at: https://www.R-project.org/, accessed 20 April 2021.

[9] RTKLIB. (2013). An Open Source Program Package for GNSS Positioning. Tokyo. Takasu, T. Available at: http://www.rtklib.com/, accessed 31 March 2022.

[10] Šakan, D., Kos, S., Ban, B. D. & Brčić, D. (2021). On Linear and Circular Approach to GPS Data Processing: Analyses of the Horizontal Positioning Deviations Based on the Adriatic Region IGS Observables. *Data, 6(9)*. doi: 10.3390/data6020009.

[11] Teunissen, P. J. G. & Montenbruck, O. (Eds.) (2017). *Springer Handbook of Global Navigation Satellite Systems*. Heidelberg: Springer-Verlag GmbH.

[12] Žic, A., Pongračić, B., Kos, S. & Brčić, D. (2020). On GPS L1 Positioning Errors' Estimation in the Adriatic Region. *Journal Maritime and Transportation Science,* 58 (1), pp. 169–174. doi: 10.18048/2020.58.11.

PPP-RTK DATA FORMATTING AND DISTRIBUTION

Josip Vuković*, **Tomislav Kos**

Abstract. *Since PPP-RTK combines information on Global Navigation Satellite Systems (GNSS) satellite orbits, satellite clocks and signal biases with atmospheric information, it is a challenge to achieve the best possible accuracy with limited data bandwidth. This paper describes the basic principles of PPP-RTK, with particular attention to the information provided in PPP-RTK messages, and the correlation between data bandwidth and accuracy. It describes the data formats currently defined and the means of distributing them. The need for standardization of the PPP-RTK data formats is highlighted.*

Keywords: *correction data; format; GNSS; RTK-PPP*

University of Zagreb, Faculty of Electrical Engineering and Computing,
Unska 3, 10000 Zagreb, Croatia
Corresponding author: Josip Vuković (josip.vukovic@fer.hr)

1. INTRODUCTION

PPP-RTK is an advanced method for improving the positioning accuracy of Global Navigation Satellite Systems (GNSS). It combines Precise of Point Positioning (PPP) and Real-Time Kinematic (RTK) techniques, and provides lower convergence time than PPP and a wider coverage area than RTK. There are many applications that would benefit from PPP-RTK, in particular autonomous automotive, unmanned vehicles, autonomous agriculture, mining and civil engineering.

2. PPP-RTK DATA, FORMATTING AND DISTRIBUTION

By combining the information traditionally contained in PPP messages, such as satellite orbits, clocks and signal biases, with information on the state of the ionosphere and troposphere, PPP-RTK provides additional accuracy over PPP as well as reduced convergence time [1]. At the same time, since the targeted operating area is larger than RTK, the atmospheric corrections represent a considerable amount of data. The data required for a successful PPP-RTK are shown in **Figure 1**.

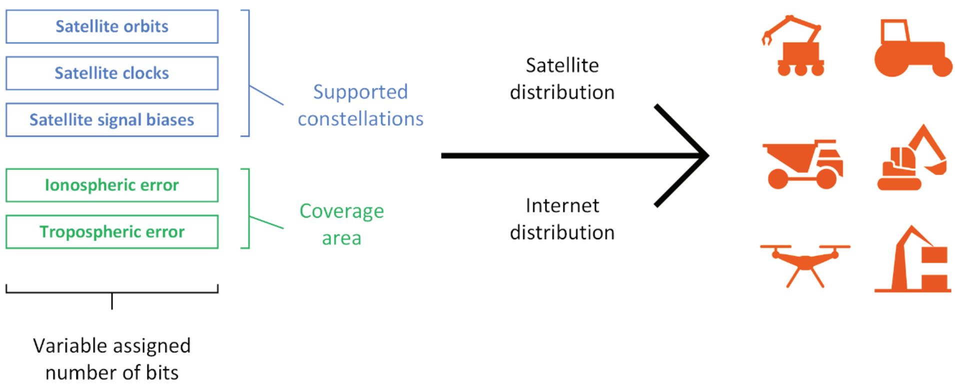


Figure 1. General PPP-RTK data structure and distribution.

The use of multiple GNSS constellations and the coverage of larger geographical areas results in larger amount of data to be transferred to the user equipment. In addition to the Internet data distribution channel, which is normally only available in populated areas, PPP-RTK data can also be transferred to users via L-band satellite links. The satellites of the GNSS and augmentation systems can transfer such data, but with limited bandwidth. Since all corrections have to fit into the bandwidth of 500-2000 bit/s, compromises have to be made in dedicating data to different corrections, which leads to limitations in accuracy [2].

3. CONCLUSIONS

Less variable corrections may have a lower frequency, while highly variable corrections may be transferred with a higher frequency. The message format can also contribute to the overall data reduction. There is no common, industry accepted protocol for transmitting PPP-RTK messages. Therefore, additional efforts are needed to combine the efforts of the Radio Technical Commission for Maritime Services (RTCM), the International GNSS Service (IGS), the European Union Agency for the Space Programme (EUSPA), the 3rd Generation Partnership Project (3GPP) and other interested parties to achieve better compatibility in future [3-5].

REFERENCES

[1] Li, X., Huang, J., Li, X. et al. (2022). Review of PPP–RTK: achievements, challenges, and opportunities. Satellite Navigation, 3, 28. https://doi.org/10.1186/s43020-022-00089-9.

[2] Hirokawa, R., Fernández-Hernández, I., Reynolds, S. (2021). PPP/PPP-RTK open formats: Overview, comparison, and proposal for an interoperable message. NAVIGATION, 68: 759– 778. https://doi.org/10.1002/navi.452.

[3] u-blox AG (2021). Secure Position Augmentation for Real-Time Navigation (SPARTN) Interface Control Document Version 2.0.1. Available from: https://www.spartnformat.org/download, accessed 10 January 2023.

[4] RTCM Special Committee No. 104. (May 20, 2021). RTCM 10403.3, Differential GNSS (Global Navigation Satellite Systems) Services – Version 3 + Amendment 2.

[5] 3GPP TS (2021). ETSI TS 137 355 V16.3.0 LTE Positioning Protocol (LPP). Available from: https://www.etsi.org/deliver/etsi_ts/137300_137399/137355/16.03.00_60/ts_137355v160300p.pdf, accessed 13 January 2023.

IMPROVEMENT OF KLOBUCHAR IONOSPHERIC MODEL BY THE GENERATION OF LOCAL COEFFICIENTS

Beldjilali Bilal[1*], Mahi Sarra[2]

Abstract. *GPS receivers use parameters broadcasted by the satellites to correct the ionospheric delay propagation based on the Klobuchar model. Since it is based on a global approach, this model can only reduce the ionospheric error by about 50% at mid-latitudes. Moreover, the Klobuchar coefficients transmitted in the navigation message are updated only once a day. To improve the effectiveness of the Klobuchar model, the proposed algorithm involves the local generation of coefficients intended by comparing the Klobuchar ionospheric model with the precise ionospheric product. Regular updating of these coefficients ensures a stable level of precision. The results show that the algorithm developed for generating the Klobuchar coefficients improves the accuracy of the calculated positions for 3 stations used in this work. In addition, the ionospheric model generated by our algorithm is more stable compared to the Klobuchar model.*

Keywords: *Klobuchar model; local coefficients; precise ionospheric product*

[1] Department of Space Geodesy, Center of Space Techniques, Algerian Space Agency, Arzew, Oran, Algeria.

[2] Scientific and Technical Research Center for the Development of the Arabic Language (CRSTDLA), Algiers, Algeria

Corresponding author: Beldjilali Bilal (bbeldjilali@cts.asal.dz)

1. INTRODUCTION

GPS signals are prone to error as they pass through the Earth's ionosphere, a layer of charged particles in the upper atmosphere. The ionosphere can cause delays and phase shifts in GPS signals, which can lead to inaccuracies in positioning information. To correct for these errors, the Klobuchar model was developed. The model uses four coefficients transmitted by GPS satellites to estimate the delay caused by the ionosphere [1].

The Klobuchar model is based on a global approach, i. e. it assumes that the ionosphere is evenly distributed around the Earth. In reality, however, the ionosphere is not uniformly distributed and can vary depending on factors such as time of day, season and location. Therefore, the Klobuchar model can only reduce the ionospheric error by about 50% at mid-latitudes [2].

To improve the effectiveness of the Klobuchar model, in this work we generate local coefficients based on accurate ionospheric products. This approach is expected to significantly improve the accuracy of GPS positioning information, especially in regions with high ionospheric activity [1].

2. METHODOLOGY

The Klobuchar model assumes that the electrical content of the ionosphere is concentrated in a thin layer at an altitude of 350 km. Therefore, the slant delay is calculated based on the vertical delay at the point where the signal penetrates the ionosphere. The GPS satellites broadcast parameters of the Klobuchar ionospheric model in the navigation message. These parameters enable the calculation and correction of ionospheric effects. The input parameters for the Klobuchar ionospheric model consist of eight coefficients denoted αi and βi, where $i = 1, 2, 3, 4$, the approximate latitude φ and longitude λ of the GPS antenna, the GPS observation time in seconds, and the azimuth A and elevation E of the observed satellite [2].

To improve the performance of the Klobuchar model, local coefficients based on the ionospheric conditions at a given location are used. This can be achieved with regression techniques that use precise ionospheric products. By using this precise data, the proposed algorithm can generate coefficients that are specific to the local ionospheric conditions, resulting in more accurate corrections for GNSS signals. This approach has been shown to significantly improve the effectiveness of the Klobuchar model, especially in regions where ionospheric variability is high [3] [4].

3. RESULTS AND DISCUSSION

GPS data from 3 stations were selected for testing and validation of the results. The sampling interval was 10 seconds, which is required for this type of regression. An elevation threshold of 15 degrees was adopted. During this period, the solar activity was relatively stable and no significant storms or gradients occurred. Therefore, the ionospheric activity in this study can be considered calm and the ionospheric conditions are suitable for testing. The following Table 1 shows a comparison between the Klobuchar parameters broadcasted by the GPS satellites and the new parameters calculated by our algorithm:

Table 1. Old and new Klobuchar coefficients.

	Station 1		Station 2	
Coff	**Old**	**New**	**Old**	**New**
α_0	+0.8382D-08	+0.7211D-07	+0.4657D-08	+0.1118D-07
α_1	+0.2235D-07	-0.2451D-08	+0.1490D-07	+0.1490D-07
α_2	-0.5960D-07	-0.4192D-06	-0.5960D-07	-0.5960D-07
α_3	-0.1192D-06	+0.1960D-07	-0.5960D-07	-0.5960D-07
β_0	+0.8602D+05	+0.9830D+05	0.7782D+05	+0.8806D+05
β_1	+0.6554D+05	-0.1192D+05	0.4915D+05	+0.1638D+05
β_2	-0.1311D+06	-0.1966D+06	-0.6554D+05	-0.1966D+06
β_3	-0.4588D+06	+0.5423D+06	-0.3277D+06	-0.1311D+06

	Station 3	
Coff	**Old**	**New**
α_0	0.1211D-07	+0.2118D-07
α_1	-0.7451D-08	+0.5490D-07
α_2	-0.1192D-06	-0.5660D-07
α_3	0.5960D-07	-0.6231D-07
β_0	0.9626D+05	+0.8806D+05
β_1	-0.3277D+05	+0.1638D+05
β_2	-0.1966D+06	-0.1966D+06
β_3	0.1966D+06	-0.1311D+06

The following **Figures 1, 2, 3** and **Table 2** show the comparison of the three-component error (X, Y, Z) when using the broadcasted Klobuchar parameters versus the new parameters.

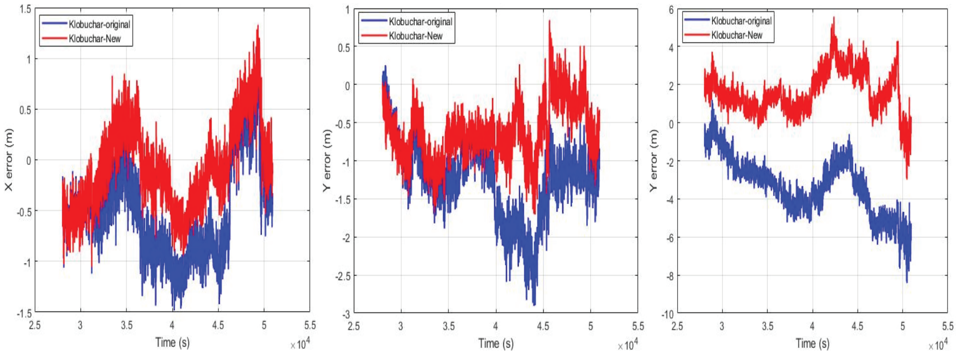


Figure 1. Station 1 X, Y and Z errors for Old and New coefficients.

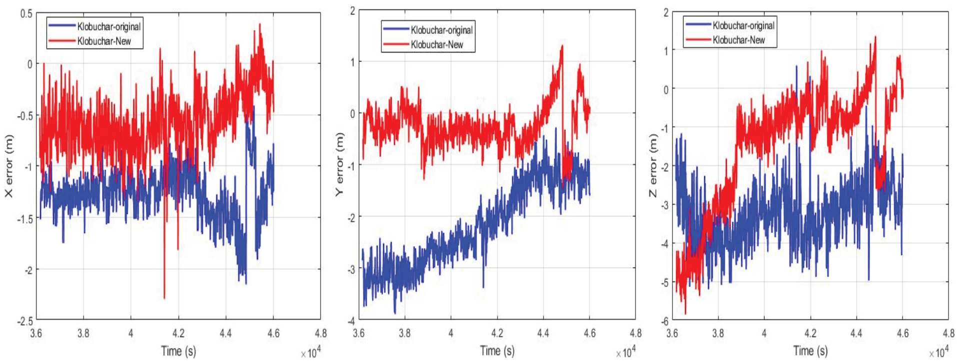


Figure 2. Station 2 X, Y and Z errors for Old and New coefficients.

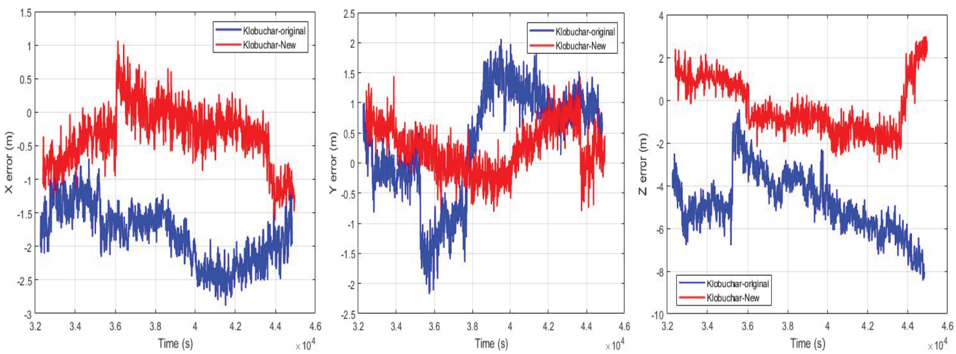


Figure 3. Station 3 X, Y and Z errors for Old and New coefficients.

Table 2. Comparison between three components errors for Old and New coefficients.

Stations	Errors	Old-Klobuchar	New-Klobuchar
Station 1	X error (m)	0.7034	0.4293
	Y error (m)	1.3512	0.7353
	Z error (m)	3.6911	1.9751
Station 2	X error (m)	08359	0.6207
	Y error (m)	2.335	2.0067
	Z error (m)	3.3249	1.9616
Station 3	X error (m)	1.1732	0.5548
	Y error (m)	1.2560	0.8396
	Z error (m)	3.6073	0.8083

From **Table 2** and the previous figures (**Figure 1, 2** and **3**), we can clearly conclude that the new parameters generated by our model can improve the accuracy of the GPS systems in the study area. The model has also become more stable, the errors are practically constant throughout the day.

The following figures (**Figure 4**) show a comparison between the RMS of the final solution using old and new coefficients of the Klobuchar model for the three stations used in our work.

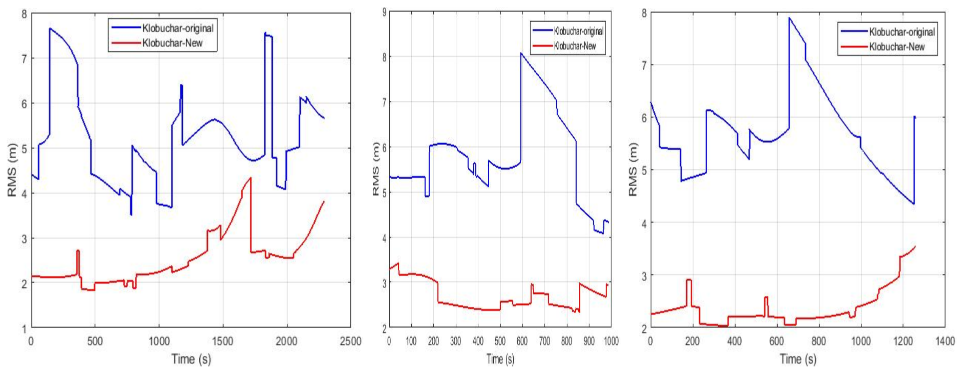


Figure 4. RMS of the final solution using old and new coefficients.

4. CONCLUSIONS

GPS data from a set of GNSS monitoring stations have been used to improve the performance of the ionospheric model distributed by GPS (Klobuchar). This paper presents an improved method to locally generate Klobuchar coefficients based on a precise product, to improve the accuracy of single-frequency receivers. A concrete implementation procedure carried out in this work can be described as follows: first, GPS data are classified and the Rinex files containing the maximum common time are selected; second, Ionex files are downloaded for the same time period; third, the refinement method based on the least squares method is applied to update the Klobuchar coefficients. Finally, the updated Klobuchar coefficients are used as ionospheric correction parameters for broadcasting and the results are compared between the old and new parameters. Theoretically, this method can be performed either in real time or in post-processing. The results obtained clearly show the influence of the new parameters on the quality of the positioning.

REFERENCES

[1] J.R.K.Kumar Dabbakuti (2021). Modeling and optimization of ionospheric model coefficients based on adjusted spherical harmonics function, Acta Astronautica, 10.1016/j.actaastro.2021.02.024, 182, (286–294).

[2] I. Lakshmi Mallika, D. Venkata Ratnam, Saravana Raman, Gampala Sivavaraprasad (2020). A New Ionospheric Model for Single Frequency GNSS User Applications Using Klobuchar Model Driven by Auto Regressive Moving Average (SAKARMA) Method Over Indian Region, IEEE Access, 10.1109/ACCESS.2020.2981365, **8**, (54535–54553).

[3] Perumalla Naveen Kumar, Achanta D. Sarma, Ammana Supraja Reddy (2014). Modelling of ionospheric time delay of Global Positioning System (GPS) signals using Taylor series expansion for GPS Aided Geo Augmented Navigation applications, IET Radar, Sonar & Navigation, 10.1049/iet-rsn.2013.0351, **8**, 9, (1081–1090).

IMPROVING THE OUTAGE PROBABILITY USING SC DIVERSITY FOR GNSS SIGNALS LIMITED BY BEAULIEU-XIE FADING AND RICIAN CO-CHANNEL INTERFERENCE

Dragana Krstić[1*], Suad Suljović[2], Devendra S. Gurjar[3], Suneel Yadav[4]

Abstract. *In this paper, an analytical framework is given for the performance analysis of global navigation satellite system (GNSS) signals subjected to Rician co-channel interference (CCI) over Beaulieu-Xie (BX) fading channels. The analysis is based on the obtained expressions for the probability density function (PDF) and the cumulative distribution function (CDF) as a function of the received signal-to-interference ratio (SIR) at the selection combining (SC) receiver. Based on these formulae, the outage probability (Pout) is determined as a function of the system parameters. An improvement in performance will be observed through a prism of applying spatial diversity techniques with the SC receiver with multiple input branches.*

Keywords: *Beaulieu-Xie fading; outage probability; Rician co-channel interference; selection combining*

[1] University of Nis, Faculty of Electronic Engineering, Niš, Serbia
[2] The Academy of Applied Technical Studies Belgrade, Belgrade, Serbia
[3] Department of ECE, National Institute of Technology Silchar, Assam, India
[4] Department of ECE, Indian Institute of Information Technology Allahabad Prayagraj, Uttar Pradesh, India
Corresponding author: Dragana Krstić (dragana.krstic@elfak.ni.ac.rs)

1. INTRODUCTION

Even if a GNSS user is in an area without buildings and other obstacles, he still suffers distortion due to the ionosphere and troposphere, which affect the GNSS signal and cause fading [1]. Significant variations in the ionosphere significantly affect the propagation of radio waves and can lead to a complete interruption of communication. For this reason, it is necessary to model these systems accurately and mitigate the influence of fading as much as possible. More recently, the Beaulieu-Xie distribution (BX) has been introduced to model the fading effect as accurately as possible [2].

2. MODEL OF OBSERVED SYSTEM

Communication via non-directional antennas and satellite relays is subject to multipath fading, especially above water. In more recent times, the Beaulieu-Xie (BX) distribution has been introduced to model the influence of fading. The BX distribution is a general distribution describing channels with and without line-of-sight (LOS), and therefore can include some other distributions: generalized Rician, κ – μ, non-central chi, and other distributions included in them [3].

Each intended signal at the input of the SC receiver has the probability density function (PDF) modelled by the BX distribution [2, Eq. (1.12)]:

$$p_{X_i}(x_i) = \frac{2m{x_i}^m}{\Omega_i \lambda^{m-1}} e^{-\frac{m}{\Omega}({x_i}^2+\lambda^2)} I_{m-1}\left(\frac{2m\lambda}{\Omega_i} x_i\right). \quad (1)$$

Here, m is the fading parameter and controls the shape; λ^2 is the LOS power whereby λ impacts the location and height of the mode; Ω_i is the non-LOS power and controls the spread [3].

The PDF presented by dint of modified Bessel function $I_v(\cdot)$ from [4; 17.7.1.1] can be expressed through the Gamma function, $\Gamma(t)$:

$$p_{X_i}(x_i) = 2e^{-\frac{m}{\Omega}({x_i}^2+\lambda^2)} \sum_{i=0}^{\infty} \frac{\lambda^{2i} {x_i}^{2i+2m-1}}{i!\Gamma(i+m)} \left(\frac{m}{\Omega_i}\right)^{2i+m}. \quad (2)$$

In mobile communications, the frequency spectrum is divided into bands that are allocated to different users, and do not overlap. However, at some distance, these frequency bands are reused, causing co-channel interference (CCI). In addition to the intended signal, other signals on the same frequencies (called co-channel signals) from the distant, unwanted transmitters arrive at the receiver and degrade receiver performance.

We have investigated the effects of fading on the useful and the interfering signal simultaneously. Here, the input envelopes of CCI, y_i, follow the Rician distribution [5, Eq. 11]:

$$p_{Y_i}(y_i) = 2e^{-\frac{(1+K_i)y_i^2}{s_i}-K_i} \sum_{i_2=0}^{\infty} \frac{K_i^{i_2} y_i^{2i_2+1}}{i_2! \Gamma(i_2+1)} \left(\frac{1+K_i}{s_i}\right)^{i_2+1}. \quad (3)$$

where s_i are input CCIs powers and K_i is Rician factor.

The intended signal to CCI ratios, $z_i = x_i/y_i$, at the ith branch of the SC receiver input are equal [6]:

$$p_{z_i}(z_i) = \int_0^{\infty} dy_i y_i p_{x_i}(z_i y_i) p_{y_i}(y_i) =$$

$$= 2e^{-\frac{m}{\Omega}\lambda^2} e^{-K_i} \sum_{i_1=0}^{\infty} \sum_{i_2=0}^{\infty} \frac{K_i^{i_2} \lambda^{2i_1} z_i^{2i_1+2m-1} m^{2i_1+m} s_i^{i_1+m} (1+K_i)^{i_2+1} \Gamma(i_1+i_2+m+1)}{i_1! i_2! \Gamma(i_1+m) \Gamma(i_2+1) \Omega_i^{i_1-i_2-1} (\Omega(1+K_i)+m s_i z_i^2)^{i_1+i_2+m+1}}. \quad (4)$$

Furthermore, the cumulative distribution function (CDF) of the SIRs z_i is:

$$F_{z_i}(z_i) = \int_0^{z_i} dt p_{z_i}(t) =$$

$$= 2e^{-\frac{m}{\Omega}\lambda^2} e^{-K_i} \sum_{i_1=0}^{\infty} \sum_{i_2=0}^{\infty} \frac{K_i^{i_2} \lambda^{2i_1} m^{2i_1+m} s_i^{i_1+m} (1+K_i)^{i_2+1} \Gamma(i_1+i_2+m+1)}{i_1!\, i_2!\, \Gamma(i_1+m) \Gamma(i_2+1) \Omega_i^{i_1-i_2-1}} \times \quad (5)$$

$$\times \int_0^{z_i} dt \frac{t^{2i_1+2m-1}}{(\Omega(1+K_i)+m s_i z_i^2)^{i_1+i_2+m+1}}.$$

The integral in previous expression can be solved in the shape:

$$F_{z_i}(z_i) = \int_0^{z_i} dt p_{z_i}(t) =$$

$$= e^{-\frac{m}{\Omega}\lambda^2} e^{-K_i} \sum_{i_1=0}^{\infty} \sum_{i_2=0}^{\infty} \frac{K_i^{i_2} \lambda^{2i_1} \Gamma(i_1+i_2+m+1)}{i_1! i_2! \Gamma(i_1+m) \Gamma(i_2+1)} \left(\frac{m}{\Omega}\right)^{i_1} B_{\frac{m s_i z_i^2}{\Omega(1+K_i)+m s_i z_i^2}}(i_1+m, i_2+1), \quad (6)$$

where $B_z(a, b)$ is the incomplete Beta function [7].

The SIR z at the SC receiver output is the maximum value of all z_i from the SC receiver output. Consequently, the outage probability (Pout) is [8]:

$$P_{out}(z) = F_{z_i}(z) = \left(F_{z_i}(z_i)\right)^L = \Bigg(e^{-\frac{m}{\Omega}\lambda^2 - K_i} \cdot \sum_{i_1=0}^{\infty}\sum_{i_2=0}^{\infty} \frac{K_i^{i_2}\lambda^{2i_1}\Gamma(i_1+i_2+m+1)}{i_1!\, i_2!\, \Gamma(i_1+m)\Gamma(i_2+1)} \left(\frac{m}{\Omega}\right) B_{\frac{m s_i z_i^2}{\Omega(1+K_i)+m s_i z_i^2}}(i_1+m, i_2+1)\Bigg)^L . \tag{7}$$

The number of terms in the sum in expression (7) for Pout to achieve the accuracy of the 5th significant digit is not greater than 30 for all values of the fading and CCI parameters and powers.

3. SYSTEM PERFORMANCE ANALYSIS

The diagram in Fig. 1 shows how much the Pout is affected by the presence of BX fading and Rician CCI.

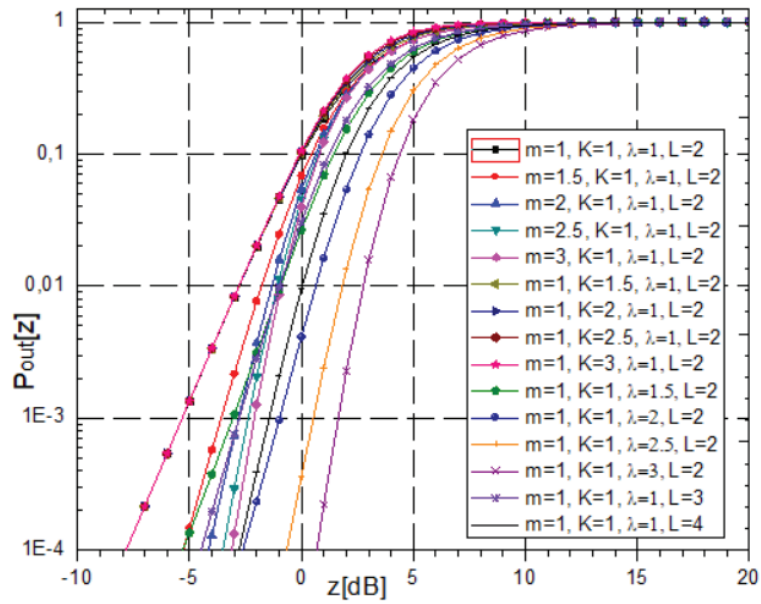


Figure 1. Normalized Pout of multi-branch SC receiver versus SIR considering different values of fading parameters m, λ, K, and the number of input branches L.

From the diagram we can see that by increasing the parameters *m* and λ and decreasing the factor *K*, the outage probability decreases and the system performs better. Such results are to be expected since increasing the parameter λ means increasing the power of direct, intended signal. Similarly, by decreasing the K factor (the ratio of direct and scattered components), the power of CCI decreases and the performance improves. If you increase the parameter *m* towards infinity, you approach the case of a channel without fading. Finally, it is evident from this figure that a large number of antennas at the receiver's input makes the system more resilient to fading and the performance is better.

4. CONCLUSIONS

One of the most important measures indicating the reliability of the system is the outage probability. In particular, Pout is calculated for a GNSS signal that is disturbed by BX fading and Rician CCI. Elimination of the influence of fading and CCI was performed by a multi-branch SC diversity receiver. For such a system configuration, we obtained an analytical expression for Pout, plotted the normalized Pout and, based on this, evaluated the influence of the fading and CCI parameters on its properties.

Acknowledgments: This work is a part of projects of the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, and the bilateral project "Development of Secure and Spectral Efficient Simultaneous Wireless Information and Power Transfer Systems for Large-Scale Wireless Networks" between the Republic of Serbia and the Republic of India.

REFERENCES

[1] Prieto-Cerdeira, R. (2007). Fading channel models for the assessment of GNSS receivers. *2nd European Conference on Antennas and Propagation (EuCAP 2007).* Edinburgh, UK, *11-16 November 2007,* doi:10.1049/ic.2007.1299.

[2] Olutayo A. (2021). *A Novel Fading Model for Emerging Wireless Communication Systems*. Doctoral dissertation. Okanagan: The University of British Columbia.

[3] Beaulieu, N. C. and Jiandong, X. (2015). A Novel Fading Model for Channels With Multiple Dominant Specular Components. *IEEE Wireless Communications Letters,* 4(1), 54–57. doi:10.1109/lwc.2014.2367501.

[4] Gradshteyn, I. S. and Ryzhik, I. M. (1980). *Tables of Integrals, Series and Products*. Academic. New York.

[5] Wongtrairat, W. and Supnithi, P. (2011). New simple form for PDF and MGF of Rician fading distribution. *2011 International Symposium on Intelligent Signal Processing and Communications Systems (ISPACS)*, December 7-9, 2011. doi:10.1109/ispacs.2011.6146087.

[6] Suljović, S., Krstić, D., Bandjur, D., Veljković, S., and Stefanović, M. (2019). Level crossing rate of macro-diversity system in the presence of fading and co-channel interference. *Revue Roumaine des Sciences Techniques,* vol. 64, pp. 63–68.

[7] DiDonato, A. R. and Jarnagin, M. P. (1967). The efficient calculation of the incomplete Beta-function ratio for half- integer values of the parameters a, b. *Mathematics of Computation*, vol. 21, no. 100, pp. 652–662.

[8] Milić, D., Vasic, S., Petrović, N., Koničanin, S., and Suljović, S. (2021). Outage probability simulation of a MIMO L-branch SC diversity system with k-μ fading and Rayleigh co-channel interference", *20th International Symposium INFOTEH-Jahorina*, 17-19 March 2021. doi: 10.1109/INFOTEH51037.2021.9400682.

AN ATTEMPT TO LOCALIZE GNSS JAMMER POSITION: A CASE STUDY

Matej Bažec[1*], Franc Dimc[1], Polona Pavlovčič Prešeren[2]

Abstract. *In a recent experiment with various GNSS jammers, it was shown that the position of the GNSS signal jammer can be localized along a road using a swarm of phones set by the road by monitoring only the carrier to noise density ratio (CNR) of the satellites. In this presentation, some important steps to determine in the jammer's position are presented. Although the data has been post-processed, the same approach could in principle be used in real time and the telephone receivers could be replaced by any GNSS-enabled device, as the CNR is reported by most of them.*

Keywords: *GNSS jamming; interference localization*

[1] University of Ljubljana, Faculty of Maritime Studies and Transport, Portorož, Slovenia

[2] University of Ljubljana, Faculty of Civil and Geodetic Engineering, Ljubljana, Slovenia

Corresponding author: Matej Bažec (matej.bazec@fpp.uni-lj.si)

1. INTRODUCTION

With the increasing use of GNSS signals in various applications, the number of intentionally interfering devices is also growing. Although their legal status does not permit their use virtually anywhere in the world, their availability has never been greater. In fact, despite having a permission from the local telecommunications authority to buy some from a China-based online retailer, they did not ask about it during customs inspection.

The most common interfering devices today are the jammers. These devices produce some kind of noise (usually a chirping signal) in the frequency band of interest to block the reception of the legitimate GNSS signal.

On 19 and 20 September 2022, a jamming experiment took place on a remote road near Črnotiče in southwestern Slovenia, using four different smartphones (Xiaomi Mi8, Xiaomi 11T, Huawei P40 and Samsung S20) among other geodetic receivers. These phones were chosen for their multi-frequency GNSS reception capability, as one of the jammers was also a multi-frequency receiver. The shape of the CNR of the different satellites was then used to determine the proximity of the jammer.

It was shown that it is possible to track the path of the jammer as it approaches the swarm. The data was then used to analyse the dependence of the CNR and position accuracy on the distance of the jammer [**1**].

2. EXPERIMENTAL SETUP

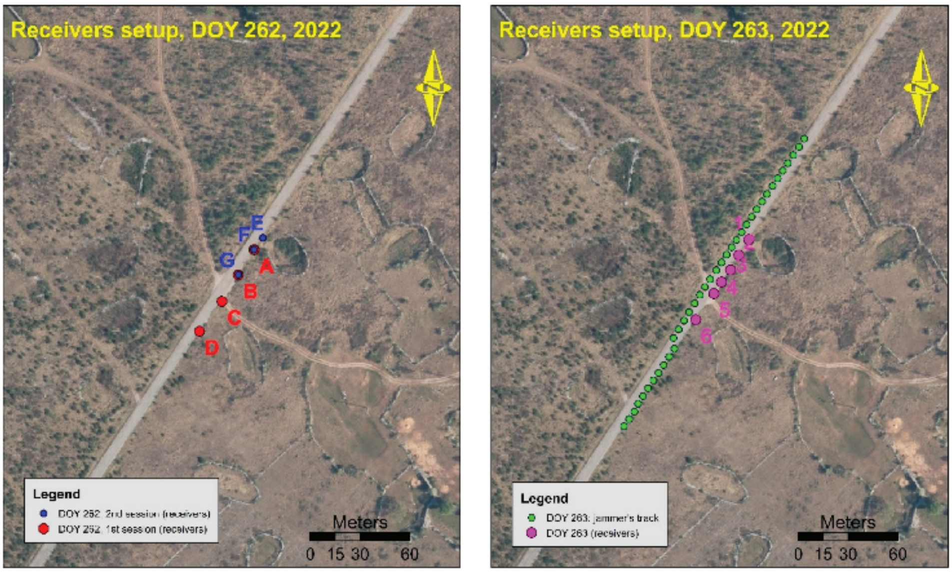
The position of the receivers was fixed and measured in advance. Their coordinates can be found in **Tables 1** and **2** or graphically in **Figure 1**. Three different jammers were placed in a car driving by multiple times, but only one was used at a time. The jammers were unbranded generic jammers, all of which produced a chirping signal. The jammer labelled 2 was a multi-frequency transmitter and jammers 1 and 3 were single-frequency transmitters. Their spectrum can be seen in **Fig. 2** (the spectrum of jammer 1 can be seen in one of our earlier studies with geodetic instruments [**2-4**]).

Table 1. Coordinates of the receivers used on DOY 262. Note that their position has changed between different series.

Site	Series	Recv.	Lat.	Long.	H [m]
A	1	Xiaomi 11T	45.56389444°N	13.89417501°E	435.046
B	1	Samsung S20	45.56375578°N	13.89405520°E	435.008
C	1	Xiaomi Mi8	45.56361287°N	13.89392920°E	435.402
D	1	Huawei P40	45.56344513°N	13.89376268°E	435.610
E	2	Xiaomi Mi8	45.56396017°N	13.89423794°E	434.688
F	2	Xiaomi 11T	45.56389605°N	13.89416995°E	433.693
G	2	Huawei P40	45.56375817°N	13.89405279°E	435.897

Table 2. Coordinates of the receivers used on DOY 263.

Site	Recv.	Lat.	Long.	H [m]
2	Samsung S20	45.56386619°N	13.89414673°E	434.916
3	Huawei P40	45.56378458°N	13.89408466°E	435.804
4	Xiaomi Mi8	45.56371192°N	13.89400552°E	433.894
5	Xiaomi 11T	45.56365512°N	13.89395938°E	435.249



(a) (b)

Figure 1. Precise position of the receivers used for each of the two days. Some labels represent devices that are not included in this study.

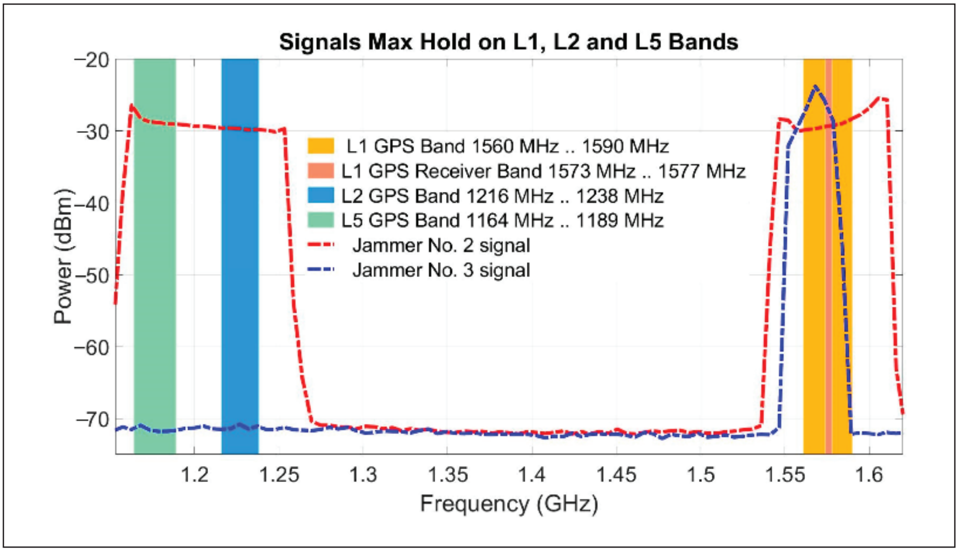


Figure 2. Spectrum of the jammers with GPS frequency bands.

3. METHODOLOGY AND RESULTS

The idea of observing the movement of the jammer based on the CNR drop from a swarm of telephones was already used by [5]. In this experiment, the concept was extended a little further by converting the observation into quantitative numbers. For this purpose, a suitable family of functions was sought to which the CNR time dependence could be fitted. This was possible by making the following assumptions. The Betz equation [6] was used as a basis:

$$CNR = -10\log\left(\frac{C}{N+J}\right), \tag{1}$$

where C is the carrier signal, N is the background noise density and J is the noise density produced by the jammer. For the latter, the assumption was made that it decreases quadratically with distance. Under the further assumption that the jammer power, the background noise, the carrier signal and the velocity are constant during the observation, the above equation can be transformed into a parametric function:

$$f = -10\log\left(a + \frac{b}{(t-t_0)^2 + c}\right). \tag{2}$$

Of all the fitting parameters only t_0 was used, which indicates the time at which the jammer was closest to the receiver. For the fitting itself, the Levenberg-Marquardt method was used. An example of how the points fit to this function can be seen in **Fig. 3**.

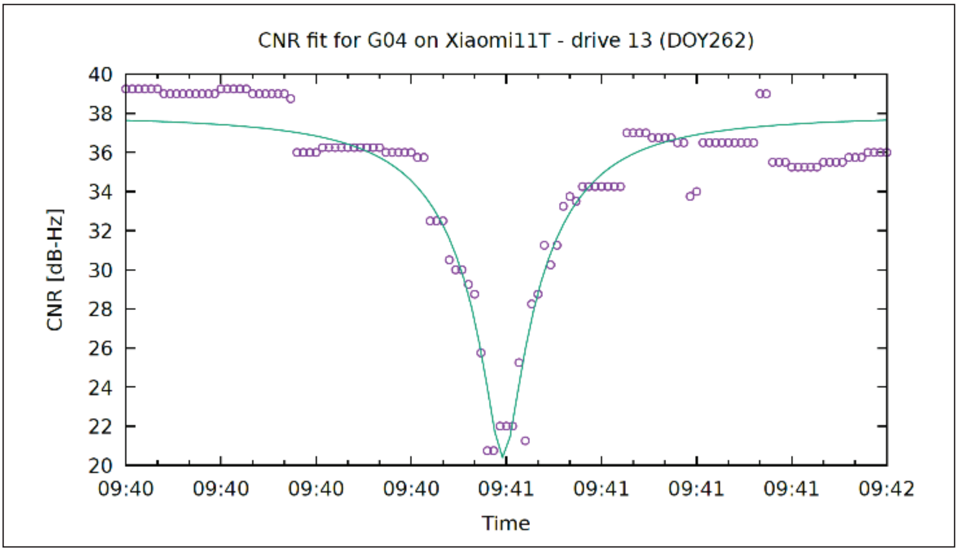


Figure 3. CNR fit example. From the minimum the time of jammer's closest proximity can be determined.

However, not all the fits were successful. Sometimes the minimum was not so numerous and the method converged to a function that covered the slow CNR drift rather than the jamming itself. In other cases (this was especially true for the low-elevation satellites), the background noise itself exhibited large fluctuations. Fortunately, for each phone, at least some satellites with good fitting results were available most of the time.

After calculating the fits for all satellites and discarding bad fits, the average over all satellites with successful fits was calculated for each phone. Since the position of the phones was known, it was possible to fit a straight line again to determine the dependence of the jammer's position on time (**Fig. 4**). In this way, the position of the jammer was approximately known for all times it was near the swarm. This allowed further analysis of the dependence of the CNR and the position accuracy on the distance of the jammer.

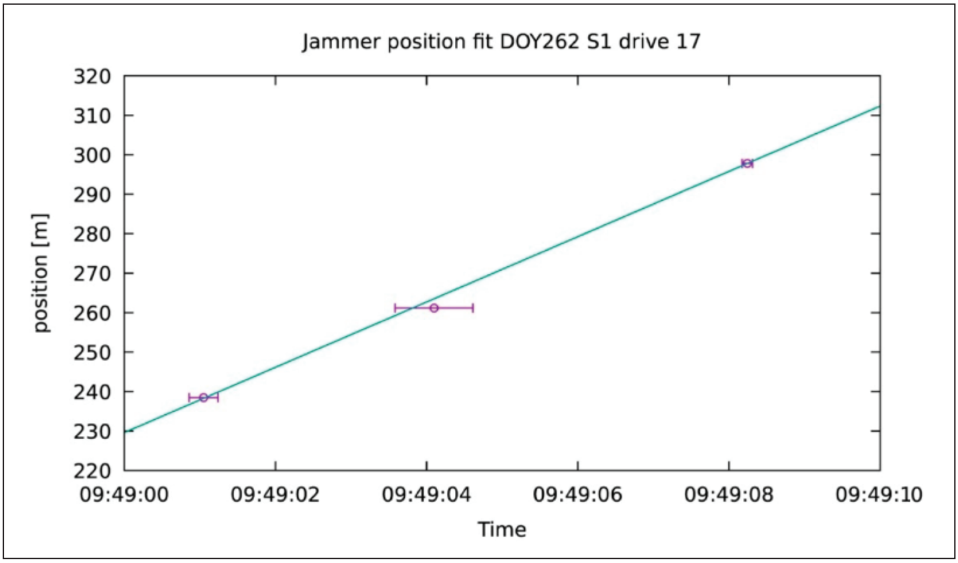


Figure 4. Fit of the position of the jammer on the average passing times.

4. CONCLUSION

It has been shown that the position of the jammer can be derived at least in one coordinate (parallel to the road). Since the CNR is reported by almost all GNSS-enabled devices, the phones could in principle be replaced by any device. However, it should be emphasized that this experiment was only intended as a proof of concept.

To make jammer detection fully functional, more sophisticated algorithms should be used to automatically exclude bad fits. This could be done parametrically or with a method that incorporates some of the approaches used in modern artificial intelligence. The method could also be extended to cover an array of receivers in two dimensions. An experiment in this direction has recently been conducted.

Acknowledgments: The authors would like to thank the Slovenian telecommunication agency AKOS for obtaining the permissions to use the jammers for these experiments.

REFERENCES

[1] Pavlovčič-Prešeren, P.; Dimc, F.; Bažec, M. Exploiting the Sensitivity of Dual-Frequency Smartphones and GNSS Geodetic Receivers for Jammer Localization. *Remote Sens.* 2023, 15, 1157.

[2] Bažec, M.; Dimc, F.; Pavlovčič-Prešeren, P. Evaluating the vulnerability of several geodetic GNSS receivers under chirp signal L1/E1 Jamming. *Sensors* 2020, 20, 814.

[3] Pavlovčič-Prešeren, P.; Dimc, F.; Bažec, M. A comparative analysis of the response of GNSS receivers under vertical and horizontal L1/E1 chirp jamming. *Sensors* 2021, 21, 1446.

[4] Dimc, F.; Pavlovčič-Prešeren, P.; Bažec, M. Robustness against Chirp Signal Interference of On-Board Vehicle Geodetic and Low-Cost GNSS Receivers. *Sensors* 2021, 21, 5257–5276.

[5] Borio, D.; Gioia, C.; Štern, A.; Dimc, F.; Baldini, G. Jammer Localization: From Crowdsourcing to Synthetic Detection. In *Proceedings of the 29th International Technical Meeting of the Satellite Division of The Institute of Navigation* (ION GNSS+ 2016), Portland, OR, USA, 12–16 September 2016; Volume 5, pp. 3107–3116.

[6] Morton, Y.J. Position, Navigation, and Timing Technologies in the 21st Century. In Integrated Satellite Navigation, Sensor Systems, and Civil Applications; Jade Mortin, Y., Ed.; The Institute of Electrical and Electrics Engineering Inc.: Hoboken, NJ, USA, 2021; Volume 1, ISBN 9781119458340.

STABILITY AND KINEMATIC BEHAVIOUR OF CROPOS GNSS STATIONS DURING THE PETRINJA 2020-2021 EARTHQUAKE SERIES

Danijel Šugar*, Luka Blagus

Abstract. *The wider surrounding area of the town of Petrinja, as well as the region of Banija in north-western Croatia, were hit by a series of earthquakes in December 2020. The series began with the M5.2 magnitude earthquake on 28 December 2020 and continued with the mainshock M6.4 magnitude earthquake the day after. CROPOS as a permanent GNSS network consisted of 33 stations installed on Croatian territory at the time of the earthquake series, with the SISA station closest to the epicentre. Static daily observation files (logging interval 15 seconds) from the SISA station were processed together with data from the 6 surrounding stations and the results were analysed to assess their stability and possible permanent displacement. In addition, kinematic observation data with a frequency of 1 Hz from the same stations were processed and analysed to detect and evaluate kinematic motion caused by the earthquake. The observation data were processed with the static PPP method using two different web services, namely Trimble RTX and CSRS-PPP. The kinematic observation files were processed using the CSRS-PPP service. The results show a maximum permanent displacement of the SISA station (5.3 cm horizontally, and -2.5 cm vertically) and its strongest kinematic movement.*

Keywords: *CROPOS; earthquake; GNSS; kinematic behaviour; PPP; permanent displacement*

University of Zagreb – Faculty of Geodesy, Zagreb, Croatia
Corresponding author: Danijel Šugar (dsugar@geof.hr)

University of Zadar

1. INTRODUCTION

The wider area surrounding the town of Petrinja in north-western Croatia was hit by a series of earthquakes in December 2020. The seismic activity triggered by the M5.2 foreshock and the M6.4 mainshock continued subsequently and is still active today (February 2023), but fortunately and as expected with less intensity. The first multidisciplinary study and analysis of the 2020-2021 Petrinja earthquake series was presented in [2]. The GNSS observation dataset considered covered one week before the earthquake series and more than two weeks after the mainshock (21 December 2020 – 14 January 2021). During this period, 8 earthquakes with M ≥ 4.5 were registered in the epicentral area. The conducted research and the obtained results are the continuation of the research presented in the 2022 edition of the Baška GNSS Conference with the keynote presentation entitled '*Kinematic effects and permanent displacement caused by December 2020 Petrinja earthquakes – assessed by CROPOS GNSS network*'. The study provided the assessment of permanent displacements and kinematic behaviour of the SISA station. In the follow-up study, the study area was extended to the CROPOS stations in the vicinity of the SISA station, namely: BJEL, NOVS, NOVI, SLUN, KARL and ZAGR.

2. METHODOLOGY

Permanent (co-seismic) displacements were assessed by processing static GNSS observation data (logging interval 15 seconds) collected at the mentioned stations of the CROPOS network. The processing was performed by two online PPP processing services (Trimble RTX and CSRS-PPP), the coordinates were given in ITRF2014, and the current epoch of the observation. After processing, a comparison of the results and the precision estimates was performed. The analysis showed a high level of agreement confirming the reliability of the results provided by both services.

In contrast to the relative kinematic PPK () used to assess the behaviour of the 2020 Zagreb earthquake, a PPP approach was adopted in this case. The results obtained with the PPK method were presented in [4] and subsequently in [5]. The main drawback of the PPK method for earthquake behaviour assessment is the use of simultaneous observations at distant reference stations (usually more than 25 km apart), which may be affected by earthquake shaking, leading to some distortion in estimated kinematics. On the other hand, the PPP method provides results in a global reference frame (e.g. ITRF2014) with slightly higher noise level and without the need for observations from a reference station. A comprehensive overview of the PPP method is given in [**1**].

The kinematic (1 Hz) GNSS observation data were processed using the CSRS-PPP service. The kinematic results were given in ITRF2014, as well as the static results. The analysis included the results from the SISA station as well as the results from the surrounding stations. The study resulted in an assessment of the kinematic motion of each station, its amplitudes, its delays and the fading of the earthquake effects as one moves away from the epicentre. The main idea in assessing the kinematic behaviour is to derive the earthquake map of the whole studied area based only on GNSS observations and station coordinates (1 Hz). Similar preliminary simulations of the Petrinja mainshock derived only from seismological data and given in terms of ground velocity components (E-W, N-S, Z) can be found at https://www.pmf.unizg.hr/geof/helena.latecki [**3**].

3. RESULTS AND DISCUSSION

Figure 1 shows the preliminary results of the permanent displacements at the CROPOS stations in the vicinity of the SISA station. The maximum permanent horizontal displacement was recorded at the SISA station: 5.3 cm in south-east direction, the subsidence was estimated at 2.5 cm. The horizontal displacement of the SLUN station was estimated at 2 mm, which was not considered statistically relevant and was therefore not shown in **Figure 1**.

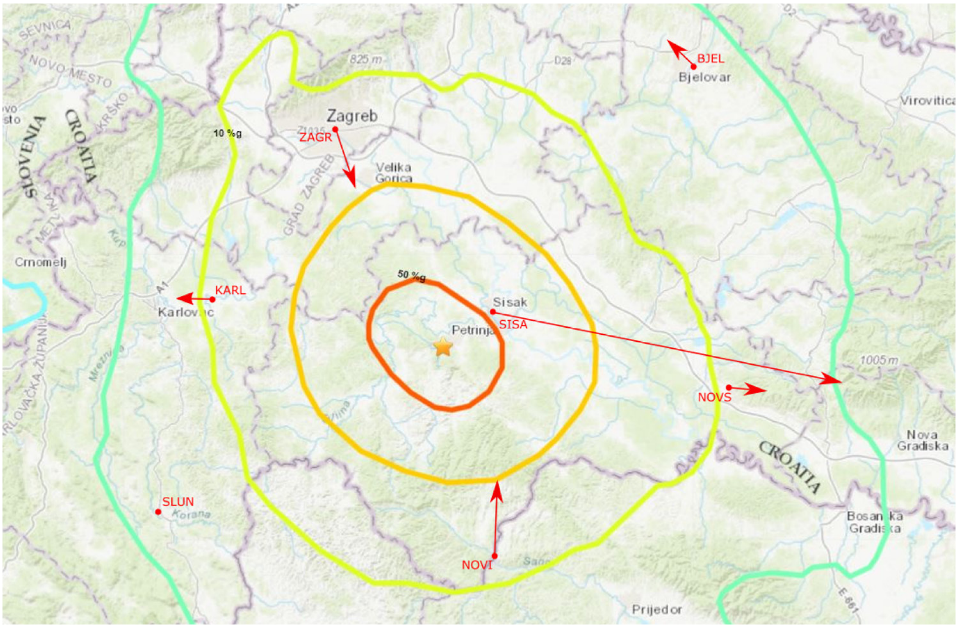


Figure 1. Estimated permanent displacements registered at stations of CROPOS network. The PGA shakemap provided by USGS [6] is overlaid with the estimated horizontal displacements.

In addition, the stations of the CROPOS network (CAKO, PORE, SIB2, VUKO), which are located at sufficient distance from the epicentre (110 – 220 km), and thus free from potential permanent displacements, were analysed. The motivation for such an analysis was to increase the reliability of the estimated permanent displacements and to confirm the stability of the stations away from the epicentral area.

The results of the kinematic processing and analysis will be announced and presented when completed. Preliminary analyses have shown a strong movement of the SISA station, with the movement being registered in a square with a side length of about 45 cm.

4. CONCLUSIONS

Preliminary results of the static PPP processing have shown the presence of permanent displacements of the stations of the CROPOS network around the epicentral area of the M6.4 Petrinja mainshock. Analysis of the 1 Hz kinematic PPP results has the potential to provide a picture of the kinematic motion caused by the earthquake.

REFERENCES

[1] Kouba, J., Lahaye, F., Tétreault, P. (2017). Precise Point Positioning. In: Teunissen, P.J., Montenbruck, O. (eds) Springer Handbook of Global Navigation Satellite Systems. Springer Handbooks. Springer, Cham. https://doi.org/10.1007/978-3-319-42928-1_25.

[2] Markušić, S., Stanko, D., Penava, D., Ivančić, I., Bjelotomić Oršulić, O., Korbar, T., Sarhosis, V. Destructive M6.2 Petrinja Earthquake (Croatia) in 2020 – Preliminary Multidisciplinary Research. Remote Sens. 2021, 13, 1095. https://doi.org/10.3390/rs13061095.

[3] Preliminary results of Petrinja mainshock simulations (2021). Available from: https://www.pmf.unizg.hr/geof/helena.latecki, accessed 27 March 2023.

[4] Šugar, D., Bačić, Ž. (2021). Kinematic effects of M5.5 Zagreb earthquake assessed by GNSS method supported by Galileo Satellite System // Proceedings of the 1st Croatian Conference on Earthquake Engineering – 1CroCEE / Lakušić, Stjepan ; Atalić, Josip (ed.), Zagreb: University of Zagreb – Faculty of Civil Engineering, 2021. pp. 385–395. doi:10.5592/CO/1CroCEE.2021.

[5] Šugar, D., Bačić, Ž., Dasović, I. (2021). Geodetic and seismological analysis of the CROPOS ZAGR station kinematics during the Zagreb 2020 ML 5.5 earthquake // Geofizika, 38 (2021), 2; 191–214. doi:10.15233/gfz.2021.38.10.

[6] United States Geological Survey (USGS). (2023). *Petrinja M6.4 Earthquake, Shakemap PGA contours*. Available from https://earthquake.usgs.gov/earthquakes/eventpage/us6000d3zh/map, accessed 26 February 2023.

EVALUATION OF MULTI-GNSS PPP INTEGRATION WITH IMU USING TC AND LC ALGORITHMS

Mahi Sarra[1*], **Beldjilali Bilal**[2]

Abstract. *This paper presents a comprehensive study on the integration of multi-GNSS PPP (Precise Point Positioning) and IMU (Inertial Measurement Unit) to improve navigation. The study focuses on the use of both tightly-coupled and loosely-coupled integration methods to combine multi-GNSS PPP and IMU data. The tightly-coupled integration involves the fusion of multi-GNSS PPP and IMU measurements at pseudo-range and carrier-phase levels, and provides high accuracy and reliability. The results show that using multi-GNSS PPP and IMU in tightly-coupled integration provides better navigation performance compared than using either system alone. Loosely-coupled integration, on the other hand, processes the multi-GNSS PPP and IMU data separately and combines the results at a lower frequency. This method offers a trade-off between accuracy and computational efficiency and is therefore suitable for applications that require a balance between these two factors. The study concludes that integrating multi-GNSS PPP and IMU using both tightly-coupled and loosely-coupled integration methods provides a robust navigation solution with improved accuracy and reliability.*

Keywords: *loosely-coupled integration method; multi-GNSS; precise point positioning; tightly-coupled integration method*

[1] Scientific and Technical Research Center for the Development of the Arabic Language (CRSTDLA), Algiers, Algeria

[2] Department of Space Geodesy, Center of Space Techniques, Algerian Space Agency, Arzew, Oran, Algeria

Corresponding author: Mahi Sarra (msarah21@hotmail.fr)

University of Zadar

1. INTRODUCTION

Multi-GNSS refers to the use of multiple Global Navigation Satellite Systems (GNSS) in a single navigation solution. Multi-GNSS can improve the accuracy and reliability of navigation solutions. It can increase the number of satellites visible to the receiver, providing more robust positioning solutions in challenging environments such as urban canyons or areas with weak GNSS signals. Multi-GNSS can also help mitigate potential errors in individual GNSS systems, resulting in more accurate and reliable navigation solutions [1].

PPP (Precise Point Positioning) is a GNSS positioning method that uses GNSS signals and precise orbital information to provide precise position information. PPP requires precise orbital information, which can be obtained from a variety of sources, including the International GNSS Service (IGS) and the Joint Institute for the Study of the Atmosphere and Ocean (JPL). With this information, ionospheric and tropospheric delays and other sources of error can be corrected, resulting in a highly accurate and reliable navigation solution [2].

The integration of GNSS and IMU refers to the combination of data from both systems to improve navigation performance. GNSS provides position and velocity information from satellite signals, while IMU provides acceleration and orientation information from onboard sensors. By combining the two systems, GNSS can overcome its limitations, such as signal loss in urban environments, and IMU can correct for drift and bias errors. The result is a more robust and accurate navigation solution [3].

2. METHODOLOGY

In this study, the integration of multi-GNSS PPP and IMU was conducted using two approaches: tightly-coupled and loosely-coupled integration.

Tightly-coupled integration refers to a method in which GNSS and IMU measurements are combined in real time to create a navigation solution. The GNSS and IMU data are fused at high frequency to provide accurate position, velocity and orientation information. The tightly-coupled integration is computationally intensive but provides high accuracy and reliability, making it a popular choice for demanding navigation applications such as autonomous vehicles [4].

In the case of multi-GNSS PPP/INS integration, the state vector is:

$$x_k = [x_{INS}\ dtr_G\ dtr_R\ dtr_E\ dtr_C\ dtr_d\ T_{ZWD}\ N^{sf}] \quad (1)$$

where dtr_G and dtr_d are the receiver clock offset and drift for GPS, respectively; dt_R,dt_E, dt_C are inter-system bias(ISB) parameters for GLONASS, GALILEO, BDS with respect to GPS.

x_{INS} is the INS state vector given by [4][5]:

$$x_{INS}^{n} = [\delta\varphi^n\ \delta v^n\ \delta r^n\ \nabla^b\ \varepsilon^b]^T \quad (2)$$

where b denotes the body frame and n is the navigation frame. $\delta\varphi^n$ δv^n and δr^n are the attitude, velocity, and position error vectors in the n-frame.

Loosely-coupled integration refers to a method where GNSS and IMU data are processed separately, combining the results at a lower frequency. In this approach, GNSS provides the primary navigation solution and the IMU measurements are used to correct for GNSS errors and to ensure continuity of the navigation solution when GNSS signals are weak or unavailable. Loosely-coupled integration is less computationally intensive but can result in lower accuracy compared to tightly-coupled integration.

For multi-GNSS PPP/INS integration the state vector is given by [4]:

$$x_k = [x_{INS}] \quad (3)$$

3. RESULTS AND DISCUSSION

The data was collected with a receiver on the roof of a car. The receiver used is a multi-GNSS receiver in addition to an IMU device. The **Figure 1** shows a comparison between the three solutions GPS PPP, PPP_TC, and PPP_LC.

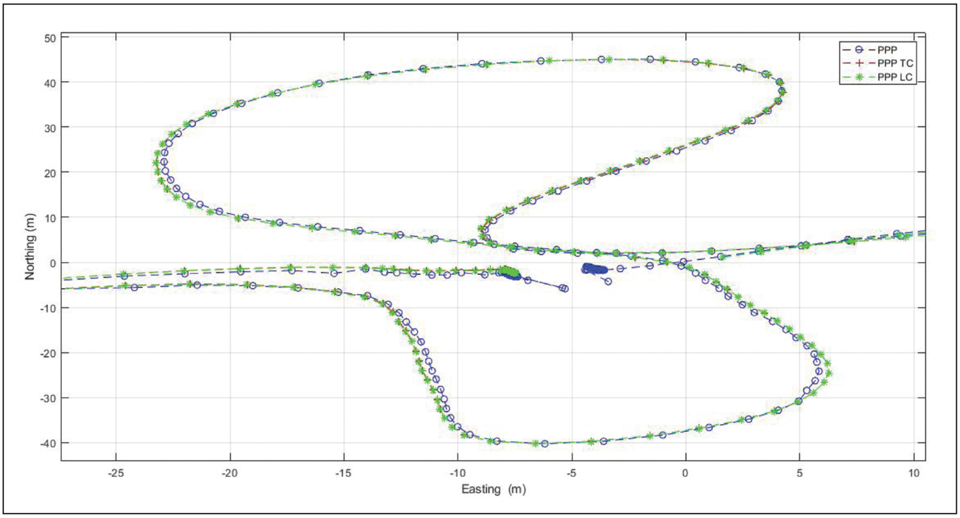


Figure 1. Part of the trajectory calculated by three solutions.

The following **Figure 2** shows the max error between each solution and the real trajectory for 95% of the time.

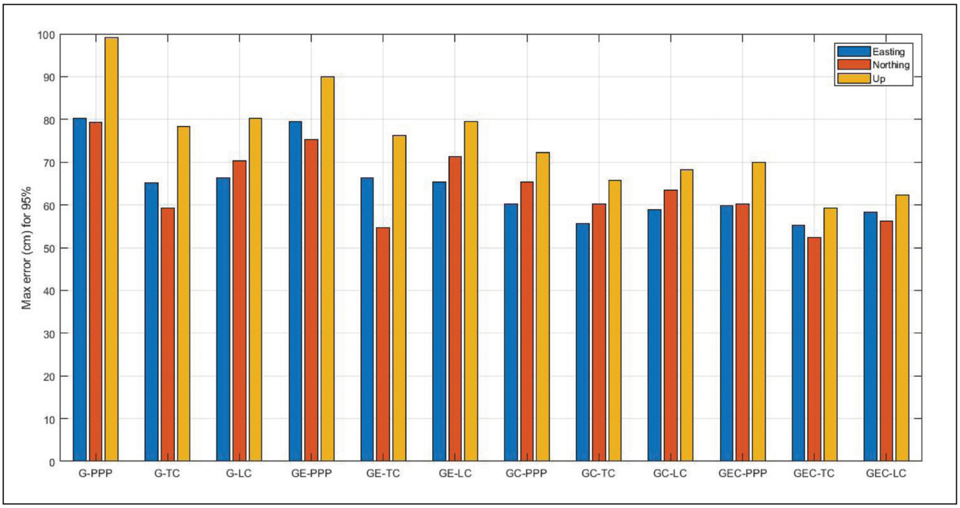


Figure 2. Max error for each solution and combination (G: GPS, GE: GPS+ Galileo, GC = GPS+ Beidou).

The following **Table 1** summarizes the RMS calculated for each solution and combination.

Table 1. RMS of each solution and combination.

GNSS	GPS			GPS+Galileo			GPS+Beidou			GPS+Galileo+Beidou		
Mode	PPP	TC	LC	PPP	TC	LC	PPP	TC	LC	PPP	TC	LC
Northing	22.3	21.2	21.5	23.4	22.8	23.5	19.9	17.8	18.6	19.4	18.2	18.6
Easting	21.1	19.1	19.8	19.9	18.6	18.9	19.6	17.3	18.6	19.0	17.9	18.3
Up	24.1	22.7	23.6	23.2	21.0	21.8	22.6	19.5	20.9	20.8	18.9	20.1

From the previous figures and table, it is can be seen that the TC algorithm gives the best results compared to LC and GNSS alone. The multi-GNSS combination GPS+Galileo+Beidou gives better results than GPS alone, but GPS+Beidou gives the best results for LC and TC algorithms.

4. CONCLUSIONS

In conclusion, the integration of multi-GNSS PPP and IMU using both tightly-coupled and loosely-coupled integration methods provides a robust navigation solution with improved accuracy and reliability. The results of this study show that the use of multi-GNSS PPP and IMU in tightly-coupled integration provides the highest accuracy and reliability, while loosely-coupled integration is a trade-off between accuracy and computational efficiency.

In summary, the integration of multi-GNSS PPP and IMU using both tightly-coupled and loosely-coupled integration methods is a promising approach to improve navigation performance and should be further researched and developed for a wide range of applications such as autonomous vehicles, unmanned aerial vehicles and geodetic surveying.

REFERENCES

[1] Li, P., Jiang, X., Zhang, X. et al. GPS + Galileo + BeiDou precise point positioning with triple-frequency ambiguity resolution. GPS Solut 24, 78 (2020). https://doi.org/10.1007/s10291-020-00992-1.

[2] Gao, Z., Shen, W., Zhang, H. et al. Real-time Kinematic Positioning of INS Tightly Aided Multi-GNSS Ionospheric Constrained PPP. Sci Rep 6, 30488 (2016). https://doi.org/10.1038/srep30488.

[3] Sun, R., Zhang, Z., Cheng, Q. et al. Pseudorange error prediction for adaptive tightly coupled GNSS/IMU navigation in urban areas. GPS Solut 26, 28 (2022). https://doi.org/10.1007/s10291-021-01213-z.

[4] Chen, K., Chang, G. & Chen, C. GINav: a MATLAB-based software for the data processing and analysis of a GNSS/INS integrated navigation system. GPS Solut 25, 108 (2021). https://doi.org/10.1007/s10291-021-01144-9.

[5] Yan, Z., Zhang, X. Assessment of the performance of GPS/Galileo PPP-RTK convergence using ionospheric corrections from networks with different scales. Earth Planets Space 74, 47 (2022). https://doi.org/10.1186/s40623-022-01602-9.

APPLICATION POSSIBILITIES OF GNSS RTK AND INS SYSTEMS FOR ESTIMATION OF SHIP MOTIONS

Marko Valčić[1*], David Brčić[2], Marko Bevandić[3], Jasna Prpić-Oršić[4]

Abstract. *Global Navigation Satellite Systems (GNSS) have found their place as the primary positioning method in maritime navigation. In terms of new technologies that can further enhance conventional GNSS capabilities, Real-Time Kinematics (RTK) is the most promising technology for advanced maritime requirements. To obtain and use such data, GNSS must be integrated with equipment using Inertial Navigation Systems (INS), implementing advanced estimation algorithms and filters. Such an implementation enables the aided system performance. This study presents an analysis of one such possible integration conducted in the Bay of Kvarner, Croatia. During the measurement campaign, the reference station Rijeka from the CROPOS network was used as the RTK base station. The main aim of the work was to compare the ideal ship heading without draught with the real one under different conditions. The results obtained can be the prerequisites for estimating the process noise caused by the ship dynamics under the influence of environmental loads.*

Keywords: *GNSS; RTK; INS; ship motions; process noise estimation*

[1] University of Zadar, Maritime Department, Zadar, Croatia

[2] University of Rijeka, Faculty of Maritime Studies, Rijeka, Croatia

[3] AITAC d.o.o., Kastav, Croatia

[4] University of Rijeka, Faculty of Engineering, Rijeka, Croatia

Corresponding author: Marko Valčić (mvalcic@unizd.hr)

1. INTRODUCTION AND BACKGROUND

The development of positioning methods allows the integration of different systems and techniques to achieve better results. Research in this area can be related to autonomous vessels and an introduction to the complex field of dynamic positioning. The GNSS Positioning, Navigation, and Timing (PNT) services meet general navigation requirements. However, in more demanding scenarios [1, 2], this accuracy is insufficient, raising the question of the use of other technologies and their behaviour on board vessels. The use of Inertial Navigation Systems (INS) has enabled highly accurate readings of vessel kinematics under specific and demanding conditions [3]. The use of new sensor technologies, such as Micro Electro-Mechanical Systems (MEMS), has enabled the implementation of robust systems such as small-scale accelerometers and gyroscopes, creating the possibility of numerous high-precision measurements and tests. The integration of GNSS and INS technologies has enabled ship navigation to obtain centimetre-level data for positioning, which is essential for high-precision tasks.

2. DATA AND METHODS

Various differential techniques can be used to augment PNT services. As a carrier-phase-based positioning method, Real-Time Kinematics allows millimetre to centimetre accuracy [4], but cannot be performed directly. Carrier-phase measurements and corrections are transmitted from the base station (or stations) to the rover, compensating for much of the stand-alone positioning errors [5]. The RTK concept is shown in **Figure 1**.

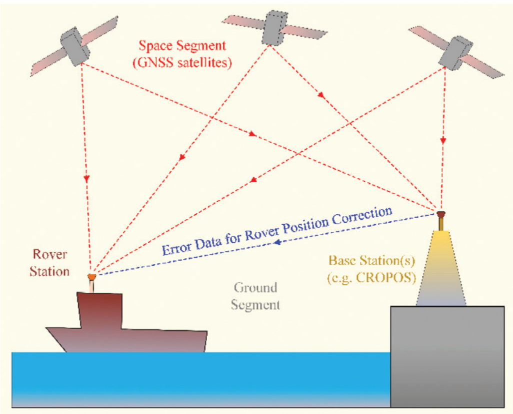


Figure 1. Integration of GNSS and RTK systems for maritime applications.

The use of the GNSS RTK and INS systems under dynamic conditions was investigated in several case studies, i.e. manoeuvres that included straight line motions with a constant heading, turning circle manoeuvres with different curve radii and a free and irregular zig-zag-like manoeuvre with intentional and continuous changes of heading.

The results presented in this paper refer exclusively to the latter case (**Figure 2**). The manoeuvres were carried out in the sea area near Kostrena, Croatia, under different engine loads.

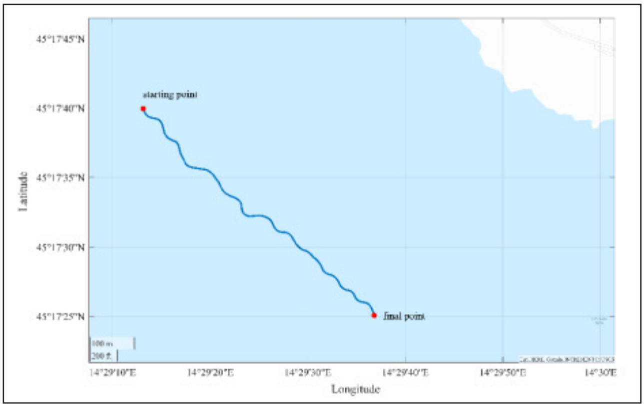


Figure 2. Irregular zig-zag lookalike manoeuvre with intentional and continuous change of heading.

The dynamic tests were carried out on a Quicksilver 470 Cabin boat with a Mercury 40 two-stroke outboard engine. The Survey Pro 700 antenna with Survey Pro Field software [6] was used as an RTK receiver, i.e., rover station, and was connected to one of the CROPOS system base stations [7]. The INS device used for the test was SBG Ellipse D [8], which was positioned approximately at the centre of gravity of the boat and was connected to dual-frequency GPS antennas, which enabled it to display the ship heading even under very static operating conditions.

All motions are shown in the NED reference frame $\{n\}$ using GNSS RTK measured positions. The origin of $\{n\}$ was the base station of the CROPOS system [7] expressed in Universal Transverse Mercator (UTM) coordinates as (5027350.040 m, 331278.165 m, -330.630 m), i.e. as (45.215680°, 14.204619°, 330.630 m) according to the WGS84 ellipsoid.

The ideal heading without drift at any chosen space or time stamp corresponds to the angle enclosed by the north axis N of the {*n*} reference frame and the tangent to the centre of gravity of the boat with respect to motion path curve. This curve, which represents the motion path function, was reconstructed from the measured RTK positions. Then, for each point the first derivative of the motion path curve had to be found to determine the slope of the tangent line, i.e. the angle at which the tangent lies in relation to the E axis. This angle is used to easily determine the ideal heading, i.e. the angle at which the tangent lies in relation to the N axis. The heading determined in this way is called ideal because it is assumed that there is no drift, but only motion in the direction of the surge. Of course, this is hardly achievable in practise, especially for small boats that are exposed to various environmental loads. However, this type of estimated heading can serve as an excellent reference for further modelling of the process noise that contaminates the gyrocompass measurements in practise.

3. RESULTS AND DISCUSSION

As mentioned earlier, the free zig-zag-like test was conducted by performing irregular zig-zag manoeuvres at variable speeds and varying engine loads with continuous change of heading. The weather conditions and geographical location limited the effects of environmental loads primarily to wind loads, the effects of waves could not be considered significant, and the effects of sea currents were unknown. However, the effects of all unmeasured or unknown variables can be considered part of unmodeled system dynamics and treated as a process noise.

As the intention was to generate as much process noise as possible, in addition to the effect of the wind, the random and deliberate motions of three people on board also contributed to increasing in the intensity of motion in the vertical degrees of freedom, especially with respect to roll and pitch. The drifting of the vessel was mainly influenced by the wind, while the intentional rolling was mainly influenced by the change in the speed of the vessel due to the change in engine load. The beginning and the end of the manoeuvre were carried out with outboard engine at full load at 4000 min^{-1}, while the middle part was carried out with engine speeds in the range of 2000 to 4000 min^{-1}. The measurement was carried out over a period of ten minutes. A graphical representation of the collected measurements and the obtained results can be found in **Figure 3**, while the statistical indicators in the form of mean values and standard deviations of the reconstructed ideal heading without drift are presented in **Table 1**.

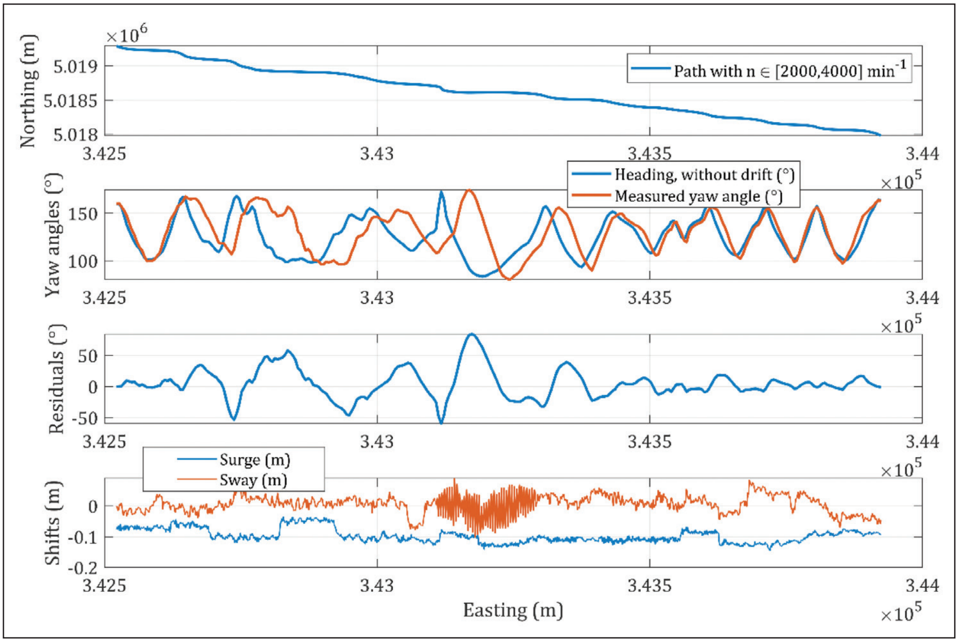


Figure 3. Graphical representation of acquired measurements and reconstructed estimated results.

It is important to note that in this manoeuvre the vessel was sailing against the wind and was at full speed at the beginning and end of the manoeuvre. This was to reduce lateral drift as much as possible. **Figure 3** also shows that during the deliberate roll of the vessel, i.e. especially in the spatial interval of easting from 3.4265E to 3.4344E UTM, the residuals increase, which in turn additionally causes the significant lead of the measured yaw angle signal compared to the estimated ideal heading.

Table 1. Statistics of the INS based measured yaw angle and the RTK based estimated heading without drift.

	RTK based estimated heading	**INS based measured yaw angle**
Mean value, μ (°)	125.4507	130.4379
Standard deviation, σ (°)	20.5737	22.1710

With the cessation of deliberate roll, i.e. from 3.4344E UTM, the boat remains only under the influence of the headwind, but without pronounced drift, and therefore the difference between the measured yaw angle and the reconstructed ideal heading is practically negligible.

It can be concluded that the ideal heading without lateral drift can be reconstructed with very high accuracy, while in the case of strong rolling and pitching motions of the boat, the differences obtained can be used to model the process noise caused by the dynamics of the ship's motion in the waves. The process noise model obtained in this way can certainly improve the estimators used in ship control systems, both in terms of accuracy and uncertainty.

4. CONCLUSIONS AND FURTHER TENDENCIES

The dynamics of ship's motion in heavy seas or other similar conditions can significantly affect the accuracy of position and heading measurements. In this context, the integration of different technologies such as GNSS RTK and INS can significantly improve the accuracy of these measurements and reduce their uncertainty. In this paper it is shown that when sailing without drift, but still under significant roll and pitch, there is almost no significant difference between the measured yaw angle and the estimated ideal heading. With drift, on the other hand, the differences mentioned are significant, as expected, but can be used to model the process noise caused by the unmodeled dynamics of the ship's motion under the influence of environmental and other loads. In this way, assumptions can be made to improve the properties of estimators used in modern ship control systems, especially with regard to the accuracy of the estimators, which is always a function of the previously mentioned uncertainty of the measured signals. Future research activities will focus on developing process noise models for the needs of different estimators such as the extended Kalman filter.

Acknowledgments: This work has been supported by the Croatian Science Foundation under the project *IP-2018-01-3739* and by the University of Rijeka under the projects *uniri-tehnic-18-18* and *uniri-tehnic-18-66*.

REFERENCES

[1] International Maritime Organization (IMO). (2001). *Resolution A.915 (22): Revised maritime policy and requirements for a future Global Navigation Satellite System (GNSS)*. London: IMO.

[2] European Union Agency for the Space Programme (EUSPA). (2021). *Report on Maritime and Inland Waterways User Needs and Requirements*. Prague: EUSPA.

[3] Farrell, J. A. (2008). *Aided Navigation: GPS with High Rate Sensors*. New York: McGraw Hill.

[4] Odijk, D. & Wanninger, L. (2017). Differential Positioning. In: Teunissen, P. J. G. & Montenbruck, O. (Eds.). *Springer Handbook of Global Navigation Satellite Systems.* New York: Springer.

[5] Rietdorf, A., Schön, S., & Schön, T. (2006). Precise positioning in real-time using navigation satellites and telecommunication. In: *Proceedings of the 3rd Workshop on Positioning, Navigation and Communication* (WPNC'06). University of Hannover, Hannover, Germany, March, 16th 2006.

[6] Trimble Navigation Limited (TNL). (2013). *Spectra Precision Survey Pro*. Westminster: TNL.

[7] State Geodetic Administration (DGU). CROPOS: The concept of networked reference stations. Available at: https://www.cropos.hr/o-sustavu/koncept-umrezenih-referentnih-stanica (accessed 19 February 2023).

[8] Guinamard, A., Ellipse, A. H. R. S., & INS-High Performance. (2014). *Miniature Inertial Sensors User Manual*. Rueil-Malmaison: SBG Systems.

EVALUATION OF VEHICLE FLOW INDICATORS BASED ON FCD DATA AND WEIBULL DISTRIBUTION

Damir Budimir*, Marko Šoštarić, Ivan Zeljko

Abstract. *Limited traffic conditions in cities, the dynamics of traffic flows and control systems with sustainable mobility require efficient monitoring of traffic flow indicators. The paper presents subjectively oriented data warehouse with an integrated time-dimensioned dataset for the FCD analysis process, which is easily accessible in real time. Following the principle of the functionally oriented warehouse, a model for comparing geometric-topological features of traffic flow in time was developed based on the collected GNSS data. The data synthesis and analysis is oriented towards the parameters of the Weibull distribution and correlates with the indicators of the state of traffic flow.*

Keywords: *data transformation models; FCD (Floating Car Data); GIS (Geographic Information System); linear referencing; mobility indicators*

Faculty of Transport and Traffic Sciences, Zagreb, Croatia
Corresponding author: Ivan Zeljko (zeljkoivan.007@gmail.com)

1. INTRODUCTION AND BACKGROUND

Detecting anomalies in traffic flow is the goal of our research. To make sense of the GNSS data describing the traffic flow, the LRS (Linear Reference System) was used, which provides the relative position of each collected traffic flow data with respect to all others. The Weibull distribution parameters related to the LRS segments quantify the characteristics of the traffic flow, which were recognized in the form of two or three parametric values.

2. METHODOLOGY

According to [7], measurement is a process of collecting data, and evaluation is the process of drawing conclusions from the collected data. It is noted that the outcome of measurement is data, while the result is the evaluation of information. FCD, as data from probe vehicles, are often used to provide traffic information as a complement to traditional traffic monitoring methods [8], [4]. The analysis of such data (GNSS data) is done by calculating the Weibull distribution parameters. The model for calculating the Weibull distribution parameters uses a functionally oriented LRS-based data warehouse [12]. This directs the data processing to segments of the transport network that are important in the context of possible delays or the occurence of anomalies in traffic flow. For example, the traffic flows at the intersection that are burdened by traffic demand.

The segmentation of the transport network was achieved by creating the LRS model. This enables geometric-topological modelling of the data in terms of traffic flow characteristics [3], [9]. It is also possible to link data more realistically to the spatial structural elements of sections and/or individual segments of traffic flow, especially at intersections. For this purpose, in the course of the research, the visual perception of the calculated parameters (correlation between the obtained parameters and defined indicators in relation to the georeferenced video on site) was realised by adapting the OptaGIS application (developed at the Faculty of Transport and Traffic Sciences) [5]. The application was also used to validate the results.

The parameters defining the shape and position are the layout of the Weibull distribution and define the indicators as a set of facts based on the distribution [6]. By correlating with the parameters obtained from the collected FCD data, the indicators were obtained.

The Weibull distribution was used in the study for several reasons. This distribution is an unusually versatile density function because it can fit a wide variety of shapes. It can even approximate the normal distribution and other distributions. In this study, the Weibull distribution with two parameters was used. It is widely used today to evaluate product reliability, analyse service life data and simulate downtime. The Weibull distribution is also suitable for a wide range of data from many other fields: biology, economics and engineering [**10**]. The most general expression of the expression of the Weibull distribution with three parameters:

$$f(t) = \frac{\beta}{\alpha}\left(\frac{t-\gamma}{\alpha}\right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\alpha}\right)^{\beta}} \quad (1)$$

where:

$$f(T) \geq 0, T \geq 0 \; or \; \alpha > 0, \beta > 0, -\infty < \Upsilon < +\infty \quad (2)$$

and:

- β is the shape parameter, also known as the Weibull slope
- α is the scale parameter
- γ is the location parameter (often set to zero).

Another task of this method is to define the range of Weibull distribution parameters that collides with a given location indicator. The approach used was the method of georeferenced video, which has achieved high precision under laboratory conditions [**5**], [**11**], with the possibility of simulating different movement scenarios based on the parameters defined for each road section, according to the traffic technology criteria. By defining the ranking of the parameters, the quantitative values are determined. By comparing them with the parameters of the Weibull distribution from the FCD data and depending on the affiliation, the indicators are determined. As shown in **Figure 1**, there is a representation of typical indicators expressed by the shape parameter β.

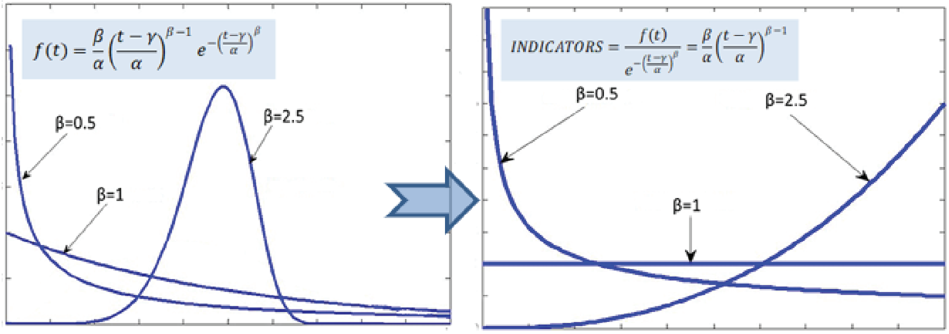


Figure 1. A graph example for the shape parameter – β for typical indicator values.

3. RESULTS AND DISCUSSION

The structure of spatial data implies a division into three levels, where the bottom level contains a metric determined by coordinates and a middle topology, while the top level determines the content [2]. Most often, the structure of spatial data refers to two levels or two main aspects: thematic (descriptive, attributive) and geometric [1]. In this context, the LRS is the linear structure of the transport network. LRS modelling also includes the design of data warehouse consisting of abstractions of parts of the traffic flows, their links and attributes. LRS as a real model is understood in the context of traffic flows and can serve as a means of grouping data that are part of the subjective database in GIS.

By extracting the parameters of the Weibull distribution from the FCD data on transport network segments (LRS), the collected data are evaluated into indicators that are significant from the perspective of traffic flows. The Weibull distribution with its display capabilities of different shapes determined by two or three parameters enables the parameter-based digitisation of FCD data over segments of the transport network. It also opens up the possibility of a new approach to the storage of GNSS data (FCD data) collected by mobile platforms.

Traffic flow indicators obtained as a result of processing the collected data (FCD data), show the anomalies of traffic flow (actual situation) in time and space. Many phenomena in the transport network (LRS) have minor or major dependencies that are detected by the relational model LRS, which is an equally important feature of this method of data processing. Linking phenomena that cause anomalies in the behaviour of traffic flows opens up additional possibilities for researching indicators in the transport network.

The disadvantage of this approach is the fact that the ranking of the parameters of the Weibull distribution must be determined for each segment on which the indicators are detected. The determined parameter values are assigned to the LRS model and become reference data for the detection of indicators.

4. CONCLUSIONS

Once the data are transformed into the parameters of the Weibull distribution, typical ranges of the characteristics of the traffic flow indicator are defined for each parameter combination. The link is established through two dimensions: space (LRS) and time (data distribution). The greater the number of internal interrelationships between the characteristics, the more likely is that their dimensional analysis will lead to more meaningful data. In linear referencing, the Weibull distribution can be used to model the probability that a given event, e.g. traffic flow, occurs at a given location along a linear feature.

REFERENCES

[1] Bartelme, N. (2000). *Geoinformatik – Modelle, Strukturen, Funktionen*. Berlin: Springer Berlin Heidelberg. https://doi.org/10.1007/b138747.

[2] Bill, Ralf. (1999). *Grundlagen der Geo-Informationssysteme: Band 1: Hardware, Software und Daten*. *iggilab.auf.uni-rostock.de*. Heidelberg: Wichmann Verlag GmbH. http://iggilab.auf.uni-rostock.de/vorlesungdoc/GIS-Grundlagen2003.pdf.

[3] Budimir, Damir. (2016). "Mobile Sensor-Based Estimation Method of Spatio-Temporal Indicators in Public Urban Transportation". https://bib.irb.hr/prikazi-rad?&rad=828026.

[4] Croce, Antonello Ignazio, Giuseppe Musolino, Corrado Rindone, and Antonino Vitetta. (2021). "Estimation of travel demand models with limited information: Floating car data for parameters' calibration". *Sustainability (Switzerland)* 13 (16). https://doi.org/10.3390/su13168838.

[5] Dadić, Ivan, Marko Ševrović, Damir Budimir, and Ana Božičević. (2008). "Geo-Referenced Video Recording and Analysis of Road Infrastructure from Driver's Perspective". In *15th World Congress on Inteligent Transport Systems*, 7. http://bib.irb.hr/prikazi-rad?lang=en&rad=409777.

[6] Das, Rahul Deb, and Stephan Winter. (2016). "Detecting Urban transport modes using a hybrid knowledge driven framework from GPS trajectory". *ISPRS International Journal of Geo-Information* 5 (11). https://doi.org/10.3390/ijgi5110207.

[7] Hardy, William C. (2001). *QoS: measurement and evaluation of telecommunications quality of service*. Wiley Chichester, England.

[8] Jiang, Yun, Guohua Song, Zeyu Zhang, Zhiqiang Zhai, and Lei Yu. (2021). "Estimation of hourly traffic flows from floating car data for vehicle emission estimation". *Journal of Advanced Transportation* 2021. https://doi.org/10.1155/2021/6628335.

[9] Jiménez, Felipe, Sergio Monzón, and Jose Eugenio Naranjo. (2016). "Definition of an enhanced map-matching algorithm for urban environments with poor GNSS signal quality". *Sensors (Switzerland)* 16 (2): 193. https://doi.org/10.3390/s16020193.

[10] Li, Rui, Shuaiyong Zheng, Zhipeng Wang, Yang Tang, Si Sun, and Zhigang Huang. (2018). "Evaluation of GNSS signal-in-space continuity: A weibull-distribution-based method". *Chinese Journal of Electronics* 27 (3). https://doi.org/10.1049/cje.2018.02.014.

[11] Šegvić, S., K. Brkić, Z. Kalafatić, V. Stanisavljević, M. Ševrović, D. Budimir, and I. Dadić. (2010). "A computer vision assisted geoinformation inventory for traffic infrastructure". In *IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC*, 66–73. https://doi.org/10.1109/ITSC.2010.5624979.

[12] Vonderohe, Alan, and Hepworth Todd. (1997). "A methodology for design of measurement systems for linear referencing". *Journal of the Urban and Regional Information Systems Association* 10 (1): 48–56. http://infoserve.sandia.gov/sand_doc/1997/970637.pdf.

TOWARDS AUTONOMOUS MARITIME SITUATIONAL AWARENESS IN SEA ICE CONDITIONS – STUDY ON AN ICEBREAKER IN THE FINNISH BOTHNIAN BAY

Martta-Kaisa Olkkonen[1*], Toni Hammarberg[1], Mika Saajasto[1], Ajinkya Gorad[2], Saiful Islam[1]

Abstract. *The project ENHANCE (Enabling Harbor to Harbor Autonomous Situational Awareness in Sea Ice Conditions) falls into the research area of collaborative positioning and situational awareness. Collaborative strategies have been used for several years as an effective way to compensate for the weaknesses of standalone navigation solutions in robotics and multi-agent systems. Artificial intelligence (AI) and machine learning (ML) algorithms in collaboration with an array of environment perception sensors are expected to give a vessel more autonomy with precise positioning and situational awareness.*

Keywords: *artificial intelligence; camera; GNSS; ice navigation; sensors; situational awareness*

[1] Department of Navigation and Positioning, Finnish Geospatial Research Institute, Espoo, Finland

[2] Department of Electrical Engineering and Automation, Aalto University, Espoo, Finland

Corresponding author: Martta-Kaisa Olkkonen (martta-kaisa.olkkonen@nls.fi)

1. INTRODUCTION

Studies on winter sea ice navigation are still scarce. We intend to bridge this gap within the project ENHANCE and show a concept demonstration of sea ice detection in the Baltic Sea during winter 2022. In addition, this project will investigate whether the global navigation satellite system (GNSS) provides resilience to the entire sensor array under ice navigation scenarios.

2. METHODOLOGY

The International Maritime Organisation (IMO) defines a Maritime Autonomous Surface Ship (MASS) as "a ship which, to a varying degree, can operate independently of human interaction" [1]. It has also been stated that autonomous systems consist of perception and control elements, such as propulsion and steering. We focus on perception in this research because integrated perception systems for the maritime environment are still insufficiently developed for autonomous operations. In particular, there is a need to complement the well-developed RADAR and GNSS techniques with other perception sensors and multi-sensor fusion through AI. Ultimately, the sensor system should provide an autonomous vessel with holistic situational awareness. At the very least, the vessel needs information about its own position as well as objects and other vessels in its path.

The project ENHANCE is a continuation of the NAVISP-EL1-020 Maritime AI-NAV project [2, 3]. AI/ML algorithms in collaboration with an assembly of environment perception sensors ultimately aim to provide an autonomous vessel with accurate positioning and situational awareness. The sensors are GNSS, visual RGB (capturing light in red, green, and blue wavelengths) and infrared (IR) cameras.

ENHANCE aims to address the following two gaps in autonomous situational awareness in winter. First, improving the traditional sensor assembly and related AI techniques and investigating their performance in winter sea and weather conditions. Secondly, the prevailing sea ice conditions need to be detected with the on-board RGB and IR cameras under all weather and visibility conditions. In addition, it is important to detect ice tracks so that the autonomous ship can safely navigate through the icy waters by following the tracks of an icebreaker. The objectives of ENHANCE are:

1. Review of the state-of-the-art in artificial intelligence algorithms for winter navigation;
2. Proof-of-concept of autonomous ice navigation capability using various sensors and systems to test the selected artificial intelligence methods and techniques;
3. Conduct a system validation campaign on a vessel using the above methods; not only in terms of accuracy, but also resilience and integrity.

The planned test vessel in ENHANCE was the same as in AI-NAV, Tallink Megastar, which operates daily on the Gulf of Finland between Helsinki and Tallinn, Estonia. However, the challenge with this wintry project was that the extent and type of ice in the south of Finland in the Helsinki region could not be guaranteed. It would be particularly unlikely to expect harder ice types such as ridges and level ice on the route. Alternatively, ice could be encountered, but only of a limited type, e.g., brash ice or thin level ice.

The ice situation on the planned test route in spring 2022 was indeed poor. Finally, we conducted the system validation campaign in the Bothnian Bay 620 km north of Helsinki on the icebreaker Sampo. It offers leisure cruises several times a week for tourists visiting Lapland and departs from the port of the city of Kemi. However, this type of scenario is rather ad hoc and leads to changes in the pre-planned test procedure, as the test equipment is to be mounted after the ship has sailed.

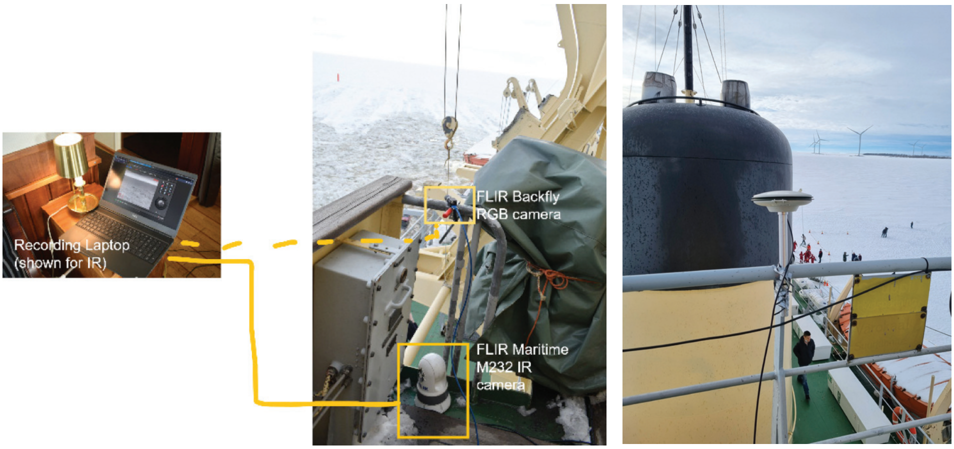


Figure 1. RGB camera and IR camera attached on a side railing of the icebreaker Sampo (in the middle). GNSS antenna attached to the railing near the top mast (on the right).

Figure 1 shows how the GNSS antenna of the Novatel-GPS-703-GGG-HV model is attached to an upper railing. This antenna can receive L1, L2, L3 and E5a/b. The FLIR Blackfly RGB camera and the FLIR Maritime M232 IR camera are mounted on the side railing. On the Sampo, it takes about 20 minutes to set up after the departure and 20 minutes to dismantle the equipment them before the approach. The cruising time of the Sampo is about 3.5 hours and the vessel stops in between for an hour and a half for tourists to walk on the ice. This type of itinerary allowed us to collect the necessary amount of variable sea ice images and perform the required GNSS measurement procedure. We measured both static and dynamic phases of maritime navigation, i.e. when the vessel was not moving and when it was moving.

3. RESULTS AND DISCUSSION

Efforts have already been made in the literature to integrate cameras into maritime autonomous systems [**4**]. However, cameras struggle with long distances and suboptimal weather conditions in winter. Integrating the IR camera into the sensor system alleviates the problem of lack of light during winter ice navigation.

AI can play a role in automating the ice navigation system by detecting and classifying of sea ice. Labelling maritime objects (other ships, buoys) during AI-NAV was a straight-forward, but tedious task and the classification of objects was reliable. Also in ENHANCE we want to train a model for the detection and classification of sea ice features using deep learning methods. However, since the labelling of sea ice features is more challenging, it requires a so-called semantic segmentation. In this paper, we present the initial results on the classification of the ongoing project ENHANCE in **Figure 2.** 'Label' denotes the hand-drawn segments of the different ice types and 'estimated' is a throughput of AI. The RGB and IR images are fused into a single 4-channel image, which is used as input for AI semantic segmentation algorithm. This fusion of RGB and IR images requires an accurate transformation between the RGB and IR image frames, which is to be taken into account.

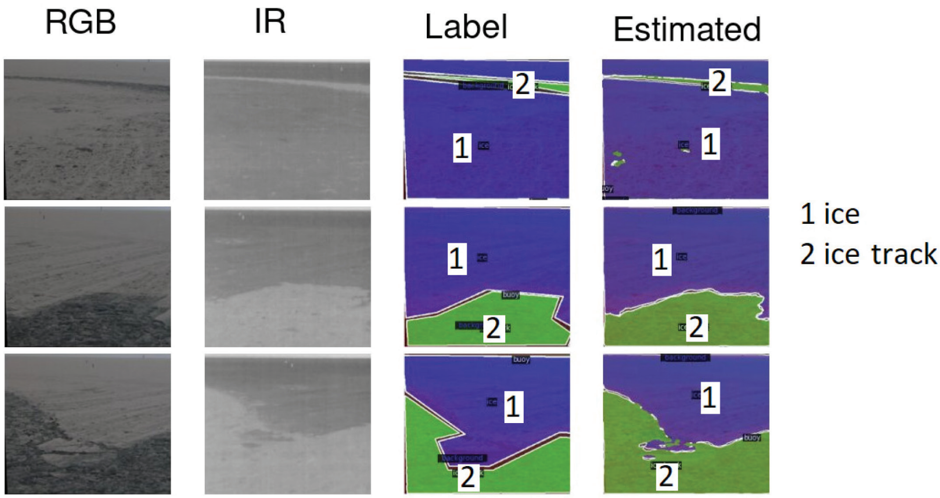


Figure 2. An example of processed sea ice images collected on Sampo.

The discussion shows that 'label' and 'estimated' in **Figure 2** correspond well, so that the validation of the method can be considered successful. All in all, recent advances in image processing have increased the likelihood that cameras will be used as a central component of future autonomous ships.

The only official horizontal alert limit (HAL) is given by the IMO and does not take into account the voyage phase of ice navigation, which still needs to be defined more precisely [5]. According to [6], the position accuracy and HAL in port calls and open sea is 25 m, but the accuracy is 10 m. All in all, precise GNSS measurements are needed in practise to keep within the limits in winter navigation together with other perception sensors. In the future, we want to investigate the resilience of the sensor assembly in the event of disruptions to the vessel's positioning system due to degradation of the GNSS signal in winter conditions. An example of such a metric is the multipath effect caused by sea ice. It has been shown that ice-free sea water absorbs the GNSS signal much more than sea ice. Therefore, we would expect a stronger multipath effect under icy conditions [7].

4. CONCLUSIONS

ENHANCE intends to develop the perception element of future autonomous winter maritime navigation. We have presented the development of ice navigation capabilities based on artificial intelligence to identify predefined ice regions in images captured on the icebreaker Sampo. Future work will involve investigating technologies that enable operational requirements to be met on multiple ice types, which has not yet been possible with our current measurement scenario.

Acknowledgments: This research was funded by ESA, contract 4000131018/20/NL/GLC/hh, as part of the Open Space Innovation Platform (OSIP). We would also like to express our gratitude to the crew of the Sampo.

REFERENCES

[1] International Maritime Organization. (2018). *IMO Takes First Steps to Address Autonomous Ships.* Available from: https://www.imo.org/en/MediaCentre/PressBriefings/Pages/08-MSC-99-MASS-scoping.aspx, accessed 19 January 2023.

[2] European Space Agency ESA (2022). *Artificial intelligence / machine learning sensor fusion for autonomous vessel navigation.* Available from: https://navisp.esa.int/project/details/51/show, accessed 19 January 2023.

[3] Thombre, S. et al. (2022). Sensors and AI Techniques for Situational Awareness in Autonomous Ships: A Review. *IEEE Transactions on Intelligent Transportation Systems*, 23(1), pp. 64–83.

[4] Kim, E., Panchi N., and Dahiya G. S. (2019). Towards automated identification of ice features for surface vessels using deep learning. *Journal of Physics: Conference Series.* 1357(1). IOP Publishing.

[5] Reid, T. G. R., Walter, T., Blanch, J. and Enge, P. K. (2015). GNSS Integrity in The Arctic. *The 28th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2015*, September 2015, Tampa, Florida.

[6] International Maritime Organization. (2001). *Resolution A.915(22) on Revised Maritime Policy and Requirements for a Future Global Navigation Satellite System (GNSS).* London: IMO.

[7] Drosinos E. C. (2016). *Gnss signal reflections off sea ice.* Master's Thesis, Chalmers University of Technology. Gothenburg, Sweden. Available from: https://hdl.handle.net/20.500.12380/246359 accessed 19 January 2023.

POSSIBILITIES OF ULTRA-WIDEBAND COMMUNICATION IN UNMANNED AERIAL VEHICLES

Luka Kramarić*, **Mario Muštra**, **Tomislav Radišić**

Abstract. *The use of unmanned aerial vehicles (UAVs) is constantly increasing. Adaptability, mobility and access to restricted areas are the main reasons for the increase in their use. UAVs rely heavily on GPS systems for navigation during flight. GPS systems use line of sight (LOS) communication and do not provide acceptable accuracy in some scenarios. Due to these limitations, additional methods for localisation are needed. In this study, we investigated how ultra-wideband (UWB) communication can be used to improve localisation accuracy of UAVs.*

Keywords: *GPS; localization; navigation; ultra-wideband communication; unmanned aerial vehicle*

University of Zagreb, Faculty of Transport and Traffic Sciences, Zagreb, Croatia
Corresponding author: Luka Kramarić (lkramaric@fpz.unizg.hr)

1. INTRODUCTION AND BACKGROUND

Ultra-wideband (UWB) is a low energy, short range, high bandwidth radio technology. Due to the high bandwidth, UWB provides fine time resolution, which enables accurate time-dependent techniques for localisation [1]. UWB systems use Time Difference of Arrival (TDoA) or Time of Flight (ToF) techniques. The aim of this study is to find out whether UWB as a ground-based localisation system has the potential to improve the performance of unmanned aerial vehicles (UAVs) and to investigate whether it can be successfully implemented. Our research was based on previous studies on the implementation of UWB as a navigation aid in UAVs. In reviewing the available studies, we found that UWB can complement GPS localisation and, despite its weaknesses, offer new opportunities for UAV localization.

2. METHODOLOGY

As a first step, we decided to look for successful cases of implementing UWB with already existing localisation systems, in particular Real-Time Kinematic GPS (RTK-GPS) and Inertial Measurement Unit (IMU), and for cases that underline the possibilities of UWB in GPS-denied areas. Both physical and simulated implementations were considered, highlighting the possibility of implementation and commercial usability of the proposed systems. We singled out five systems that met the above criteria. [2] proposed a system that provides localisation in GPS-denied environments using UWB and achieves an accuracy of 0.162 m for the x and y axis and 0.354 m for the z axis. They used two different localisation methods, the Extended Kalman Filter (EKF) and Non-Linear Regression (NLR). NLR gave better peak results, but EKF gave better results over time. In [3], simulations were used to show how much UWB helps RTK-GPS systems in GPS dropout and landing scenarios. Using UWB, the error drops from 2.91 m to 0.53 m and from 1.6 m to 0.32 m, respectively. [4] saw the potential of using UWB in reducing the cumulative error in IMU. Their experiment focused on comparing the accuracy of UWB-only and UWB/IMU systems, with the latter giving better results. After obtaining these results, the authors also concluded that UWB suppresses error accumulation in IMU. [5] proposed an innovative system using GPS to navigate distant UAVs and UWB to navigate nearby UAVs. Their experiment and ideas for further improvements are very promising for navigation of multi-UAV systems without the need for a control server on the ground. Lastly, [6] showed how TDoA is suitable for EKF as a localisation method, while previous works have considered the use of ToF.

3. RESULTS AND DISCUSSION

The advantages of UWB complement the disadvantages of GPS very well, and this is where we see a potential use of UWB indoors and in urban areas where GPS signal cannot be accounted for. UAVs equipped with UWB tags should be able to operate solely relying on communicating with UWB anchors set up indoors and possibly even in larger outdoor areas (**Figure 1 (a)**). The second potential use of UWB is in operations that require high accuracy. UWB anchors can be placed in landing zones to provide redundancy and increase the probability of a successful landing. The third and most exciting potential use case of UWB is multi-UAV systems, where UAVs communicate with each other without the need for a control unit (**Figure 1 (b)**).

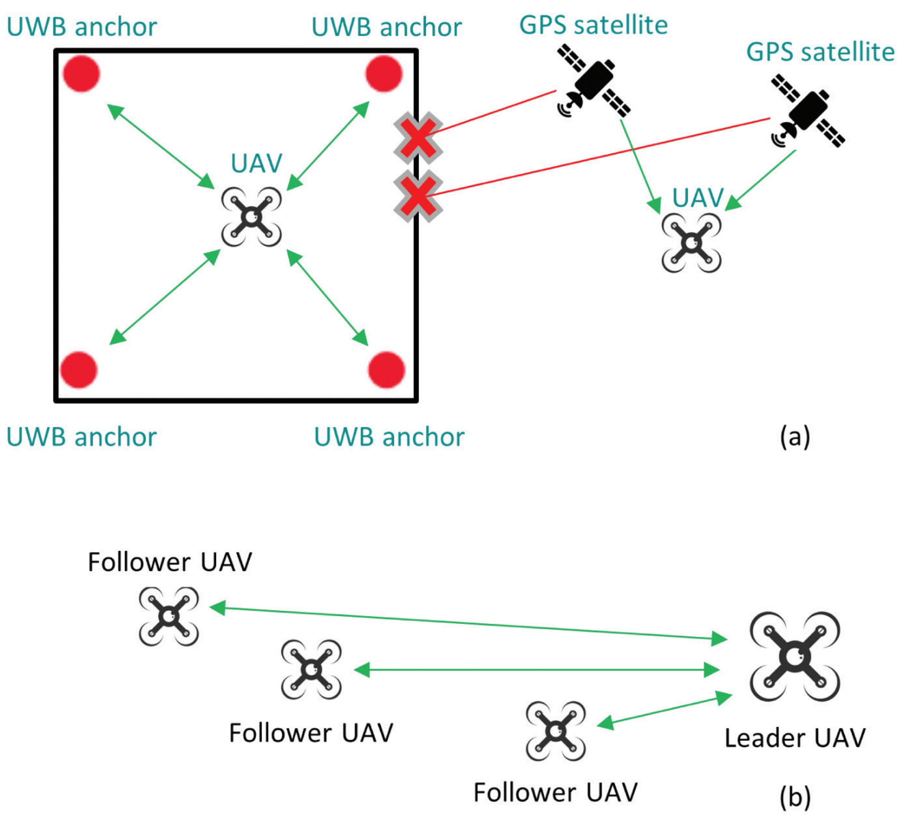


Figure 1. (a) Indoor positioning of UAVs using UWB anchors;
(b) Formation of UAVs creating a formation by following the leader.

In this use case, one UAV would be the designated leader equipped with a UWB anchor, while the other UAVs are equipped with UWB tags and follow the leader, creating a "lead-follow" formation. To get maximum benefit from UWB, it is necessary to optimise it and find out which current technology is best. We plan to develop and test our own multi-UAV system by implementing and improving the ideas from the referenced articles. For creating an initial setup, we think the NLR localisation method is more acceptable, as it has a lower setup time, while EKF localisation method is preferred for obtaining location data. For UWB communication, ToF is easier to implement but offers poor scalability and despite a slight increase in cost, due to precise synchronisation, while TDoA fits better with the idea of creating a large UWB anchor network for UAVs.

4. CONCLUSIONS

Much research has been conducted on the use of UWB as a localisation tool for UAVs, and the research continues to grow and generate new ideas and potential uses in UAVs. In this review, we have highlighted the approaches that we think are particularly interesting and promising. The high accuracy of UWB in a limited area can be a perfect tool for the low accuracy of GPS. Today, UWB is not yet used commercially with UAVs, but due to its low cost and ease of implementation, we are convinced that it will be in the near future. Setting up entire cities with UWB anchors to enable UWB-only flight in urban areas is also a possibility worth considering.

REFERENCES

[1] R. Mazraani, M. Saez, L. Govoni, and D. Knobloch, "Experimental results of a combined TDOA/TOF technique for UWB based localization systems," in *2017 IEEE International Conference on Communications Workshops (ICC Workshops)*, Paris, France: IEEE, May 2017, pp. 1043–1048. doi: 10.1109/ICCW.2017.7962796.

[2] T. M. Nguyen, A. H. Zaini, K. Guo, and L. Xie, "An Ultra-Wideband-based Multi-UAV Localization System in GPS-denied environments," 2016.

[3] K. Gryte, J. M. Hansen, T. Johansen, and T. I. Fossen, "Robust Navigation of UAV using Inertial Sensors Aided by UWB and RTK GPS," in *AIAA Guidance, Navigation, and Control Conference*, Grapevine, Texas: American Institute of Aeronautics and Astronautics, Jan. 2017. doi: 10.2514/6.2017-1035.

[4] W. You, F. Li, L. Liao, and M. Huang, "Data Fusion of UWB and IMU Based on Unscented Kalman Filter for Indoor Localization of Quadrotor UAV," *IEEE Access*, vol. 8, pp. 64971–64981, 2020, doi: 10.1109/ACCESS.2020.2985053.

[5] S. Cao, Y. Zhou, D. Yin, and J. Lai, "UWB Based Integrated Communication and Positioning System for Multi-UAVs Close Formation," presented at the 2018 International Conference on Mechanical, Electronic, Control and Automation Engineering (MECAE 2018), Atlantis Press, Mar. 2018, pp. 475–484. doi: 10.2991/mecae-18.2018.98.

[6] J. Tiemann and C. Wietfeld, "Scalable and precise multi-UAV indoor navigation using TDOA-based UWB localization," in *2017 International Conference on Indoor Positioning and Indoor Navigation (IPIN)*, Sep. 2017, pp. 1–7. doi: 10.1109/IPIN.2017.8115937.

A DATA COMPRESSION APPROACH TO REDUCING DEMANDS ON MARITIME COMMUNICATION SYSTEMS

Nikola Lopac[1,2*], Irena Jurdana[1], Nobukazu Wakabayashi[3], Hongze Liu[3]

Abstract. *Ship digitalization and the associated introduction of various measurment systems generate massive amounts of data that must be transmitted in real time. However, maritime communication systems are still limited in terms of communication speed, capacity and reliability. Therefore, improvements in the maritime communication infrastructure are necessary. This work addresses one of the approaches for these improvements, which is based on the compressing the collected data with navigation and ship performance information.*

Keywords: *data compression; data transmission; maritime communications; ship digitalization*

[1] University of Rijeka, Faculty of Maritime Studies, 51000 Rijeka, Croatia
[2] Center for Artificial Intelligence and Cybersecurity, University of Rijeka, 51000 Rijeka, Croatia
[3] Graduate School of Maritime Sciences, Kobe University, Kobe 658-0022, Japan
Corresponding author: Nikola Lopac (nikola.lopac@pfri.uniri.hr)

1. INTRODUCTION AND BACKGROUND

The increasing digitalisation of ships and their equipment with various sensors and measurement systems [1] as well as the introduction of novel concepts, such as autonomous ships, lead to safer navigation and more efficient ship operation [2]. These trends lead to large amounts of navigation and ship performance data that can be further utilised by implementing more advanced functions [3].

2. METHODOLOGY

This massive digital data generated on board the ship needs to be adequately stored and, more importantly, continuously transmitted in real time to other vessels or coastal stations. Furthermore, this requires a reliable and high transmission rate, unlike the standard Automatic Identification System (AIS) [4-6], which only transmits a limited amount of predefined data.

This requirement places an additional burden on the already strained maritime communication systems, which are characterised by limited availability, low communication speeds and limited communication capacity. The future modernisation and digitalisation of maritime transport therefore requires significant improvements to maritime communication networks.

3. RESULTS AND DISCUSSION

Although there are several efforts in this direction [7-9], most of these approaches focus on modernisation and upgrading maritime communications infrastructure, which involves a significant allocation of both financial and human resources.

In contrast, an alternative approach to this problem, which has not yet attracted much attention, focuses on reducing the volume of data to be transmitted. Besides the techniques used in big data handling and processing [10], approaches based on data compression seem promising. The basic idea of these approaches is illustrated in **Figure 1**.

Figure 1. Data compression approach.

In this context, a method for compressing navigation and ship performance data based on deep learning techniques was proposed [11-12]. This method used principal component analysis and autoencoder system architecture to compress data. The method enabled the transfer of data over communication networks in the form of reduced datasets. Despite promising results, this type of data compression method is quite complex and computationally intensive.

On the other hand, a recent study proposed an adaptive method for compressing ship data based on variable-record-length encoding [13-14]. More specifically, the proposed method used a six-bit differential binary encoding of the acquired data, transmitting only the changed data items. This straightforward method gave excellent results in experimental tests in terms of data compression efficiency, while being computationally efficient.

4. CONCLUSIONS

This work focused on data compression approaches to reduce the load on maritime communication systems. It has been shown that relatively simple methods that are not computationally intensive can significantly reduce the size of digital data that needs to be transmitted from the ship. These methods can be easily integrated into existing ship and communication infrastructure, reducing the required transmission rate and reducing the need for maritime communication network upgrades required for the digitalisation of maritime transport.

Acknowledgments: This research was funded by the University of Rijeka under the project “Analysis and Classification of Non-Stationary Signals Using Advanced Deep Learning Methods” (uniri-mladi-tehnic-22-16).

REFERENCES

[1] Lopac, N., Jurdana, I., Brnelić, A. and Krljan, T. (2022). Application of Laser Systems for Detection and Ranging in the Modern Road Transportation and Maritime Sector. *Sensors*, 22 (16), 5946. doi: 10.3390/s22165946.

[2] Dujmović, J., Krljan, T., Lopac, N. and Žuškin, S. (2022). Emphasis on Occupancy Rates in Carbon Emission Comparison for Maritime and Road Passenger Transportation Modes. *Journal of Marine Science and Engineering*, 10 (4), 459. doi: 10.3390/jmse10040459.

[3] Lopac, N., Jurdana, I., Lerga, J. and Wakabayashi, N. (2021). Particle-Swarm-Optimization-Enhanced Radial-Basis-Function-Kernel-Based Adaptive Filtering Applied to Maritime Data. *Journal of Marine Science and Engineering*, 9 (4), 439. doi: 10.3390/jmse9040439.

[4] International Telecommunication Union Radiocommunication Sector (ITU-R). (2014). *ITU-R M.1371-5: Technical Characteristics for an Automatic Identification System Using Time Division Multiple Access in the VHF Maritime Mobile Frequency Band*. Recommendation. Geneva, Switzerland: ITU-R.

[5] Liu, H., Jurdana, I., Lopac, N. and Wakabayashi, N. (2022). BlueNavi: A Microservices Architecture-Styled Platform Providing Maritime Information. *Sustainability*, 14 (4), 2173. doi: 10.3390/su14042173.

[6] Lopac, N., Jurdana, I., Wakabayashi, N. and Liu, H. (2022). Application of Advanced Digital Technologies for AIS Data Utilization. In: Brčić, D., Valčić, M., Kos, S. and Vuković, J. (eds.). *Book of Extended Abstracts of the 15th Baška GNSS Conference: Technologies, Techniques and Applications Across PNT and The 2nd Workshop on Smart, Blue and Green Maritime Technologies*, pp. 145–148. 08–13 May 2022, Baška, Croatia. Rijeka: University of Rijeka, Faculty of Maritime Studies.

[7] Wang, J., Zhou, H., Li, Y., Sun, Q., Wu, Y., Jin, S., Quek, T. and Xu, C. (2018). Wireless Channel Models for Maritime Communications. *IEEE Access*, 6, pp. 68070–68088. doi: 10.1109/ACCESS.2018.2879902.

[8] Xia, T., Wang, M. M., Zhang, J. and Wang, L. (2020). Maritime Internet of Things: Challenges and Solutions. *IEEE Wireless Communications*, 27 (2), pp. 188–196. doi: 10.1109/MWC.001.1900322.

[9] Wei, T., Feng, W., Chen, Y., Wang, C. X., Ge, N. and Lu, J. (2021). Hybrid Satellite-Terrestrial Communication Networks for the Maritime Internet of Things: Key Technologies, Opportunities, and Challenges. *IEEE Internet of Things Journal*, 8 (11), pp. 8910–8934. doi: 10.1109/JIOT.2021.3056091.

[10] Perera, L. P. (2017). Handling Big Data in Ship Performance and Navigation Monitoring. In: *Smart Ship Technology*, pp. 89–97. 24–25 January 2017, London, UK. London: The Royal Institution of Naval Architects.

[11] Perera, L. P. and Mo, B. (2016). Data Compression of Ship Performance and Navigation Information Under Deep Learning. In: *Proceedings of the 35th International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2016)*, V007T06A086. 19–24 June 2016, Busan, South Korea. Busan: American Society of Mechanical Engineers (ASME). doi: 10.1115/OMAE2016-54093.

[12] Perera, L. P. and Mo, B. (2018). Ship performance and navigation data compression and communication under autoencoder system architecture. *Journal of Ocean Engineering and Science*, 3 (2), pp. 133–143. doi: 10.1016/j.joes.2018.04.002.

[13] Wakabayashi, N. and Jurdana, I. (2020). Maritime Communications and Remote Voyage Monitoring. In: *Proceedings of the International Conference on Broadband*

Communications for Next Generation Networks and Multimedia Applications (CoBCom), pp. 1–8. 07–09 July 2020, Graz, Austria. Graz: Graz University of Technology. doi: 10.1109/CoBCom49975.2020.9174182.

[14] Jurdana, I., Lopac, N., Wakabayashi, N. and Liu, H. (2021). Shipboard Data Compression Method for Sustainable Real-Time Maritime Communication in Remote Voyage Monitoring of Autonomous Ships. *Sustainability*, 13 (15), 8264. doi: 10.3390/su13158264.

DEVELOPING GENERAL TRANSIT FEED SPECIFICATION DATA FOR MODELING OF MARITIME PUBLIC SERVICE NETWORK: THE USE CASE FOR NORTHERN ADRIATIC SEA NETWORK SECTION

Neven Grubisic*, **Tomislav Krljan, Pia Biondic**

Abstract. *The General Transit Feed Specification (GTFS) could be extended to maritime public transport lines to integrate maritime services with land-based public passenger transport services. In this way, accurate information on shipping lines, routes, stops, and service timetables could be provided in electronic datasets. After the development of GTFS and proper coding of the datasets, the data was imported into macroscopic modelling software (PTV-Visum) to integrate it into the existing transport supply network. We give an example for the Northern Adriatic area. Finally, some traffic demands were generated and assigned to transit service lines to test the functionality of the model and obtain the results.*

Keywords: *GTFS static; maritime public service; PTV-Visum; transport modelling*

University of Rijeka, Faculty of Maritime Studies, Rijeka, Croatia
Corresponding author: Neven Grubisic (neven.grubisic@uniri.hr)

1. INTRODUCTION

The General Transit Feed Specification (GTFS) is a standard public transit data format for collecting, storing and exchanging transport information. It can be based on static or dynamic data and is mainly used in urban or suburban areas. It contains datasets organised in several text files with information about public transport service lines, routes, stops, scheduled journeys and timetables.

The question is how this standard can be used to code the database fields and properly create datasets for maritime transportation GTFS. Below is an example of a created trip.txt file (selected records only) for the use case (**Table 1**).

Table 1. Example of GTFS file structure (trip.txt file).

route_id	service_id	trip_id	trip_short_name	dir.id
JL-9308-DK	JL23-0101-0106-1#	9308-23-0101-0106-1#.01	ML-RI-1	0
JL-9308-DK	JL23-0101-0106-1#	9308-23-0101-0106-1#.02	RI-ML-1	1
JL-9309-DK	JL23-0101-0106-0#7	9309-23-0101-0106-0#7.01	NV-RI-1	0
JL-9309-DK	JL23-0101-0106-0#7	9309-23-0101-0106-0#7.02	RI-NV-1	1
JL-0332-DT	JL23-0101-3103-0#	0332-23-0101-3103-0#.09	MG-VB-5	0
JL-0332-DT	JL23-0101-3103-0#	0332-23-0101-3103-0#.10	VB-MG-5	1
JL-0334-DT	JL23-0101-3103-0#	0334-23-0101-3103-0#.03	PZ-BR-2	0
JL-0334-DT	JL23-0101-3103-0#	0334-23-0101-3103-0#.04	BR-PZ-2	1

2. METHODOLOGY

As the data for the maritime public service does not exist or is not available in electronic form, we had to create a database for the test area based on manual input of the crucial elements of the structure of the GTFS dataset. The objective was to create the static transit feed specification and to test the spatial and temporal consistency of information created with the traffic simulation software.

The methodology consists of several steps: first, information on transit lines, routes, timetables, and stops/ports is collected from the Internet. Then, the correct format for unique keys in the fields of datasets is designed and the database structure is created. As a result, six text files are generated as minimum requirements, representing routes, stops, stop times, trips, calendar dates, and agency information.

Finally, the datasets are imported into a transport modelling software (PTV-Visum was used) to visualise them and test their functionality. This step required a transport supply network model previously created for the test area. The tentative traffic demand in the form of an origin-destination matrix is added to the supply model, followed by the allocation procedure, which generates the public transport flows on the corresponding shipping routes.

3. RESULTS AND DISCUSSION

After importing data from GTFS into the traffic model, new elements are created for the network supply. The newly created elements include public transport lines, journeys, ports/stops, and sailing schedules (**Figures 1** and **2**).

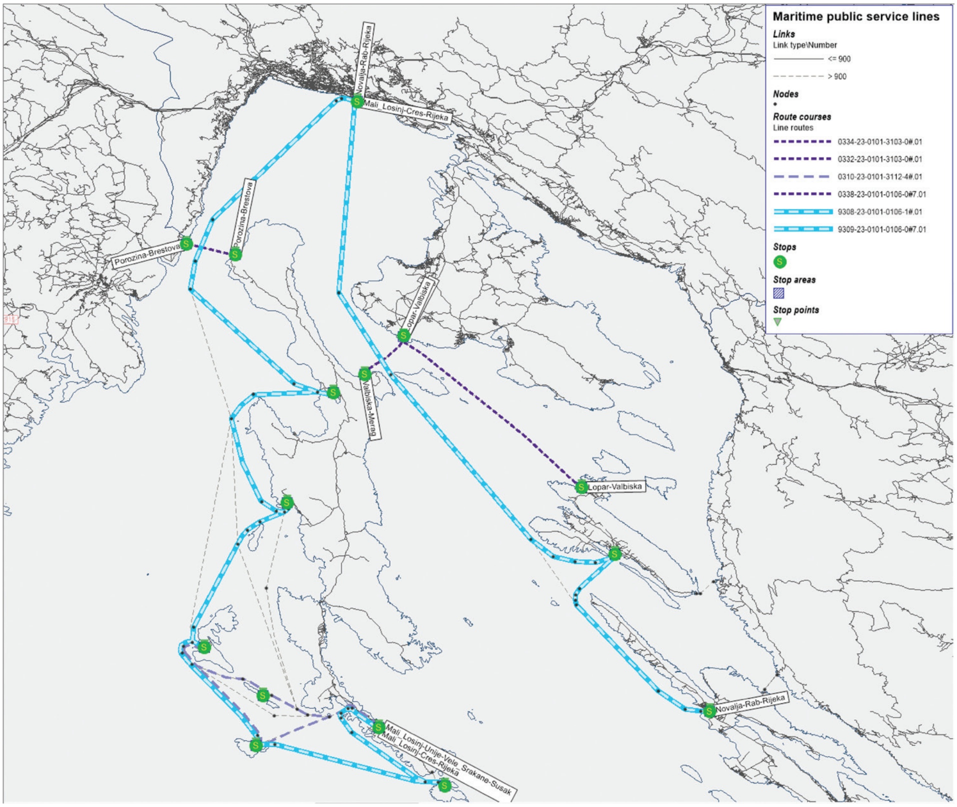


Figure 1. Result of the model network after GTFS import.

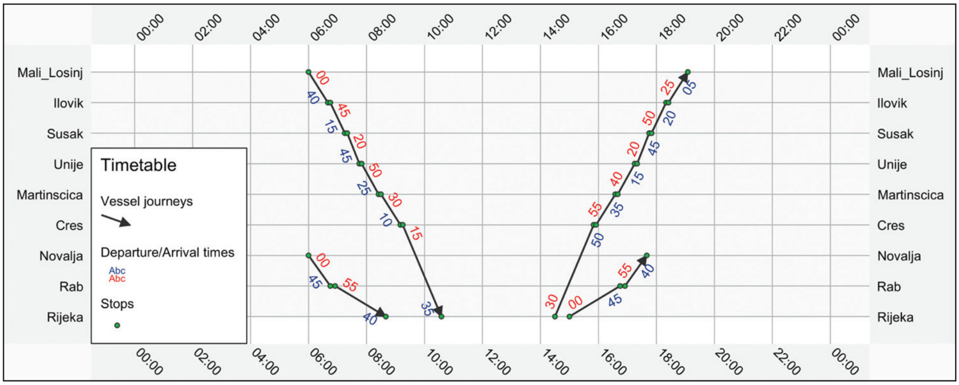


Figure 2. Timetable visualization based on GTFS data import.

Different route journeys (with different paths) may exist for the same service route. Moreover, these paths might not match the actual navigation routes if we omit the shape.txt file as part of GTFS. In this case, two solutions are possible: the first solution is to include the shape data as an attribute in the trip.txt file to identify the path of a trip. The second solution is to manually edit the route in the modelling software. The second solution requires the definition and creation links with specific configurations suitable for maritime transport.

4. CONCLUSION

Tailored to the maritime public service network, the General Transit Feed Specification contributes to the further development of IT-based applications for various interest groups – shipping operators, passengers, tourists, administrative authorities, etc. Furthermore, the integration into the transport model enhances the possibilities for service optimisation and service performance monitoring. Furthermore, the implementation of the static GTFS in maritime transport is a prerequisite for the intermodal integration of public transit data and for the development of a dynamic GTFS for data exchange.

REFERENCES

[1] General Transit Feed Specification. *GTFS Schedule Reference*. Available from: https://gtfs.org/, accessed 23 February 2023.

[2] Ballis, H., Alogdianakis, F., Nikolaou, P., Stylianou, K. and L. Dimitriou (2021). Fusion of General Transit Feed Specification (GTFS) and passenger count data: A case study on Cyprus Transit System. *MT-ITS 2021: 7th International Conference on Models and Technologies for Intelligent Transportation Systems,* pp. 1–6. 16-17 June 2021, Heraklion, Greece. doi: 10.1109/MT-ITS49943.2021.9529286.

[3] Chin, T. K., Xian, (Tim), T., Marks, B., Nelson, J.D., and Moylan, E. (2022). Data pipeline for GTFS transit arrival and departure information. To be published in Springer Nature. doi: https://doi.org/10.21203/rs.3.rs-2090922/v1.

[4] Hoover, S., Kost, A., and David Porter, J. (2022). Using General Transit Feed Specification-Ride to Identify Riders' Use of Transfer Opportunities. Transportation Research Record, 2676(6), pp. 197–206. doi: https://doi.org/10.1177/03611981211073311.

[5] Bok, J.; Kwon, Y. (2016). Comparable Measures of Accessibility to Public Transport Using the General Transit Feed Specification. *Sustainability* 2016, *8*, 224. doi: https://doi.org/10.3390/su8030224.

SMARTSEA – MASTER PILOT PROGRAMME

Aleksander Grm*, **Franc Dimc**

Abstract. *SMARTSEA is an acronym for the ERAMSMUS+ K2 project derived from "Surveying & MARiTime internet of thingS EducAtion". The project aimed to develop an advanced, interactive, certified MSc course related to IoT applications in maritime and surveying that would train individuals with the necessary skills and knowledge to work in the emerging "Smart Maritime & Surveying" industry. The course also aims to develop cross-cutting skills such as a higher level of initiative and entrepreneurship. The course is designed to meet the standards of the European Credit Transfer and Accumulation System (ECTS) for EU-wide recognition of certification.*

Keywords: *education; IoT; master program; maritime survey*

University of Ljubljana, Faculty of Maritime Technology and Transport, Portorož, Slovenia
Corresponding author: Aleksander Grm (aleksander.grm@fpp.uni-lj.si)

1. INTRODUCTION

The pilot programme's innovative curriculum incorporates interactive teaching methods and partnerships with expert academic and maritime organisations to provide students with a solid background for a successful career in the industry [1]. The course duration is eight months, plus a one-month maritime internship (on the job) that takes place one month after the end of the course duration. Three mobility phases are foreseen during the implementation of the course. During the first two (14-day) phases, students, and faculty travel from one university to another and vice versa to participate in large-scale laboratories. The third phase (1 month), on the other hand, is dedicated to practical training at sea.

The project started on 01/11/2019 and ended on 31/10/2022 and consisted of six work packages. In WP-1 to WP-3, a complete Master's programme was developed, consisting of 20 introductory courses, two language courses and two project courses. For each course, 2 ECTS credits were awarded so that a complete programme reached 60 ECTS credits. The courses could also include practical exercises, such as using a computer or performing cutting tests on electronic components, which the students then assembled into a dedicated unit for specific operations.

2. METHODOLOGY

The course development was divided into three work packages WP1, WP2 and WP3. Work package WP4 defines a complete description of the implementation and execution of the course.

In work package WP1, teachers had to create a syllabus for each course, defining lessons, content and assessment methods. After the syllabi were finalised, the course delivery started with the preparation of lecture notes, homework assignments, slides and exams, which were specified in WP2. Each part of the course delivery was designed as a separate work package. In work package WP3, the teachers conducting the experiments in their classes had to develop all experiments with descriptions and, if necessary, supporting programmes. The codes for the supporting programmes were mainly written in MatLab.

The implementation of the programme is described in WP4. Guidelines for the online lectures, experiments, proposed schedules, etc. are presented here.

Two dissemination and exploitation tasks are foreseen between the project implementation, all described in WP5. General project management is described in WP6.

3. RESULTS AND DISCUSSION

A pilot programme was carried out in WP-4. It was conducted during the period from 01/10/2021 to 31/10/2022. All courses were taught online, except for the practical exercises, which were conducted on-site during the mobility phase in May 2022. The mobility phase was divided into two parts: Students spent two weeks in Slovenia at the University of Ljubljana and two weeks in Greece at the International Hellenic University.

ULFPP was involved in the development and delivery of the following courses: Maritime Surveying, Underwater Communications and Navigation [2, 4], Geographic Information System and Underwater Physics [3, 5]. During the first mobility period, the students stayed at ULFPP and worked on their project tasks. The main project task was Augmented Reality (AR) in the context of maritime surveying. The main direction of AR development was related to the use of Internet of Things (IoT) components with Microsoft Hololens (MS-HL). The students developed the entire platform integrating sensors, data transmission, data processing and display on MS-HL. The main development platform was LabView from National Instruments (NI-LV). One of the moments of the project development can be seen in **Figure 1**.

(a) (b)

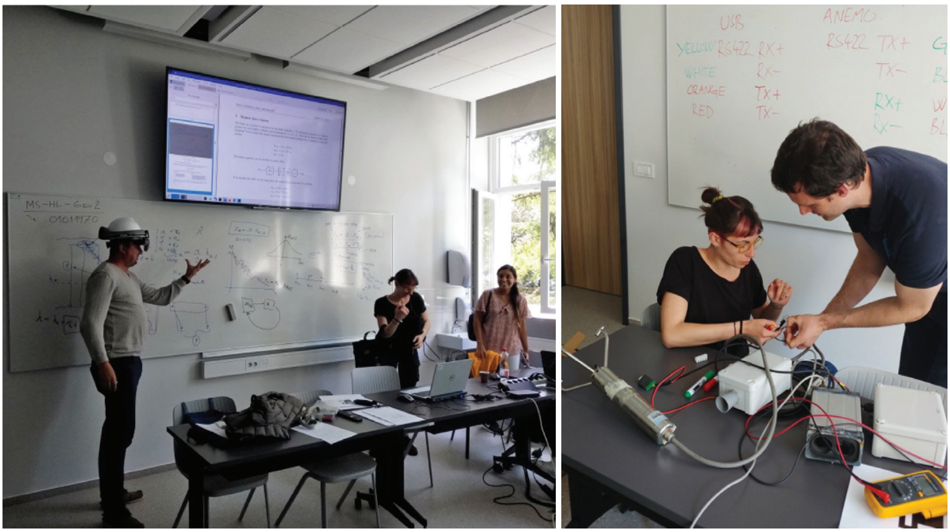


Figure 1. Students AR platform development moments.
(a) testing MS-HL display sensor data, (b) sensor connection with NI-LV system.

In June 2022, the students completed a one-month internship with the industrial partners involved in the project. After that, they had two months to write their master's thesis. The defence of the thesis took place on 17/10/ 2022, at IHU in Thessaloniki. The programme was open to 40 students. During enrolment, only 35 students were selected; in the end, 22 students completed the Master's programme.

The future study programme is designed as a two-year Master's programme with 120 ECTS. The redesign of the study programme envisages the introduction of three different modules. Each module will be designed as a stand-alone module that can be certified. All students who complete the module will receive a micro-certificate proving their competence in that module.

5. CONCLUSION

The one-year Master's course presented focuses on training marine engineers for general surveys using various IoT platforms. The results show that the course was perfectly designed and delivered. The students received basic and advanced knowledge for performing various marine surveying tasks.

REFERENCES

[1] SMARTSEA (2022). Surveying & MARiTime internet of thingS EducAtion, Aviable from: https://www.smart-sea.eu, accessed 15.01.2023.

[2] Grm, A. (2017). Mathematical model for riverboat dynamics. Brodogradnja: Teorija i praksa brodogradnje i pomorske tehnike, 68(3), pp. 25–35.

[3] Grm, G. and Grm, A. (2021). Testing the Functionality and Applicability of Smart Devices for a Handheld Celestial Navigation System. NAŠE MORE: znanstveni časopis za more i pomorstvo, 68(3), pp. 157–166.

[4] Baldini, G., Steri, G., Dimc, F., Giuliani, R. and Kamnik, R. (2016). Experimental identification of smartphones using fingerprints of built-in micro-electro mechanical systems (MEMS). Sensors, 16(6), p. 818.

[5] Baldini, G., Dimc, F., Kamnik, R., Steri, G., Giuliani, R. and Gentile, C. (2017). Identification of mobile phones using the built-in magnetometers stimulated by motion patterns. Sensors, 17(4), p. 783.

THE MASK PROJECT – USING MARINE ROBOTICS TO INCREASE SEA KNOWLEDGE AWARENESS AMONG HIGH SCHOOL STUDENTS

Fausto Ferreira[1*], **Đula Nađ**[1], **Lovro Maglić**[2], **Antonio Blažina**[2], **Francesco Maurelli**[3], **Tomislav Jagušt**[1], **Nikola Mišković**[1]

Abstract. *This extended abstract introduces the Marine Robots for better Sea Knowledge awareness (MASK) project. The main aim of the project MASK is to teach, learn and train late high school students and their teachers in marine robotics and Artificial Intelligence (AI) for environmental monitoring and protection. Inspired by the constraints of the COVID-19 pandemic and the need to reduce the ecological footprint, special attention is given to the possibilities of remote access to infrastructures (telerobotics). It uses a combination of remote lectures, remote trials and finally trials at sea to raise awareness of environmental issues that can be addressed with robots.*

Keywords: *climate change; education; environmental awareness; marine robotics; remote learning*

[1] University of Zagreb, Faculty of Electrical Engineering and Computing, Zagreb, Croatia

[2] University of Rijeka, Faculty of Maritime Studies, Rijeka, Croatia

[3] Constructor University, Bremen, Germany

Corresponding author: Fausto Ferreira (Fausto.ferreira@fer.hr)

1. INTRODUCTION

In this paper, we give a brief overview of the project MASK. Three universities and two high schools from two different countries (Germany and Croatia) are participating in this Erasmus+ KA220 project. The project started in November 2022 and will run until October 2024. The paper will present the methodology of the project and first results. As this is a project in its infancy, some core components will be implemented in the following months and presented during the conference.

2. METHODOLOGY

The project MASK [1] has five main objectives that implement the main goal described in the abstract:

1. stimulate interest in both students and teachers towards robotics, artificial intelligence, and STEM in general, by encouraging students to work in STEM-related projects and use marine robots;
2. engage and keep students motivated, with the goals of a) contributing to a decrease in dropout rates and b) encourage a STEM career for every student, with particular attention to underrepresented groups;
3. improve the digital competences and skills of students and teachers, with an emphasis on applications in new technologies, robotics and artificial intelligence;
4. exploit the possibilities introduced by remote access/remote learning to deliver high quality lectures by university experts and perform remote robotic trials contributing to sustainable development and avoiding unnecessary travel;
5. raise awareness of climate change and environmental protection and mitigation, using marine robotics as a field of application, especially for the detection, recognition and removal of seabed litter.

To achieve these objectives, a series of activities have been developed as part of the methodology. These activities are guided by the constraints imposed by COVID-19, its impact on the environment and the need for environmental sustainability for projects activities as well. Indeed, during the pandemic, a shift towards remote learning was observed in many areas including robotics education [2]. On the other hand, the massive use of protective devices such as gloves, masks, etc. at sea also had an impact on the environment [3]. In order to use the possibilities of distance learning and raise awareness of the environmental issues affecting the ocean (not only COVID-19 related), the following activities have been developed.

Firstly, high-quality distance learning lectures run by the university partners will teach the students about the basics of marine robotics and Artificial Intelligence (AI) and their applications, with a particular focus on the field of environmental protection and mitigation.

The second activity focuses on the high-school teachers, as we want to achieve a broader impact and increase the sustainability of the project in the long term. By training the trainers (teachers), we enable these teachers to continue engaging new students in marine robotics even after the end of the project, without having to rely on university support. As the project creates a course with materials, these materials can be easily used by the teachers in the following years.

In preparation for the tests at sea, the third activity will involve remote trials, where students will be able to control Remotely Operated Vehicles (ROVs) in the pools of two of the universities from their schools. This will make full use of the infrastructure [4] available for remote access due to and during the COVID-19 pandemic. All three activities are linked to Objectives 3 and 4. In addition, the frequent use of remote lectures and remote trials throughout the project aims to reduce the carbon footprint and avoid travelling for trials at sea, which provide invaluable experiences for students.

The culmination of the previous three activities is the experimental phase at sea. There will be two trials (one per year). The first trial will take place during the 16th Baška GNSS Conference [5], as the plan is to give high school students the opportunity to interact with senior researchers and better disseminate the practical activities. The conference participants will also be able to try out the robots and learn from the students how to drive these ROVs. While the focus of the first trial is to put into practise the piloting skills acquired during the remote tests and the operational procedures for launching, operating, recovering and maintaining the ROVs, data collection will also take place. Indeed, as a use case of the project, it is planned to detect and collect COVID-19 related protection masks (in conjunction with to Objective 5). This will be tested in the the second trial, but in order to train the AI, visual data from masks deployed on the seabed will be collected in the first trial. All masks and other equipment will be recovered after the trial so as not to pollute the environment.

Finally, the dissemination of the project through a major event guarantees that the results obtained and the methodology used are well disseminated in the marine robotics community. This will happen during OCEANS 2023 Limerick [**6**], which will take place from the 6 to 9 June in Limerick, Ireland. OCEANS 2023 Limerick is an important event in the marine engineering community and provides an excellent opportunity to present the preliminary results of the project. As the goal is to disseminate and share best practises, the MASK consortium is also organizing a special session on marine robotics education, presenting a series of projects on this topic for different target groups (high schools, universities, adult education).

3. RESULTS AND DISCUSSION

The first four months of the project focused on the first two activities. Six lectures were given at each school by the different universities and a meeting was held to train the trainers. Nevertheless, all activities were active. In particular, preparations were made for setting up the remote connection and remote control of ROVs. The next training of the trainers will be deal with the installation of a Virtual Private Network (VPN) and the testing of the remote connection to a robot. After that, the remote tests will take place in March/April 2023, in preparation for the tests at sea in May 2023. Regarding the trials at sea, a preparatory visit has taken place to identify the best deployment and working area based on logistical requirements. Finally, an abstract for OCEANS 2023 Limerick was submitted and accepted and a very popular special session (eight papers accepted) is being organized.

The project is going according to plan and the methodology has been effective. The biggest challenge has been to reconcile the different experiences of the universities and schools. While there is overlap between the universities, there is also complementarity. Therefore, the curriculum was designed in such a way that each university teaches what it does best without much overlap with the other university. On the other hand, school students have very different backgrounds, with one school more involved in drawing and construction and the second school more involved in programming and ICT. This fact has led us to slightly change the curricula to suit each school. In particular, the students of the first school were given a conceptual design task, while the students of the second school were given a programming task.

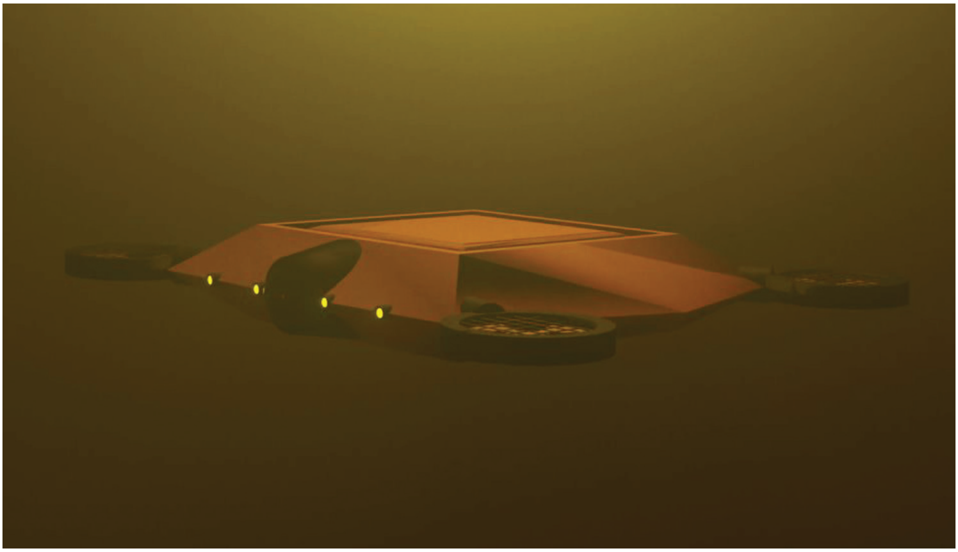


Figure 1. Conceptual design by one of the students involved in the project.

The feedback and interest of the students was great, fulfilling the first main objective of the project. The creativity of the students was also exceptional. As an example, **Figure 1** shows some conceptual designs of underwater robots created by the students of one of the schools.

4. CONCLUSION

Although the project started less than six months ago, the activities have started well and the interest of the students is very high. Both target groups (students and teachers) are very engaged and want to learn more about marine robots and even move on to building their own robot (which was not originally foreseen) to fulfil the objective 1 of the project. Given the short distances, the schools will visit the universities before the tests at sea so that they can see the laboratories and a wider range of technologies than those brought for the trials.

Acknowledgments: This work was supported by the project MASK. The project MASK – Marine Robots for better Sea Knowledge awareness has received funding from the EU Erasmus+ program, Key Action 2, 2022-1-HR01-KA210-SCH000082831. This publication reflects the views only of the authors, and the

Commission cannot be held responsible for any use which may be made of the information contained therein.

REFERENCES

[1] University of Zagreb Faculty of Electrical Engineering and Computing. (2023). MASK – Marine Robots for better Sea Knowledge awareness. Available from: https://mask.fer.hr/, accessed 25 February 2023.

[2] Birk, A., Simunovic, D. (2021). Robotics labs and other hands-on teaching during covid-19: Change is here to stay?. IEEE Robotics Automation Magazine, 28 (4), pp. 92–102.

[3] Mail Online. (2020). Face masks and latex gloves are found strewn along a French seabed raising concerns of coronavirus related littering. Available from: https://www.dailymail.co.uk/news/article-8359569/Face-masks-latex-gloves-strewn-French-seabed.html, accessed 25 February 2023.

[4] Ferreira, F., Kvasić, I., Nađ, Đ., Mandić, L., Obradović, J. and Mišković, N. (2022). In: OCEANS 2022 – Chennai. Creating a remote access-ready infrastructure for the future. pp. 1–5. 21-24 February 2022, Chennai, India. Piscataway: Institute of Electrical and Electronics Engineers.

[5] Royal Institute of Navigation. (2023). 16th Baška GNSS Conference: Technologies, Techniques and Applications Across PNT and The 3rd Workshop on Smart Blue and Green Maritime Technologies. Available from: https://rin.org.uk/mpage/BaskaGNSSHome, accessed 25 February 2023.

[6] OCEANS Conference. (2023). OCEANS 2023 Limerick, 5-8 June Blue Ocean Planet Earth. Available from: https://limerick23.oceansconference.org/, accessed 25 February 2023.

INCREASING MARITIME SAFETY INCLUDING WEARABLE BIOMETRICAL SENSORS

Dejan Žagar*, Tina Šfiligoj, Tanja Brcko Satler, Franc Dimc

Abstract. *To improve maritime safety, in this paper we present a biometric wearable system that monitors navigators' body parameters and, after post-processing, supports the reliability of navigational decision-making processes. In maritime applications, e-Navigation enables a VHF data exchange system (VDES) between on-board systems, navigators, and shore personnel. Wearable biometric sensors, e-Navigation and Internet of Things (IoT) technology can detect the potential for Human Erroneous Action (HEA) on the ship's bridge, whereupon the vessel traffic service (VTS) is informed and assists the ship.*

Keywords: *biometrical readings; e-Navigation; fatigue; human performance; VDES*

[1] University of Ljubljana, Faculty of Maritime Studies and Transport,
**Corresponding author: dejan.zagar@fpp.edu*

1. INTRODUCTION

The advantage of portable devices to measure workload, cardiac arrhythmias, and fatigue on the bridge is that the data can be collected while the person is performing daily tasks [1], [2]. To improve maritime safety from the perspective of coastal services, sharing biometric data can alert navigators and coastal services of vessels when navigators' biometric responses deviate from the average. The results shed light on the state of workload and awareness and highlight the potential causes of human error, which are becoming increasingly important in shipping and modern navigation.

2. METHODOLOGY

Monitoring the bridge instruments and comparing the apparent position with the ship's desired route during navigation is the primary task of the ship's officer on watch [3]. Cognitively, this task becomes more demanding in in areas of dense traffic and during port approach, as working memory processes increase due to situational awareness, leading to specific reactions of the human body [4].

The simulated task involved a large container ship with a draught of 14 m approaching the 15 m dredged channel, similar to the widely known obstruction case of the container ship Ever Given in the Suez Canal in 2021, so there was not much margin for error. The participants were experienced local ship captains (N=6) who were familiar with the local environmental conditions, including port approach. Data collection was conducted using a wireless biometric wristband sensor, which allows for a non-invasive approach and low noise ratio. Therefore, post-processing is theoretically less complex. A potential weakness is the low sampling frequency. The main metrics are a) blood volume pulse (BVP) and b) electrodermal activity (EDA), which indirectly indicates the density of cognitive processes during the simulated navigation tasks. The recorded data is statistically analysed by taking a moving average, which is a set of average values of different subsets of the data set, and comparing them to the average value of all participants in all sessions. The result represents the biometric response and consequently shows the workload during the decision-making processes at a given point of interest. E-navigation and IoT, including VDES, enable networking with coastal stations such as VTS, which provide additional support to the vessel when needed.

3. RESULTS AND DISCUSSION

The time of interest is chosen between thirty seconds before and thirty seconds after channel entry, assuming that the cognitively demanding task triggers the biometric data. Before the time of channel entry (before time "zero"), participants closely observe both the external situation and the navigation instruments. Based on the obtained results, we hypothesise that (mental) effort during a demanding cognitive task influences the EDA and BVP signal, as shown in **Figure 1** and **Figure 2**. The aim of the study is to find similarities in the participants' body responses triggered by the demanding cognitive phase of the task. A high EDA amplitude indicates that the participant is aroused. Despite the promising results, we encounter two limitations. The time interval between the disturbance and the measured change can range from several seconds to several minutes, depending on the participant's body tissue, thermal mass, and blood vessel density. Therefore, it is difficult to quantify the response outside of laboratory conditions. Another limitation is that only the degree of arousal, but not the valence (positive/negative), could be extracted from the recorded data. For this reason, we correlated the EDA and BVP signals and applied the statistical time series approach to both signals during the interval of interest using the discrete-time sequence. Comparing the average signal amplitude of all participants across all sessions provides us with information about the participants' state of arousal and indicates the increased density of working memory processes.

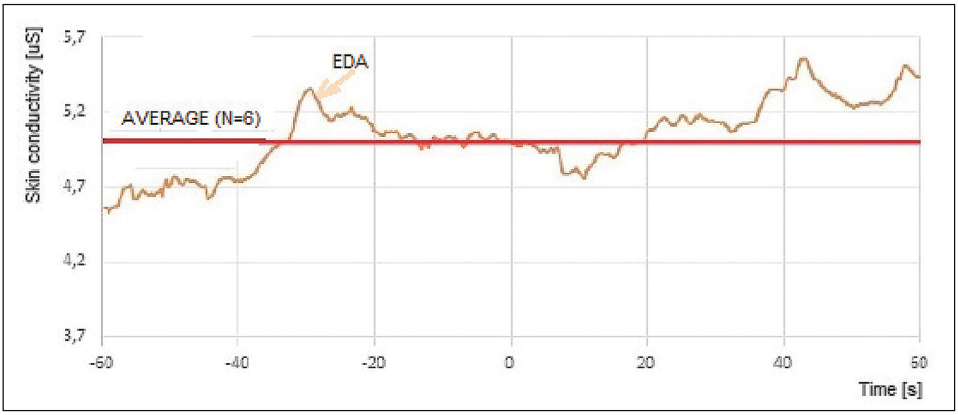


Figure 1. EDA: Before point of interest (time "zero") the amplitude is above average value, indicating the high workload of the participants.

Similarly, the amplitude of the BVP signal is high before the point of interest, indicating an increased density of cognitive processes in the participants' working memory.

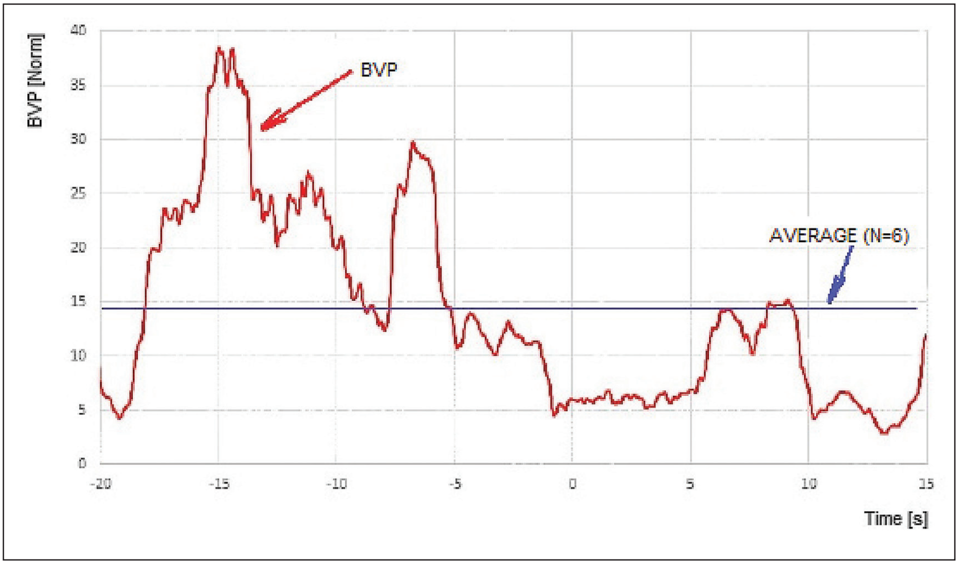


Figure 2. BVP: Participant's normalized readings during the session: The interval of interest is channel entrance, around time "zero" (horizontal axis). The blue line represents the normalized BVP signal amplitude of all participants of all session, and the red line moving average time series around the point of interest.

The measurement signal could be added to the VDES signal [5] so that authorities and coastal stations could be informed in real time and prepare or perhaps provide additional assistance to vessels where an increase in biometrics is detected. Despite the legal and ethical issues associated with accessing and sharing personal biometric data, we expect that in the near future, biometrics on the ship's bridge will be part of the navigation tools in one way or another, including the integrity and awareness of navigators. On the other hand, the safety of navigation is higher when several devices or systems detect that the ship stays on the desired course. Therefore, we expect that such a system, when fully operational, will prevent and anticipate the potential incidents related to the so-called human factor error.

Acknowledgments: "This research was supported by the Nielsen company and project P2-0246 ICT4QoL – Information and Communications Technologies for Quality of Life".

REFERENCES

[1] Borisov V., Kasneci E., Kasneci G. (2021). Robust cognitive load detection from wristband sensors, *Computers in Human Behavior Reports,* Vol. 4, 2021. Available: https://doi.org/10.1016/j.chbr.2021.100116. Accessed 17 June 2022.

[2] Dunn, J., Runge, R., Snyder, M. (2018). Wearables and the medical revolution. Pers. Med. 15 (5), 429–448. Available: https://pubmed.ncbi.nlm.nih.gov/30259801/.

[3] Barnett, M.L. (2005). Searching for the Root Causes of the Maritime Casualties. *WMU Journal of Maritime Affairs,* Vol. 4/2, pp. 131–145, Available: https://doi.org/10.1007/BF03195070, accessed 15 February 2021.

[4] Žagar, D., Svetina, M., Brcko, T., Perkovič, M., Dimc, F., Košir, A. (2022). Analysis of Marine-Pilot Biometric Data Recordings during Port-Approach Using a Full-Mission Simulator. *Sensors* 2022, 22, 2701. https://doi.org/10.3390/s22072701, accessed 31 March 2022.

[5] Xia, T., Wang, M. M., Zhang, J., & Wang, L. (2020). Maritime internet of things: Challenges and solutions. IEEE Wireless Communications, 27(2), 188-196. Available: https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=9163413.

DIGITAL TWIN CONCEPT IN SHIP ROUTING DECISION SUPPORT SYSTEM

Duško Pavletić*, Jasna Prpić-Oršić, Sandro Doboviček, Elvis Krulčić

Abstract. *In this study, a digital twin framework is presented to provide real-time prediction of environmental conditions and hydrodynamic performance for the purpose of risk assessment and optimal route planning. The concept of the digital twin is explained, and the main challenges associated with its implementation are highlighted. The authors provide a comprehensive overview of the proposed digital twin approach, integrated into a decision support system for ship route planning.*

Keywords: *decision support system; digital twin; ship routing*

University of Rijeka, Faculty of Engineering, Rijeka, Croatia
Corresponding author: Duško Pavletić (dusko.pavletic@riteh.hr)

1. INTRODUCTION

A Digital Twin (DT) is a set of digital models that represent real-world objects. By continuously collecting data from the real objects, the models adapt to changes in the real object over time. As a digital representative of a real object, DT can be used to predict the future state and behaviour of a real object based on exchanged data, make more accurate predictions and create situational awareness [1].

2. DIGITAL TWIN CONCEPT

The DT concepts was introduced by Michael Grieves in 2002 [1]. The DT concept includes a real object or process, a virtual representation of that object or process, and two-way communication between the real object or process and its virtual representative. This communication allows data to be collected from the real object or process and information to flow from the virtual representation of the object or process to the real object or process. A DT can be explained as a virtual copy of a real object or process whose behaviour is continuously monitored and transformed into a virtual object or process to achieve a high degree of synchronisation between the two components [3, 4]. In the following year, the DT concept became key for data-driven decision making, monitoring complex systems and managing the lifecycle of objects [2].

While the concept of DT is new, the idea of simulating a real object is quite mature and various digital concepts such as digital model, digital shadow, and DT are used. The main difference between these concepts is the way and direction of data exchange between the real and the virtual part [1].

A digital model is a digital version of an existing or planned real object or process. In the concept of digital model, there is no automatic exchange of data between the real object and the digital model. After the digital model is created, changes to the real object or process do not affect the digital model [5].

A digital shadow concept builds on a digital model by collecting data from real-world objects and feeding it into the digital model to update it with the latest information from the real world.

In the DT concept, data flows between the existing real object and the digital object. Changes made to the real object are implemented in the virtual object, while information from the virtual object automatically flows into the real object.

The core element of DT is the connection between the virtual object and the real object, which enables uninterrupted communication between them. In this way, the DTs concept enables real-time and knowledge-based decision-making and management of real objects or processes, as well as prediction of future system behaviour and process improvement, **Figure 1**.

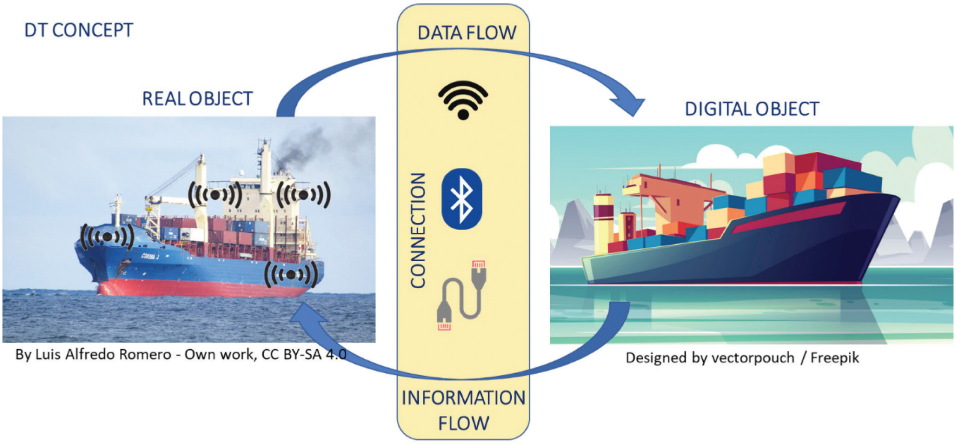


Figure 1. Digital Twin concept.

The DT thus consists of a model of the object, an evolving set of data relating to the object, and a means of dynamically updating or adjusting the model in accordance with the data, and one of the most important aspects is that a DT must be linked to an actually existing object [**6**].

The implementation of the DT concept in this paper is of interest for the development of an effective Decision Support System (DSS) for ship masters and chief engineers, which would contribute to safer navigation of ships. Such a DSS aims to minimise human error and provide the most credible data and guidance to those in charge on board during navigation in order to reduce pollution and increase the safety of people and cargo. Through the DSS, the decision-making of the responsible persons on board is supported by a "virtual master model" to simulate, plan and decide the navigation route in changing (worse) weather conditions.

In this configuration, DT is a core component of the DSS that can be used to monitor safety and mitigate risk during navigation and in emergencies. With regard to the main definition of DT, it should be noted that DT (DSS) does not autonomously implement the decisions made in this context, but supports the responsible person on board (master) with all necessary information about the future predicted condition and expected ship behaviour, taking into account different loading conditions, ship routes and weather scenarios. Incorporating all aspects of ship safety into a single tool could reduce human errors that occur when a large amount of data needs to be processed simultaneously (a critical process, especially during emergencies), **Figure 2**.

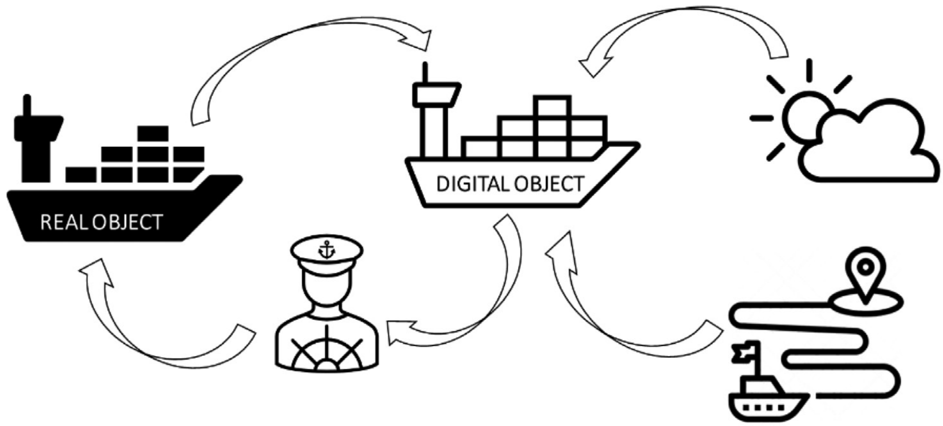


Figure 2. Decision Support System based on Digital Twin concept.

3. POSSIBLE ISSUES IN IMPLEMENTATION

As a core component of DSS DT, reliability is of immense importance. This means that there must be confidence in the data, confidence in the model, and confidence in the DT updat procedure [6]. Confidence in the model requires verification and validation procedures (comparison with reality). This area is mature and best practises exist, but some problems, such as linking different computational models into a whole, still need to be solved. Solving these models sequentially usually requires using the results of one model as input to another. This may require interpolation and processing of the results, as well as the introduction of additional errors and approximations to be considered in the verification process [6]. A further complication is that the presence of uncertainty means that validation must be treated as a statistical process. All measurements must be subject to uncertainty in order to be meaningful. This means that model inputs, and therefore model results and validation data, are subject to uncertainty. Therefore, comparing data with model results should yield an estimate of the probability with which the values match. Assessing uncertainty also provides a better understanding of how much confidence can be placed in the model results. This confidence is particularly important for models that include parameters that cannot be determined independently. For these models, the concept of DT is particularly useful: it provides an estimate of what cannot be measured directly, thus improving the model [6]. Confidence in data collected by sensors can be strengthened in part by adding additional information about sensors and measurement processes to the data. Such additional information about the measurement process (e.g., sensor type, accuracy, standard uncertainty, date of last calibration, time of data collection, location of the sensor, etc.), which may be relevant for understanding the reliability of the measurement, is called metadata.

Another challenge is ensuring an uninterrupted data flow. For a DT to be operational, an uninterrupted closed-loop data flow is required, where data from testing and operation are integrated into a digital domain to support prediction and decision-making processes, and information from the digital domain is fed back to the real object [7, 8].

The low cost of sensors and easy access to cloud storage have led to the widespread collection of extremely large data sets. These datasets often consist of data from multiple sensors of different types collected at short intervals. The challenge in using such datasets in DT is to determine which measurements at which locations or times have the greatest impact on the parameters to be updated in the twin. Data reduction techniques can be used to overcome this challenge [6].

The literature points to some significant challenges in the adoption of DT technology [2]:

- Issues related to data – trust, privacy, cybersecurity, convergence and governance, collection and large-scale analytics [9].
- Barriers related to the communications network. There is a need to create faster and more efficient communication interfaces.
- High implementation costs due to the increasing number of sensors required and the associated complexity related to data connectivity and processing [10].

– The use of AI (Artificial Intelligence) and Big Data to meet the requirements of long-term big data analytics [**11**, **12**]. Given the significant amounts of data generated and analysed in DT systems, Big Data algorithms and IoT (Internet of Things) technology can be successfully used to implement DT [**13**].

4. CONCLUSIONS

This paper presents a digital twin concept for predicting environmental conditions and hydrodynamic performances such as v behaviour in waves and manoeuvring, which can be used to predict risks and the optimal route in real time. The use of DT in various fields is increasing. Combined with technologies such as Big Data, ML (Machine Learning), advanced modelling, simulation, and advanced communication interfaces, it provides insights into the operation of its physical twin in a way that is useful and actionable for the designer or operator. These insights lead to data-driven decision making, which is the main advantage of DTs [**2**].

Acknowledgments: This work has been fully supported by the Croatian Science Foundation under the project IP-2018-01-3739. This work was also supported by the University of Rijeka (contract no. uniri-tehnic-18-18, uniri-tehnic-sp-21-14, and uniri-tehnic-18-33).

REFERENCES

[1] Segovia, M.; Garcia-Alfaro, J. Design, Modelling and Implementation of Digital Twins. Sensors 2022, 22, 5396. https://doi.org/10.3390/s22145396.

[2] Botín-Sanabria, D.M.; Mihaita, A.-S.; Peimbert-García, R.E.; Ramírez-Moreno, M.A.; Ramírez-Mendoza, R.A.; Lozoya-Santos, J.d.J. Digital Twin Technology Challenges and Applications: A Comprehensive Review. Remote Sens. 2022, 14, 1335. https://doi.org/10.3390/rs14061335.

[3] Liu, Z.; Meyendorf, N.; Mrad, N. The role of data fusion in predictive maintenance using digital twin. AIP Conf. Proc. 2018, 1949, 020023.

[4] Mathupriya, S.; Saira Banu, S.; Sridhar, S.; Arthi, B. Digital twin technology on IoT, industries & other smart environments: A survey. Mater. Today Proc. 2020, in press.

[5] Fuller, A.; Fan, Z.; Day, C.; Barlow, C. Digital Twin: Enabling Technologies, Challenges and Open Research. IEEE Access 2020, 8, 108952–108971.

[6] Wright, L., Davidson, S. How to tell the difference between a model and a digital twin. Adv. Model. and Simul. in Eng. Sci. **7**, 13 (2020). https://doi.org/10.1186/s40323-020-00147-4.

[7] Ríos, José & Staudter, Georg & Weber, Moritz & Anderl, Reiner & Bernard, Alain. (2020). Uncertainty of data and the digital twin: a review. International Journal of Product Lifecycle Management. 12. 329–358. 10.1504/IJPLM.2020.10035102.

[8] Singh, V. and Willcox, K.E. (2018). 'Engineering design with digital thread', AIAA Journal, Vol. 56, No. 11, pp. 4515–4528, [online] https://doi.org/10.2514/1.j057255.

[9] Singh, M.; Fuenmayor, E.; Hinchy, E.P.; Qiao, Y.; Murray, N.; Devine, D. Digital Twin: Origin to Future. Appl. Syst. Innov. 2021, 4, 36.

[10] Rathore, M.; Shah, S.; Shukla, D.; Bentafat, E.; Bakiras, S. The Role of AI, Machine Learning, and Big Data in Digital Twinning: A Systematic Literature Review, Challenges, and Opportunities. IEEE Access 2021, 9, 32030–32052.

[11] Juarez, M.; Botti, V.; Giret, A. Digital Twins: Review and Challenges. J. Comput. Inf. Sci. Eng. 2021, 21, 030802.

[12] Koturwar, P.; Girase, S.; Mukhopadhyay, D. A Survey of Classification Techniques in the Area of Big Data. arXiv 2015, arxiv:1503.07477.

[13] Oracle. Developing Applications with Oracle Internet of Things Cloud Service: Digital Twins. Oracle 2018 Available online: https://docs.oracle.com/en/cloud/paas/iot-cloud/iotgs/oracle-iot-digital-twin-implementation.html (accessed on 7 February 2022).

DECISION-MAKING PROCESS FOR PLACES OF REFUGE THROUGH THE STM SYSTEM

Marko Strabić*, David Brčić, Vlado Frančić, Srđan Žuškin

ABSTRACT. The risks of accidents at sea are steadily increasing with the growth of the associated maritime transport. Various measures are being taken to minimise the risk. However, one of the main problems is a situation where a particular vessel is already in distress at sea. The International Maritime Organization (IMO) provides guidelines for places of refuge for vessels in need of assistance. In some situations, deciding on a suitable place of refuge is a lengthy process that depends on a variety of influencing factors. The aim of the paper is to propose, present and discuss a solution to optimise time and improve communication processes when deciding on a place of refuge, based on a case study introduced in the Republic of Croatia. The architecture of the proposed solution is presented as a possible integration of the Sea Traffic Management (STM) system and the GIS application.

Keywords: *multi-criteria decision making; places of refuge; sea traffic management; geographic information system; integration*

University of Rijeka, Faculty of Maritime Studies, Rijeka, Croatia
Corresponding author: Marko Strabić (marko.strabic@pfri.uniri.hr)

1. INTRODUCTION

A place of refuges is a place where a ship in need of assistance can take action to stabilise its condition, reduce hazards to navigation, and protect human life and the environment [1]. Such places may be a port, a shelter near the coast, a cove, a lee, a fjord or a bay or any part of the coast. The most common reasons leading to the need for places of refuge are accidents such as fire, explosion, collision and impaired vessel stability. A good example of the decision-making process for places of refuge is the procedure implemented in the Republic of Croatia. The Croatian approach is a combination of the procedural and pre-selection models. The procedural model includes procedures to be followed by the competent authorities, while the pre-selection model consists of a list of places of refuge that is reduced using a decision support system [2]. The decision-making method for places of refuge in Croatia is based on the application of a geographical information system (GIS) [3]. The proposed article discusses a conceptual integration of the GIS application into the Sea Traffic Management (STM) system, which provides a decision-making process that can shorten the procedure and provide an optimal decision for places of refuge. The proposed solution refers to the countries that have already implemented the STM system and GIS for the decision-making process.

2. METHODOLOGY

In the Croatian model, the selection of the most suitable location for refuge is based on the multi-criteria decision analysis (MCDA), which, together with the information from the GIS application, forms the basis for the decision-making process [4]. The purpose of the application is to evaluate and compare different criteria such as the nature of distress, navigation approach, the length of the vessel, socio-economic criteria, etc. in order to make the most appropriate decision in each case (**Figure 1**).

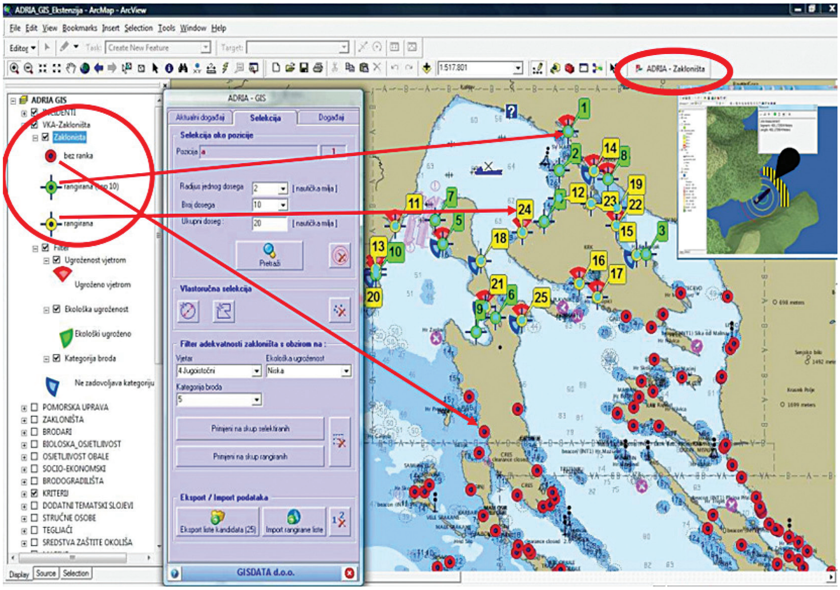


Figure 1. Multi-criteria analysis – selection and ranking based on previous input value into GIS application [2].

Based on the current data in terms of meteorological data, ship data, etc., juxtaposed with the criteria, the optimal place of refuge was determined using the presented GIS application.

3. RESULTS AND DISCUSSION

The architecture of the newly proposed process, which allows for time optimisation and improved communication between the respective stakeholders via the STM is presented as a decision-making algorithm (**Figure 2**).

The process starts by collecting all relevant information required to decide on a suitable place of refuge, such as type of accident, information about the vessel, position, dangerous goods, weather and sea conditions, assessment of urgency, etc. This information is entered by the vessel into the STM/GIS integration system. In case of an approved decision for a place of refuge, the officers on board have a visible route in STM, which leads them to the place of refuge predefined in the GIS database.

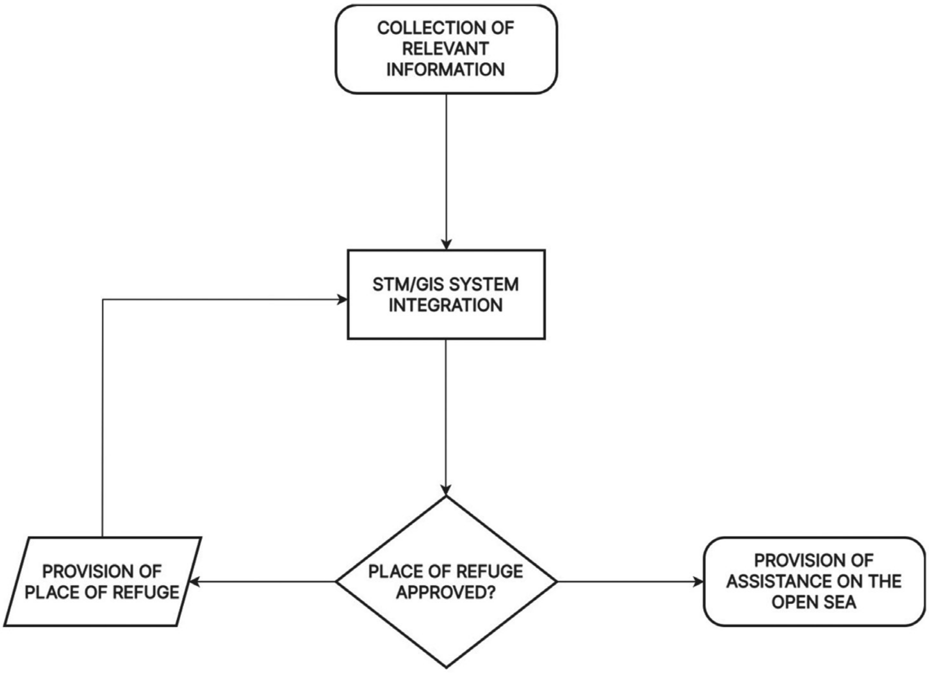


Figure 2. Decision-making process for place of refuge.

The need for continuous improvement of the database, including continuous measurements such as hydrography, oceanology, and other information relevant to the choice of a suitable place of refuge, both static and dynamic, together with other necessary conditions, including adequate education and training of the relevant personnel, remains a matter for further refinement and work on the implementation of the proposal.

4. CONCLUSION

If a vessel finds itself in a situation where it requires assistance, the respective stakeholders (i.e. the VTS operators) who ultimately manage the vessel, must respond as quickly as possible. The proposed integration between the STM system and the GIS application can significantly reduce the time of information exchange between the ship in distress and those in charge ashore and provide sound and clear instructions towards the place of refuge.

Acknowledgments: This research was supported by the project EUREKA – Adriatic-Ionian joint approach for development and harmonisation of procedures and regulations in the field of navigation safety, funded by INTERREG V-B Adriatic-Ionian ADRION Programme 2014-2020.

REFERENCES

[1] IMO, Resolution A.949 (2023). Guidelines on Places of Refuge for ships in need of assistance. Available from: https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/AssemblyDocuments/A.949(23).pdf, accessed 3 January 2023.

[2] Šarunić, E., Bradarić, Ž. (2018). The Place of Refuge for Ships in Need Assistance – Croatian Operational Solution and Opportunity for EU MS / EMSA, *HLSG expert sub-group "Cooperation Group on Places of Refuge"*. Brussels.

[3] Hydrographic Institute of the Republic of Croatia. (2023). Place of refuge. Available from: https://www.hhi.hr/en/about-us/projects/place-of-refuge, accessed 16 January 2023.

[4] Story maps and arcgis. (2019). *Multi-Criteria Decision Analysis and GIS.* Available from: https://storymaps.arcgis.com/stories/b60b7399f6944bca86d1be6616c178cf, accessed 20 January 2023.

HFACS-MA AND 4-MOP INTEGRATED METHODOLOGY FOR THE ASSESSMENT OF HUMAN FACTORS IN MARITIME ACCIDENTS

Nermin Hasanspahić*, Tonći Biočić, Maro Car, Srđan Vujičić

Abstract. *Maritime accidents resulting in deaths, injuries, equipment loss and damage, loss of cargo and environmental pollution are negative events that need to be reduced to the lowest possible level. Therefore, accidents must be thoroughly investigated and analysed to find and leran from immediate and root causes. In this study, an integrated 4-MOP and HFACS-MA framework for the analysis of maritime accidents is introduced to find and classify the most common causes. Based on the findings, preventive measures are proposed.*

Keywords: *accident analysis; collision; grounding; shipping*

University of Dubrovnik, Maritime department, Dubrovnik, Croatia
Corresponding author: Nermin Hasanspahić (nermin.hasanspahic@unidu.hr)

1. INTRODUCTION

With more than 80% of the volume of all goods in international trade being transported by sea [7], it is essential to make the shipping industry as safe as possible. However, despite all efforts to date, accidents still occur at sea. According to [6], the human factor is the cause of about 80% of maritime accidents. In order to uncover the causes of accidents and learn from such adverse events, careful analysis of accident report is necessary.

2. METHODOLOGY

In this paper, the authors integrated the 4M (Man, Machine, Media, Management) Overturned Pyramid (MOP) [3] and the Human Factor Analysis and Classification System for Maritime Accidents (HFACS-MA) [1] methods to analyse maritime accident reports. The authors searched the Marine Accident Investigation Board (MAIB) United Kingdom (UK) database [2] for specific types of maritime accidents: groundings, collisions and contacts. The study included maritime accident reports involving ships of more than 100 GT that occurred after 1 July 2012. The accident causation model developed by Reason provided a framework for understanding human error within a system. The HFACS framework was created to provide a means of accident analysis that complements Reason's model (**Figure 1**) [4].

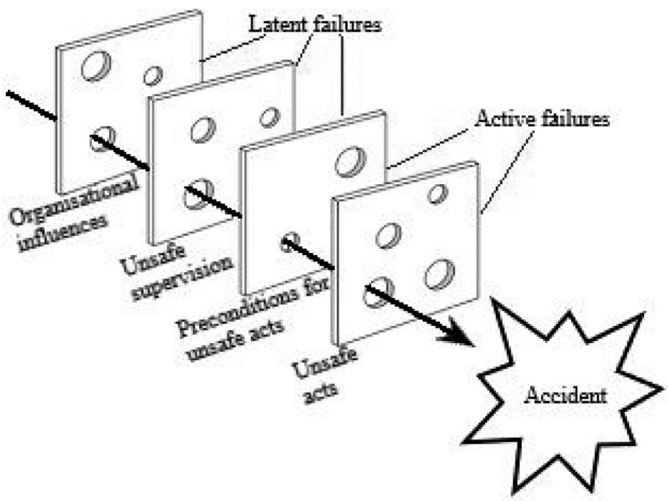


Figure 1. HFACS framework adapted to Reason's model (adopted from [5]).

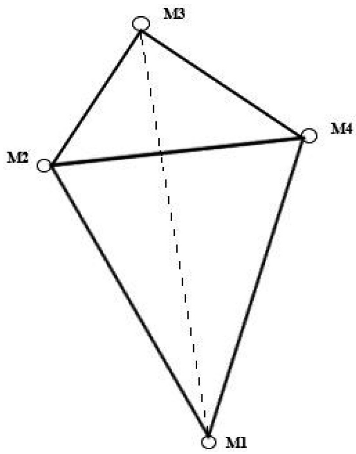


Figure 2. 4-MOP model (adopted from [3]).

The 4-MOP model represents a three-sided, inverted pyramid whose vertices (corners) correspond to the 4M factors, and the edges represent the interactions between two 4M factors (line relationship) (Figure 2).

By integrating the HFACS-MA causal categories into the 4-MOP model, a standardised classification of the factors influencing the occurrence of maritime accidents was made possible. Table 1 shows the classification of causal factors used in this study.

Table 1. Classification of causal factors of accidents.

4-MOP category	HFACS-MA causative factors	4-MOP code
Man (Human)	Condition of operator(s)	M1-01
	Liveware	M1-02
	Skill-based errors	M1-03
	Rule-based mistakes	M1-04
	Knowledge-based mistakes	M1-05
	Routine violations	M1-06
	Exceptional violations	M1-07
Machine	Software	M2-01
	Hardware	M2-02
Media (Environment)	Design flaws	M3-01
	Physical environment	M3-02
	Technological environment	M3-03
Management	Organisational climate	M4-01
	Organisational process	M4-02
	Inadequate supervision	M4-03
	Supervisory violations	M4-04
	Failure to correct known problem	M4-05
	Planned inappropriate operation	M4-06
	Resource management	M4-07
	Legislation gaps	M4-08
	Administration oversights	M4-09

Source: Authors adopted from [1, 3, 5].

The aim of the study was to classify and identify the most common and important causal factors of accidents.

3. RESULTS AND DISCUSSION

Figures 3, **4**, **5** and **6** show the analysed accident reports causal factors classified according to the integrated 4-MOP and HFACS-MA methodology.

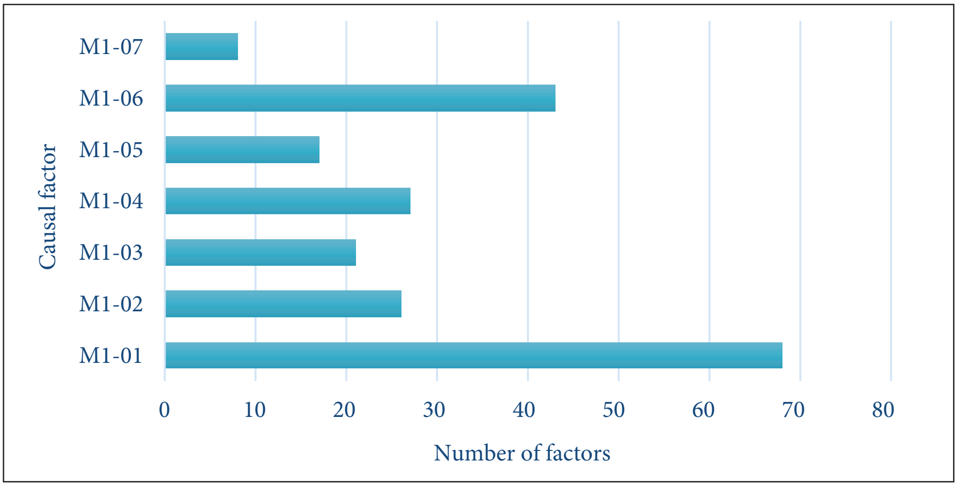


Figure 3. Causal factors categorised as man factors.

Condition of operator and routine violations were identified as the most common factors among human factors. Condition of operator includes loss of situational awareness, fatigue, drunkenness, illness, inadequate knowledge and complacency. Routine violations include habitual violations due to poorly written procedures and inadequately defined work practices, where the error occurs because seafarers cut corners trying to speed up the process [**1**].

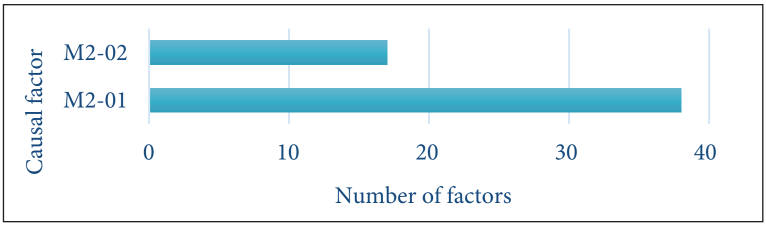


Figure 4. Causal factors that are categorised as machine factors.

The most common machine-related causal factor was software, which includes the lack of formal instructions such as operating manuals and instructions, navigation charts and computer programmes [1].

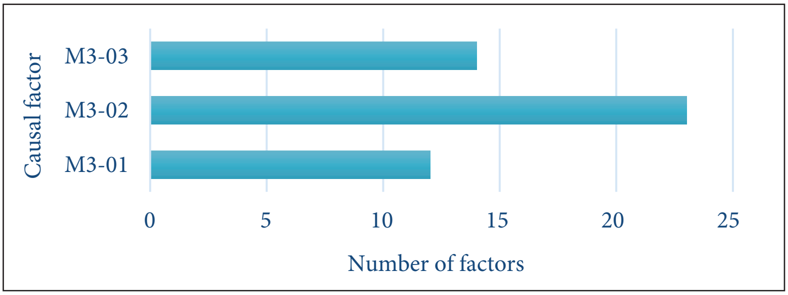


Figure 5. Causal factors that are categorised as media (environment) factors.

The most common environmental causal factor was the physical environment, including natural forces that affect seafarers' decisions and actions, such as storms, tidal streams, large waves and reduced visibility due to fog or heavy rain [1].

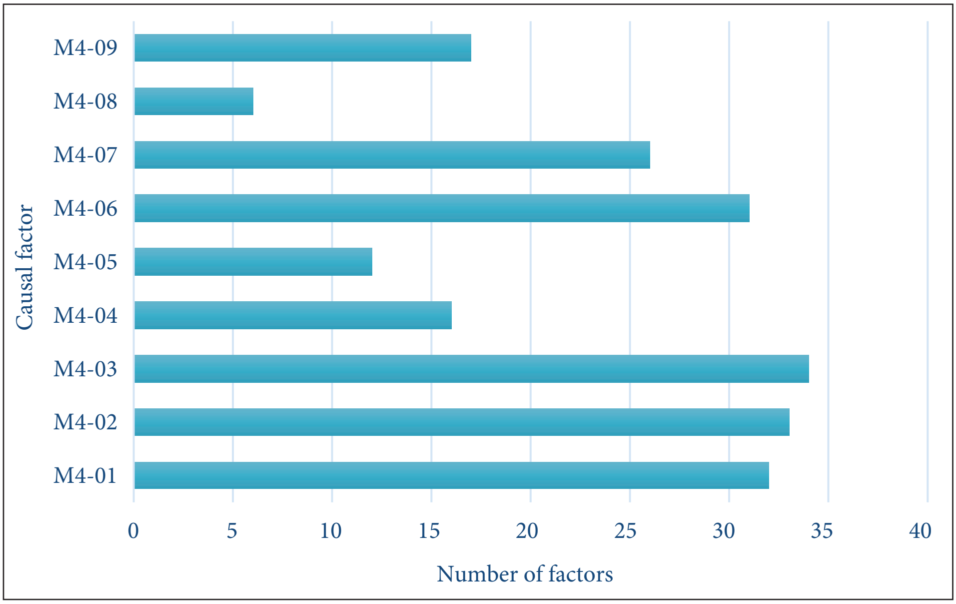


Figure 6. Causal factors that are categorised as management factors.

Inadequate supervision and Organisational process have been found to be the most common management factors affecting maritime accidents. Organisational process includes the existence of and compliance with formal policies implemented onboard ships regarding shipboard operations, procedures, and supervision by crewmembers. Inadequate supervision includes failures by ship management to supervise crewmembers performing certain tasks (e.g. lack of training, guidance and the like) [1].

Figure 7 shows all ausal factors found for accidents at sea and included in the 4-MOP framework.

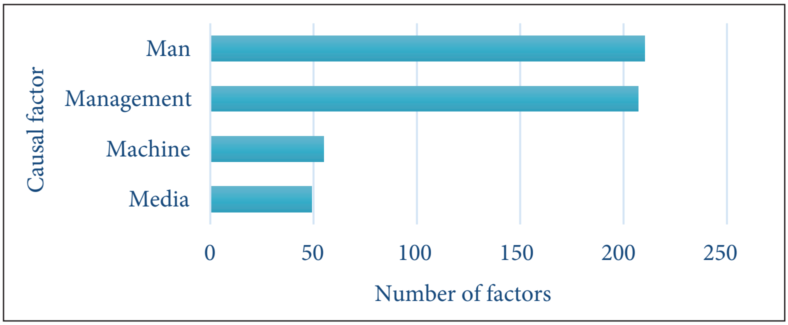


Figure 7. 4-MOP causal factors.

Man and management have been found to be the most common causal factors, and an appropriate approach is needed to reduce the impact of these factors on the occurrence of maritime accidents. When nalysing the causal factors by the type of accident (grounding or collision/contact), it was found that there are greater differences in M1-06 (routine violations), M1-07 (exceptional violations), M2-02 (hardware), M4-02 (organisational process), M4-03 (inadequate supervision), M4-04 (supervisory violations), M4-05 (failure to correct known problem), M4-07 (resource management) and M4-08 (legal loopholes) (**Figure 8**). In addition, causal factors M1-06, M4-02, M4-03, M4-04, M4-05 and M4-07 are found to be more associated with collision accidents, while M1-07, M2-02 and M4-08 are more associated with collision/contact accidents.

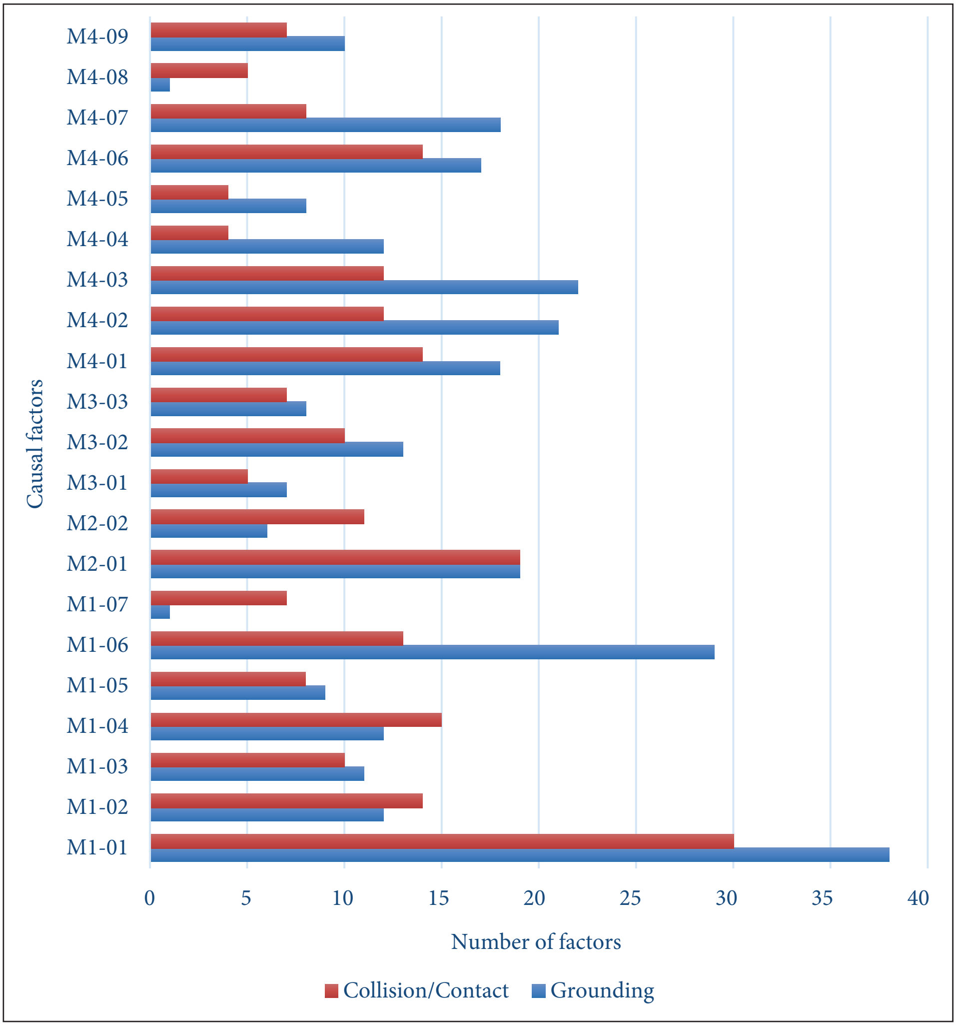


Figure 8. Causal factors according to the type of accident.

4. CONCLUSIONS

The study analysed the maritime accident reports and used the integrated 4-MOP and HFACS-MA framework to classify and find the most common factors that influence the occurrence of a maritime accident. According to the 4-MOP framework, the most common factors are man and machine, with the most common causal factors being M1-01 (condition of operator), M1-06 (routine violations), and M2-01 (software). Therefore, maritime transportation stakeholders should respond with various measures, including maritime education and training (MET), shipboard familiarisation, monthly safety meetings and adequate risk assessments to make seafarers aware of the most common causes of maritime accidents and try to reduce their impact and reduce undesirable consequences.

REFERENCES

[1] Chen, S.-T., Wall, A., Davies, P., Yang, Z., Wang, J. and Chou, Y.-H. (2013). A Human and Organisational Factors (HOFs) analysis method for marine casualties using HFACS-Maritime Accidents (HFACS-MA). *Safety Science*, 60, pp. 105–114. http://dx.doi.org/10.1016/j.ssci.2013.06.009.

[2] Marine Accident Investigation Branch (MAIB) reports. Available from: https://www.gov.uk/maib-reports?, accessed 10 February 2023.

[3] Mutmainnah, W., Bowo, L.P., Sulistiyono, A.B. and Furusho, M. (2018). Causative Chains that Leads to Ship Collisions in Japanese Maritime Traffic System (MTS) as Final Outcome of MOP Model. *Applied Mechanics and Materials*, Vol. 874, pp. 221–227. doi:10.4028/www.scientific.net/AMM.874.221.

[4] Schröder-Hinrichs, J.U., Baldauf, M., Ghirxi, K.T. (2011). Accident investigation reporting deficiencies related to organisational factors in machinery space fires and explosions. *Accident Analysis and Prevention*, 43, pp. 1187–1196. doi:10.1016/j.aap.2010.12.033.

[5] Shappell, S. and Wiegmann, D. (2003). *A Human Error Approach to Aviation Accident Analysis – The Human Factor Analysis and Classification System*. Ashgate Press, USA. ISBN 07546-1873-0.

[6] Ugurlu, O., Yildirim, U. and Basar, E. (2015). Analysis of grounding accidents caused by human error. *Journal of Marine Science and Technology*, 23(5) pp. 748–760. doi: 10.6119/JMST-015-0615-1.

[7] United Nations Conference on Trade and Development (UNCTAD). Launch of the Review of Maritime Transport 2020. Available from: https://unctad.org/meeting/launch-review-maritime-transport-2020, accessed 15 September 2021.

FEASIBILITY STUDY OF THE CONVERSION OF A COASTAL TANKER IN A REC OIL SHIP

Samuele Utzeri*, Luca Braidotti, Serena Bertagna, Vittorio Bucci

Abstract. *The maritime transport sector contributes to air pollution. Today, new types of fuels and bunkers need to be investigated to reduce pollutant emissions. The Isyport project aims to study the possibility of installing an LNG bunkering facility for the strategically located Port of Augusta. This paper will deal with the selection of LNG bunkering systems that can be considered for the context under consideration and the preliminary study for the conversion of a Rec-Oil class tanker from conventional heavy fuel propulsion to LNG.*

Keywords: *bunkering station; LNG; rec-oil; refitting*

Department of Engineering and Architecture,University of Trieste, Trieste, Italy
E-mail: samuele.utzeri@phd.units.it; lbraidotti@units.it; sbertagna@units.it; vbucci@units.it
Corresponding author: Samuele Utzeri (samuele.utzeri@phd.units.it)

1. INTRODUCTION

Liquefied natural gas (LNG) is now considered the cleanest fuel in the fossil fuel family [1] (CO_2 reduction of 20–30%, NO_X 80–85%, SO_X 92–99%, PM 95–97% [2], [3]). This and other technical and economic aspects favoured its introduction as a marine fuel to replace the usual marine gas oil (MGO) and fuel oil (HFO). At the same time, the growing demand due to the rapid expansion of the global LNG-fuelled fleet brings with it the need to increase the number of LNG bunkering sites and their capacity, while ensuring the safety aspects of bunkering operations, which are significantly more complex than for conventional liquid fuels. The present work aims to develop a new bunkering facility in a port area of Augusta and to prepare a preliminary study for the conversion of recovery oil class tanker that will also be based in Augusta too.

2. METHODOLOGY

The Porto di Augusta terminal brings together numerous industrial sites dedicated to the petrochemical sector and the production of fuels and chemicals. The entire site, along with the industrialised coastal areas of Priolo Gargallo and Melilli, is referred to as the Syracuse petrochemical pole. The main activities of the site are oil refining, oil derivatives processing and energy production. The strategic location of the Port of Augusta in the centre of the Mediterranean and the lack of LNG bunkering facilites in this area make the development of an LNG bunkering service particularly promising.

When planning a new LNG bunkering service [4], the choice of the logistics chain to be used is of utmost importance. It depends on the specifics of the port area where the service is to be provided, as well as on the sources of supply and the way in which the LNG is brought on board the supplied ships. LNG bunkering requires more complex and expensive resources and equipment, both in terms of acquisition and operating costs. The main cause is the cryogenic temperature at which LNG is stored. Therefore, it is important to find a good compromise between the different conflicting requirements and especially between cost and safety aspects. Similar to conventional liquid fuels, LNG bunkering can be performed in several ways. These include truck-to-ship (TTS), shore/pipeline-to-ship (PTS), ship-to-ship (STS), and container-to-ship (CTS).

A Strengths, Weaknesses, Opportunities and Threats Analysis (SWOT) was carried out to decide which bunkering system is the best for the studied area according to EMSA [5]. The site has some critical issues related to the presence of petrochemical industries whose open flames can be a source of ignition if LNG escapes into the atmosphere. Therefore, the choice of bunkering method was a combination of STS performed by ships and PTS with a non-self-propelled barge (ISO/TS 18683 – Guidelines for systems and installations for the supply of LNG as fuel to ships).

A preliminary study was conducted to select a ship for STS bunkering. The vessel selected is a Marine Fuel Oil tanker with additional Rec-Oil class notation (**Figure 1**). The first step was to see if the ship itself could be converted to LNG by complying with the MARPOL Emission Control Areas (ECA).

The main characteristics of the ship are L_{OA} =70.750 m, L_{BP} =64.000 m, B=11.800 m, T=4.313 m, GT=1276 GT, V=11.000 kn. One of the biggest problems in converting an existing ship to gas propulsion is finding the right space to store the LNG fuel. The amount of LNG needed to propel the ship was calculated by determining a range that would allow the full development of the ship's two operating profiles: a supply barge and Rec-Oil.

According to EMSA, Rec-Oil units must be ready to depart within 24 hours from the call with the appropriate equipment on board. To ensure this readiness, the modular design approach was used. Rec-Oil equipment such as skimmer, sweeping arms or boom set can be placed in containers and loaded and unloaded when required.

The ship range was determined based on the Rec-Oil deployment profile, assuming an oil spill occurs in the Adriatic Sea. Taking the city of Augusta as the starting port and Termoli as the destination port, the distance to be covered is about one thousand nautical miles. Taking into account a safety margin of five hundred miles, the total range is one thousand five hundred nautical miles.

The propulsion engines of the existing tanker were more than 40 years old. It was therefore decided to replace them with a new generation of low-pressure dual-fuel engines, that would give the unit a high degree of operational ductility in times of rising LNG prices, as has recently happened. Considering the predicted ship resistance and assuming an operating speed of 11 kn, a Wärtsilä 6L20DF was selected.

With reference to the provisions of the IGF Code [6], the volumes for LNG storage were calculated and it was found that the existing fuel tanks are sufficient

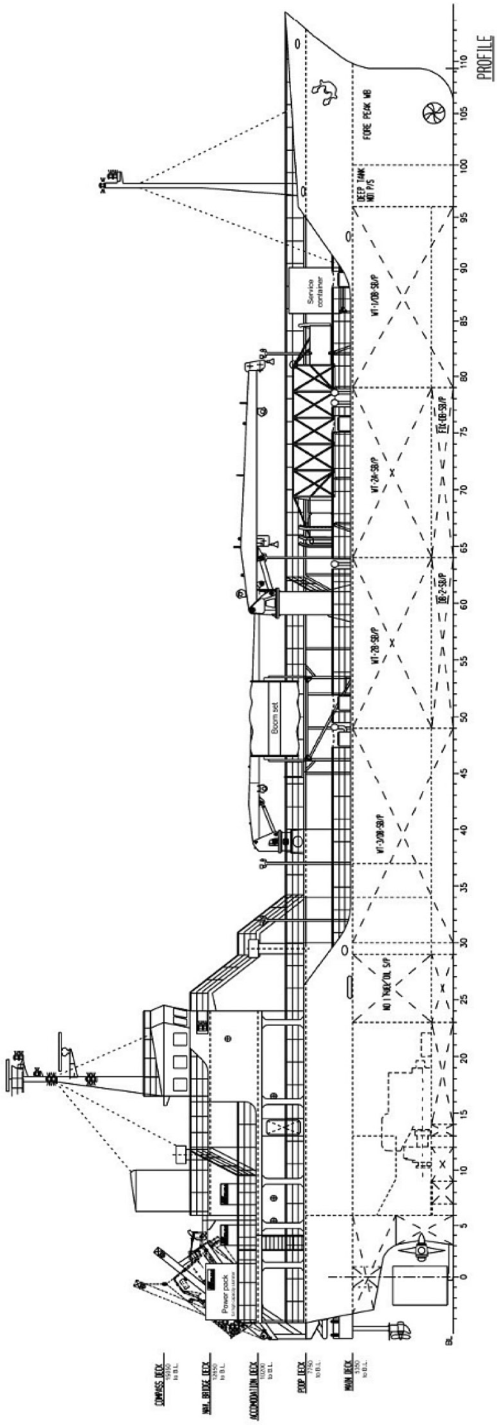


Figure 1. Case study-Rec Oil tanker.

for light pilot fuel and distilled marine fuel oil if the engine is not refuelled with liquefied gas. **Table 1** shows all assumptions for LNG, light pilot fuel and light fuel oil (LFO).

Table 1. Characteristics of LNG, light pilot fuel and LFO.

LNG			Pilot fuel light		LFO		
BSEC	LHV	ρ	$SFOC_{80\%MCR}$	ρ	$SFOC_{ISO}$	LHV	ρ
(kJ/kWh)	(kJ/kg)	(t/m^3)	(g/kWh)	(t/m^3)	(g/kWh)	(kJ/kg)	(t/m^3)
8053	49200	0.45	5.700	0.900	189.590	42700	0.900

At the range under consideration, the volume required for LNG storage is 50 m^3 and the oil tanks currently on board are sufficient for LFO storage. Without disturbing the current arrangements on board with major structural modifications, the Independent Tank type C storage technology was chosen. In addition, the LNG storage system was placed on the main deck, respecting the constraints of the IGF Code, which requires tanks for a tanker to be located in a ventilated space with a minimum distance of B/5 from the sides of the vessel.

3. RESULTS AND DISCUSSION

The available space for the LNG tank location is limited to a central area of the main deck as the vessel in question has been converted to a Rec-Oil unit in the past. By relocating the Rec-Oil units, it is possible to install the LNG storage in the area highlighted in **Figure 2**.

From a technical point of view, the assessments show that the conversion of the propulsion system to gas is feasible. Considering that the Mediterranean Sea is likely to become ECA soon, the conversion of the propulsion system will allow the ship to continue to operate. The low emission levels of the gas propulsion system will allow the vessel to comply with all European restrictions.

The location of the LNG storage system could be also optimal for PTS refuelling purposes. Considering the width of the roadstead of the port of Augusta, it would therefore be advantageous to implement a PTS solution with a permanent, non-auto-propelled barge, as this would not take up large areas of land and would simplify the regulatory framework by limiting it to maritime regulations. In addition, the Rec-Oil tanker under study, using the barge as primary LNG storage

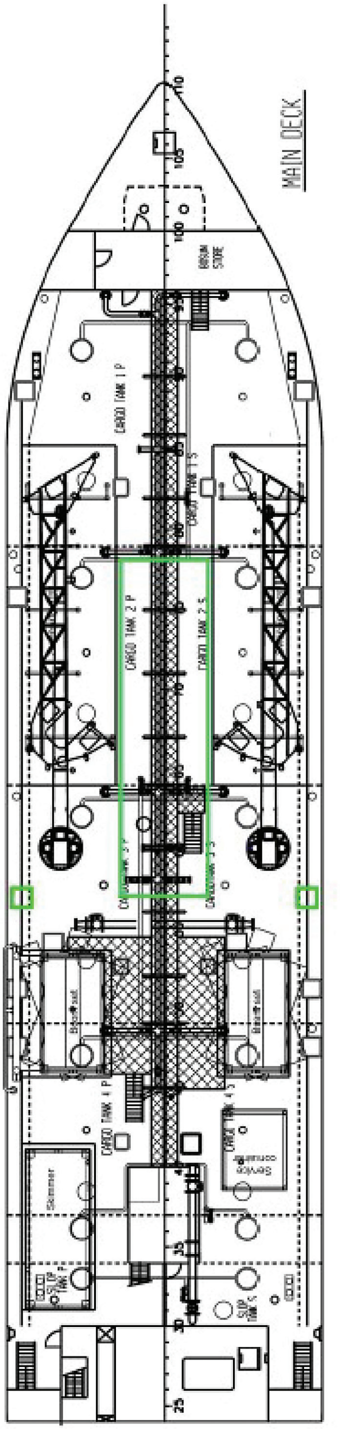


Figure 2. Location selected for the installation of the LNG storage system on the main deck.

could refuel ships in the port or in the surrounding area without them having to reach the peer where the barge is moored.

4. CONCLUSION

Given the predisposition of the port of Augusta to bunkering from both a strategic and territorial point of view, it could lead to a further development of the Isyport project to investigate the conversion of the bunkering vessel, which is currently also used for marine fuel oil, for LNG bunkering. As the Rec-Oil vessel, by fully containerising the Rec-Oil equipment, more space can be made available for LNG storage in ISO-containers. In this way, a higher capacity can be achieved when the ship is in port and used for bunkering purposes.

Acknowledgements: This work was fully supported by PNR 2015-2020, PON Ricerca e Innovazione, ARS01_01202 Progetto Isyport – "Sistema integrato per la mitigazione dei rischi della navigazione in aree portuali" founded by MIUR "Università e Ricerca".

REFERENCES

[1] N. Gray, S. McDonagh, R. O'Shea, B. Smyth, and J. D. Murphy, "Decarbonising ships, planes and trucks: An analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors", Adv. Appl. Energy, vol. 1, p. 100008, 2021.

[2] S. Bertagna, I. Kouznetsov, L. Braidotti, A. Marinò, and V. Bucci, "A Rational Approach to the Ecological Transition in the Cruise Market: Technologies and Design Compromises for the Fuel Switch", J. Mar. Sci. Eng., vol. 11, fasc. 1, p. 67, gen. 2023, doi: 10.3390/jmse11010067.

[3] I. S. Seddiek and M. M. Elgohary, "Eco-friendly selection of ship emissions reduction strategies with an emphasis on SOx and NOx emissions", Int. J. Nav. Archit. Ocean Eng., vol. 6, fasc. 3, pp. 737–748, set. 2014, doi: 10.2478/IJNAOE-2013-0209.

[4] IACS – LNG Bunkering guidelines, 2016.

[5] EMSA Guidance on LNG Bunkering to Port Authorities and Administrations, 2018.

[6] International Maritime Organization. International Code of Safety for Ship Using Gases or Other Low-Flashpoint Fuels (IGF Code) 2016. Available online: https://www.imo.org/en/ourwork/safety/pages/igf-code.aspx (accessed on 18 October 2022).

HYBRID-ELECTRIC PASSENGER CRAFT FOR THE VENICE LAGOON

Donato Padolecchia*, Vittorio Bucci, Alberto Marinò

Abstract. *Measures to reduce pollution include proposing innovative boats for passenger mobility, that can incorporate the principles of environmental sustainability. The design phases for such units require careful study of both the working environment, the hull shapes, due to their impact on the wave pattern generated, and the operating profile due to its impact on the choice of propulsion system. This paper presents an innovative taxi boat for the Venice lagoon that allows both small wave generation and navigation in zero emission mode.*

Keywords: *catamaran; CFD; sustainable mobility; taxi boat; zero emission mode navigation*

Department of Engineering and Architecture, University of Trieste, Trieste, Italy
Corresponding author: Donato Padolecchia (donato.padolecchia@phd.units.it)

1. INTRODUCTION

The fleet of boats currently operating in the Venice lagoon consists of obsolete units that are not equipped with the latest innovations able to reduce pollution.

In this context, a taxi boat in the form of a catamaran configuration has been specifically designed for routes connecting certain places in the Venice lagoon.

As far as propulsion is concerned, a hybrid-electric propulsion system with series configuration is presented, which can be considered a fully electric system due to the design choices made [1], [2].

2. METHODOLOGY

In this section, a brief overview of the techniques used for the catamaran performance predictions is firstly given: the objective is achieved by appropriate proper hull shapes. Secondly, a brief overview of hybrid-electric propulsion systems is given, focusing on the option chosen for this design.

2.1. Hull Forms Design

A two-step approach is used to design accurate hull forms: a parametric analysis is performed using systematic series' power predictions. The hull is then modelled in 3D and tested at CFD to investigate interference and wave patterns [3]. The method is presented for hard-chine hull shapes, which are more suitable for high-speed operations than round-bilge catamarans. The hulls from the '89 series are used as a reference [4].

2.2. Hybrid propulsion system

Hybrid-electric propulsion systems can be defined as propulsion systems that combine an endothermic engine with an electric motor/electric generator and an energy storage system. Essentially, two types of hybrid propulsion systems can be distinguished: the hybrid series or the hybrid parallel.

In this application, the hybrid series option was chosen. It consists of a heat engine coupled with electric generators; two electric motors are then used as prime movers. Usually, the main switchboards are connected to battery packs that can be charged via the generator(s) and supply power to the electric motors for propulsion. This type of configuration is particularly well suited for units that need to navigate in Zero Emission Mode (ZEM). Therefore, the unit can be manned as a fully electric vessel, with the generator on-board serving only as an emergency source of power [5].

3. RESULTS AND DISCUSSION

In this section, the methodology described earlier is applied to the design of a small passenger catamaran for the Venice lagoon. First, the specifications of the ship and the operational scenario are presented. Then, the results are presented and discussed.

3.1. Analysis of the routes

Taxi boats operating in the Venice lagoon do not have a fixed operational profile that can be used as a reference for the design of the propulsion system [5]. Therefore, in order to select the right hull and onboard storage system, several routes were considered, including both internal and external routes, as listed below:

- Route 1: Airport – Venezia Santa Lucia train station;
- Route 2: Venezia Santa Lucia train station – Hotel Gritti (San Marco);
- Route 3: Gritti Hotel (San Marco) – Torcello Island;
- Route 4: Airport – Gritti Hotel (San Marco);
- Route 5: Airport – Torcello Island.

They were analysed in terms of length, average speed and travel time, as shown in Table 1, with the aim of determining an adequate capacity of the batteries to allow more than one run without recharging.

Table 1. Route analysis.

Route	Length [km]	Average speed [km/h]	Travel time [h]
Route 1	7.58	13.1	00:34:45
Route 2	2.92	7.00	00:24:59
Route 3	13.8	15.8	00:52:35
Route 4	10.1	11.6	00:52:15
Route 5	23.9	14.0	01:42:25

3.2. Hull Design

Considering the routes described above, an hard-chine symmetric hull was chosen [6]. The demi-hull was modelled in 3D according to the parametric analysis.

CFD was applied to test the chosen demi-hull of the catamaran; the finally resistance of the catamaran is shown in **Figure 1**.

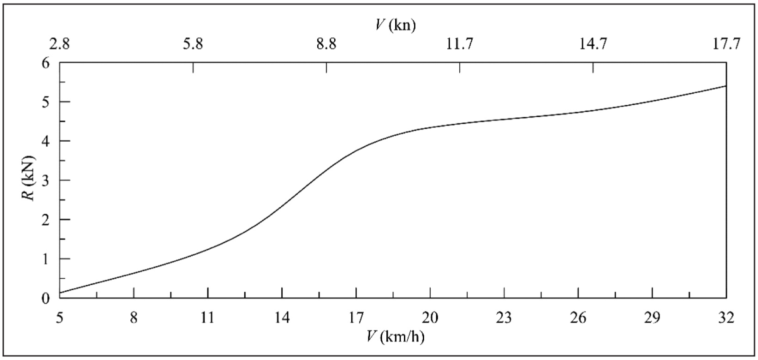


Figure 1. Resistance of the catamaran.

3.3. Design and general arrangements

To highlight the break with the tradition of taxi boats used in Venice, it was decided to propose a completely innovative design, as shown in **Figure 2**. It offered much more space to passengers, which was also used to accommodate passengers with reduced mobility.

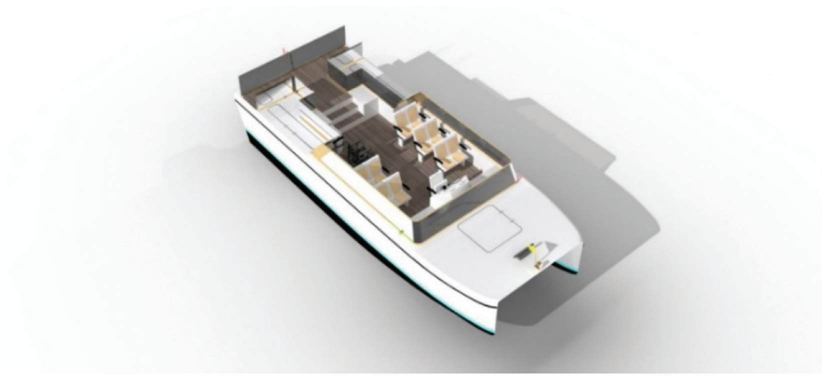


Figure 2. Design concept of the taxi boat.

Figure 3 shows the general arrangement plan of the taxi boat: passengers board from a large platform on the deck. The wheelhouse is forward in a central position to ensure maximum visibility. On the deck, there are two hatches at the stern for access to the lockers housing the two battery packs. There is also another hatch in the bow for access to the Diesel generator compartment. Finally, two electric outboard motors are installed on suitable supports at the extreme stern.

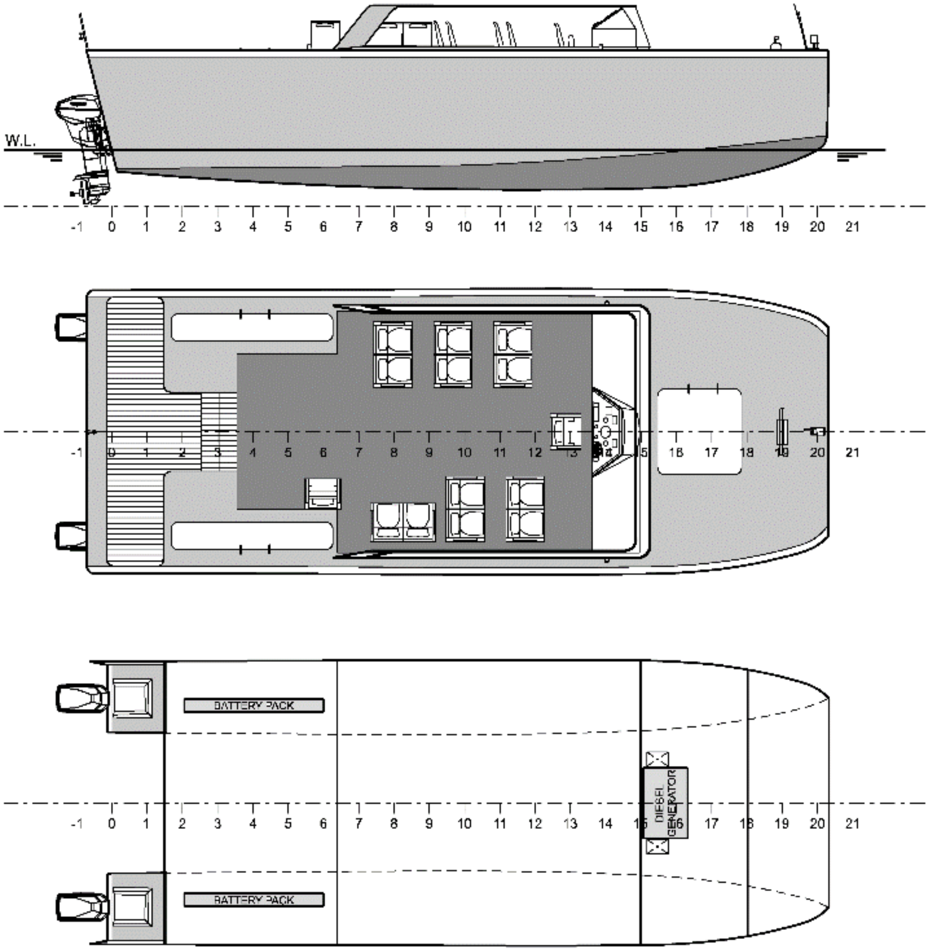


Figure 3. General arrangement of the taxi boat.

Table 2 summarises the main particulars of the vessel.

Table 2. Main characteristics of the taxi boat.

Characteristic	Symbol	Value	Unit
Length overall	L_{OA}	10.4	m
Waterline length	L_{WL}	9.85	m
Breadth	B	4.00	m
Breadth of a single hull	B_H	1.00	m
Depth	D	1.95	m
Draught, design	T	0.55	m
Displacement, full load	Δ	5.28	t
Passengers	/	13	/

3.4. Integrated Power System

To enable ZEM navigation for as long as possible, the Integrated Power System (IPS) is to be developed. The IPS architecture used in the new taxi-boat is shown in **Figure 4**, where a low-voltage DC distribution system (LVDC) has been set up to facilitate the integration of battery packs.

The LVDC shipboard power system (DC bus voltage of 360 V) consists of the following components:

- Diesel generator (DG) with a power of 18 kWe at a rated speed of 3000 rpm 230V 50 Hz AC;
- AC/DC power converter (D) as interface between the AC diesel generator and the LVDC bus;
- DC/AC power converter (PD) to supply the electric propulsion motor (EM) 2 × 50 kW @2400 rpm;
- 2 BMW i3 battery packs, each with a capacity of 42.3 kWh@360V;
- DC/DC power converter (C), for feeding the low voltage (24 V) DC users;
- DC/AC power converter to supply the shore connection.

Based on the choices made regarding the batteries and assuming an average consumption of 3kW for the different users on board, **Table 3** shows the energy demand for each route analysed and the number of consecutive runs that can be made before recharging, which can be done either from the stations or the on-board diesel generator.

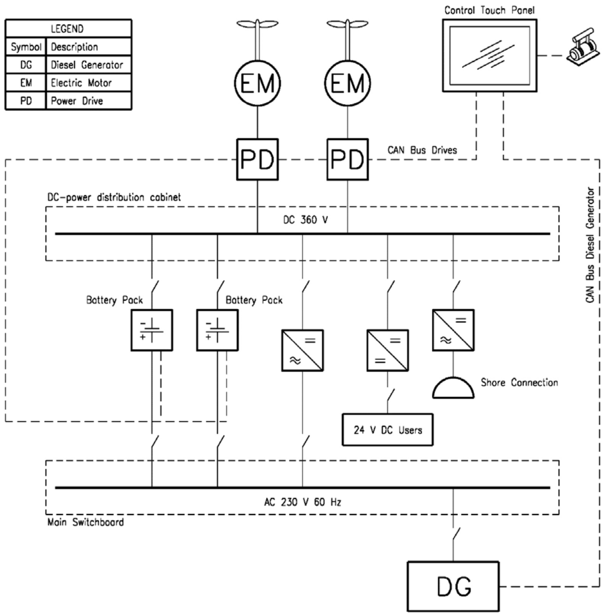


Figure 4. Integrated LVDC shipboard power system.

Table 3. Management of the integrated LVDC power system.

Route	Energy need [kWh]	Number of consecutive runs
1	14.1	5
2	2.1	31
3	28.2	2
4	13.8	4
5	42.2	1

4. CONCLUSIONS

This paper presented a study on the design of a catamaran as a new generation of taxi boats for public transport in the Venice lagoon, capable of ZEM navigation, to contribute to environmental pollution and wave formation.

In particular, the application of CFD analysis, has made it possible to choose the right distance between the demi-hulls to keep the wave pattern as flat as possible at high speed.

In conclusion, the environmental sustainability, as the ultimate goal of this study, highlights the importance of finding solutions that favour the use of new technologies as fundamental resources for the protection of the planet.

REFERENCES

[1] G. Degan, L. Braidotti, D. Bosich, G. Sulligoi, V. Bucci, and A. Marino, "Feasibility Study of a DC Hybrid-Electric Catamaran for River Navigation", in *2021 Sixteenth International Conference on Ecological Vehicles and Renewable Energies (EVER)*, Monte-Carlo, Monaco, mag. 2021, pp. 1–5. doi: 10.1109/EVER52347.2021.9456624.

[2] C. Nasso *et al.*, "Integrated design of an eco-friendly wooden passenger craft for inland navigation", *Int. Shipbuild. Prog.*, vol. 66, fasc. 1, pp. 35–55, 2019.

[3] L. Braidotti, S. Bertagna, M. Zanin, D. Padolecchia, A. Marinò, and V. Bucci, "A Methodology for the Hull Forms Design of a Passenger Catamaran for the Venice Lagoon", in *Progress in Marine Science and Technology*, E. Rizzuto e V. Ruggiero, A c. di IOS Press, 2022. doi: 10.3233/PMST220065.

[4] B. Mnller-Graf, D. Radojeie, and A. Simie, "Resistance and Propulsion Characteristics of the VWS Hard Chine Catamaran, Hull Series '89".

[5] S. Bertagna, L. Braidotti, D. Padolecchia, A. Marinò, and V. Bucci, "Feasibility Study of a Hybrid-electric Taxi Boat for the Venice Lagoon", in *2022 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*, Sorrento, Italy, giu. 2022, pp. 701–706. doi: 10.1109/SPEEDAM53979.2022.9842145.

[6] M. Insel, "An investigation into the resistance components of high speed displacement catamarans", 1990.

CORRELATION ANALYSIS AMONG WEATHER FACTORS UNDER ROUGH SEA VOYAGE

Sang-Won Lee[1*], Tomoya Masagaki[1], Kenji Sasa[1], Chen Chen[2]

Abstract. *Although the importance of optimal ship routing is emphasised, ships are still exposed to the risk of rough seas. There have been various studies on ship routing, but most have focused on avoiding strong winds and waves to reduce resistance. However, it is necessary to understand the relationship between weather factors, as meteorological factors change in relation to each other. Ship routing can be improved if the patterns of different meteorological factors are identified. In this study, different weather patterns were confirmed by onboard measurements and applied to ship routing.*

Keywords: *correlation analysis; optimal ship routing;, ship motions; weather forecast; weather pattern*

[1] Kobe University, Kobe, Japan
[2] Wuhan University of Technology, Wuhan, China
Corresponding author: Sang-Won Lee (leesw@port.kobe-u.ac.jp)

1. INTRODUCTION

Developing optimal ship routing and weather forecasting is crucial to ensure the safety and efficiency of ship operations [2, 6, 7]. However, weather forecasts can fail, resulting in rough sea voyages [3-5]. In this study, correlations between weather parameters were analysed to identify patterns in ship operations and meteorological information in the North Pacific Ocean. This could contribute to optimal ship routing.

2. ONBOARD MEASUREMENT AND WEATHER FACTORS

Measurements were taken onboard to verify the actual route of the 63,000 DWT bulk carriers. Measurements have been taken since 2018; this study includes a case study in rough seas in April 2018, during which time the ship was mainly located in the North Pacific. Due to the rough seas caused by the low pressure, large ship motions occured with a maximum roll of 20° and a pitch of 5°, as shown in **Figure 1.**

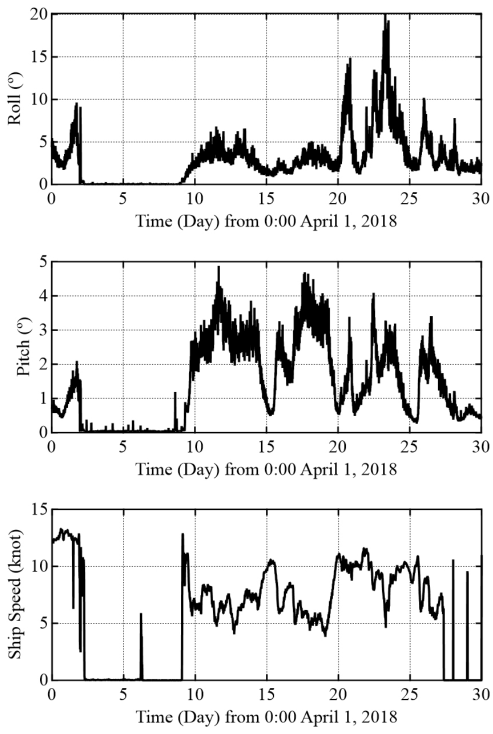


Figure 1. Observation of large ship motions and speed reduction in rough seas.

This shows that weather forecasting and ship routing services can fail. Therefore, this study tries to find an additional safety method to prepare for forecasting errors based on the correlation between weather factors.

To analyse the correlation between weather factors, it is necessary to collect weather information for the target period and region. The weather factors considered in this study were information on atmospheric pressure, waves, and wind provided by the National Centres for Environmental Prediction Final (NCEP-FNL) [1]. The time intervals were 3 h for winds and waves and 6 h for atmospheric pressure. The distribution of the individual weather factors is shown in **Figure 2**.

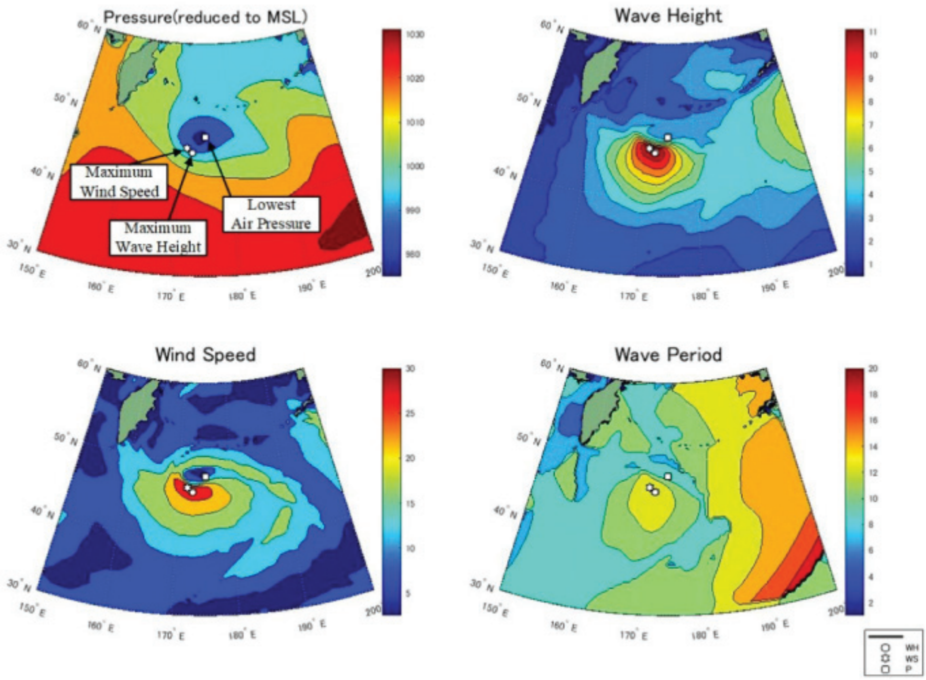


Figure 2. Distribution of air pressure, wave, and wind in target area.

The rest of this article is structured as follows. First, a specific area near the ship's position was selected. Next, the locations of maximum wind speed, wave height, and lowest air pressure were determined. Time series analysis was used to check the time difference between the peak values of each weather factor. Finally, the correlation with weather patterns can be used for ship routing.

3. RESULTS AND DISCUSSION

Wind waves can be generated by strong winds caused by low atmospheric pressure, e.g. typhoons. Therefore, the wind follows the low pressure area that is created. Eventually, the high wave approaches the ship, as shown in **Figure 3**.

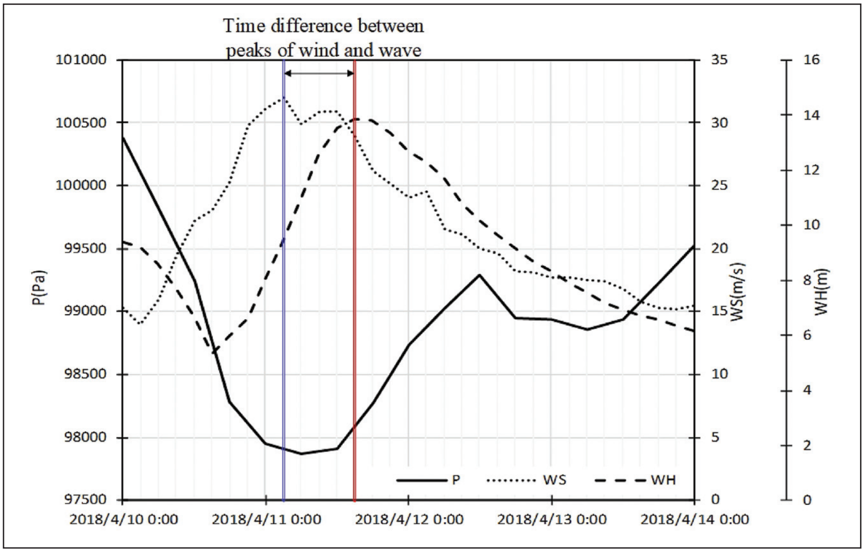


Figure 3. Variations in air pressure, wind speed and wave height.

The correlation between the three factors can also be seen in **Figure 4**. The wind speed and wave height tended to increase at the same time, and the low pressure resulted in strong winds and high waves. However, it is necessary to conduct further analysis in different situations as the correlation was not significantly studied.

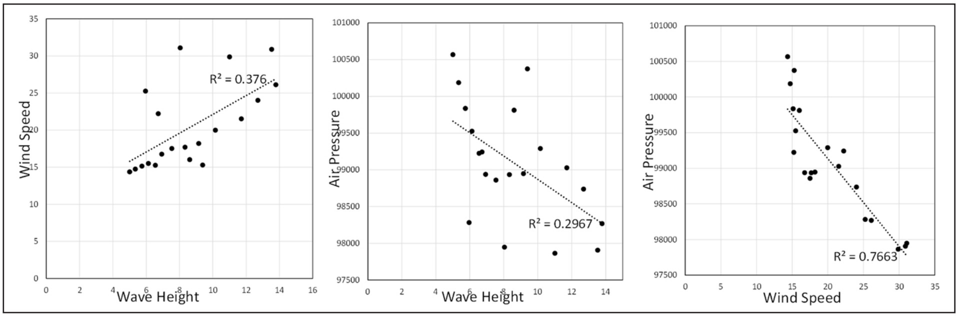


Figure 4. Correlation between air pressure, wind speed and wave height.

The specific pattern shown in this study may be different in each case as the air pressure distribution and other considerations may vary from case to case. However, if the characteristics of these weather patterns can be identified and analysed in advance, this could contribute significantly to the development of optimal ship routing.

4. CONCLUSIONS

Despite technological advances, ship routing services still fail in many cases, posing a risk to safe ship operations. In this study, a rough sea voyage in the North Pacific was presented. Some patterns were identified through variations in temporal and spatial weather factors. First, it was confirmed that a low pressure area developed and was followed by a strong wind; after about 12 hours, the maximum wave developed. Considering further situations, this could contribute to the development of optimal ship routing by characterising weather patterns.

Acknowledgments: The authors wish to extend their gratitude to Shoei Kisen Kaisha, Ltd. and Imabari Shipbuilding Co. Ltd., for their cooperation in taking onboard measurements of the 63,000-DWT bulk carrier from 2018. This study was financially supported by Scientific Research (B) (Project No. 20H02398, 2020–2024, represented by Kenji Sasa) and Fostering Joint International Research (B) (Project No. 18KK0131, 2018–2022, represented by Kenji Sasa) under the Grants-in-Aid for Scientific Research, Japan Society for the Promotion of Science.

REFERENCES

[1] Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R. and Joseph, D. (1996). The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorology Society*, 77 (3), pp. 437–471. doi: 10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2.

[2] Roh, M.I. (2013). Determination of an economical shipping route considering the effects of sea state for lower fuel consumption. *International Journal of Naval Architecture and Ocean Engineering,* 5 (2), pp. 246–262. doi: 10.2478/IJNAOE-2013-0130.

[3] Sasa, K., Faltinsen, O.M., Lu, L.F., Sasaki, W., Prpić-Oršić, J., Kashiwagi, M. and Ikebuchi, T. (2017). Development and validation of speed loss for a blunt-shaped ship in two rough sea voyages in the Southern Hemisphere. *Ocean Engineering*, 142, pp. 577–596. doi: 10.1016/j.oceaneng.2017.07.029.

[4] Sasa, K., Takeuchi, K., Chen, C., Faltinsen, O.M., Prpić-Oršić, J., Valčić, M., Mrakovčić, T. and Herai, N. (2019). Evaluation of speed loss in bulk carriers with actual data from rough sea voyages. *Ocean Engineering*, 187, 106162, pp. 1–19. doi: 10.1016/j.oceaneng.2019.106162.

[5] Sasa, K., Chen, C., Fujimatsu, T., Shoji, R. and Maki, A. (2021). Speed loss analysis and rough wave avoidance algorithms for optimal ship routing simulation of 28,000-DWT bulk carrier. *Ocean Engineering*, 228, 108800. doi: 10.1016/j.oceaneng.2021.108800.

[6] Zaccone, R., Ottaviani, E., Figari, M. and Altosole, M. (2018). Ship voyage optimization for safe and energy-efficient navigation: a dynamic programming approach. *Ocean Engineering*, 153, pp. 215–224. doi: 10.1016/j.oceaneng.2018.01.100.

[7] Zyczkowski, M., Szlapczynska, J. and Szlapczynski, R. (2019). Review of weather forecast services for ship routing purposes. Polish Maritime Research, 26, pp. 80–89. doi: 10.2478/pomr-2019-0069.

ASSESSING THE ACCURACY OF SHIP-BASED SEA STATE MEASUREMENTS USING STATISTICAL CORRELATION ANALYSIS AND HINDCAST WAVE DATABASES

Marijana Balas[1*], Jasna Prpić-Oršić[1], Marko Valčić[2], Kenji Sasa[3]

Abstract. *Effective decision support systems and aids to ship routing depend heavily on reliable data quality and its integration. Since data-driven decisions are only as correct as their findings, this statistical analysis takes a closer look at the accuracy of different data sources. Different wave data sets are considered, one from direct measurements on the ship and the other from global wave databases. Correlation analysis was mainly used to investigate the strength of the relationship between the two datasets. The results provide information on the accuracy and reliability of the global wave databases and their potential use in wave modelling and forecasting.*

Keywords: *hindcast databases; ship-based measurements; wave statistics; weather routing*

[1] University of Rijeka, Faculty of Engineering, Croatia
[2] University of Zadar, Maritime Department, Croatia
[3] Kobe University, Faculty of Maritime Science, Japan
Corresponding author: Marijana Balas (mbalas@riteh.hr)

1. INTRODUCTION AND BACKGROUND

Measurements of sea state and ship motions on board a 28 000 DWT bulk carrier were carried out from 2010 to 2016. The ship's route passed through some high-risk navigation areas in the Southern Hemisphere, which made the observation even more interesting for observation. Extensive research was conducted with the data obtained in [1], [2] and [3].

Sea state data play a crucial role in maritime safety, and their accurate estimation is essential. However, obtaining reliable data can be challenging due to the harsh and dynamic marine environment. In this study, data was further analysed to compare the reliability of different wave hindcasts. The data was pre-processed and cleaned to remove any missing or invalid values.

2. METHODOLOGY

To gain insight into the accuracy of the measurement data obtained from a ship and to highlight the importance of using hindcast wave databases for validation and calibration purposes, statistical correlation analysis can serve as a tool to assess data accuracy and identify the factors that influence its reliability.

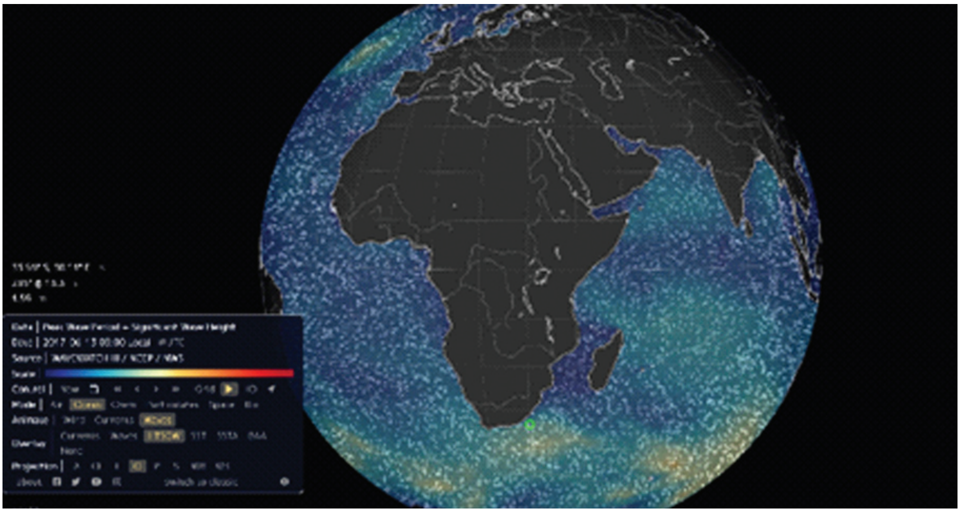


Figure 1. The visually attractive earth simulation that was used for data comparison as well, source: https://earth.nullschool.net.

Statistical analysis methods were used to compare the datasets. First, descriptive statistics were used to summarise the most important characteristics of the datasets. Then, correlation analysis was performed to further explore the relationship between the two datasets. Uncertainty analysis of the datasets revealed that the measured data had a higher degree of uncertainty than the hindcast data. This could be due to the measurement method and the instruments used on the voyage. However, the hindcast data also had a certain degree of uncertainty due to the limitations of the wave modelling algorithms, as described in [4] and [5].

The methodology allowed a comprehensive comparison of the two wave datasets and provided insight into the accuracy and reliability of the global wave database. The techniques used in this analysis can be applied to similar datasets in the future to compare and validate wave data from different sources.

3. RESULTS AND DISCUSSION

Weather conditions were analysed during rough sea voyages in the Indian Ocean, Atlantic Ocean and Tasman Sea in 2013. Correlation analysis showed good agreement between measured sea state data from the ship and hindcast wave data for wave height and period, but showed some discrepancies for wave direction. The uncertainty analysis showed that the measured data had a larger uncertainty compared to the hindcast data. Overall, these results suggest that hindcast wave data can be a useful resource for predicting sea state conditions while underway, but that caution should be exercised when interpreting the data, particularly with regard to wave direction.

It should be noted, however, that the statistical analysis was limited to a specific point in the ocean and a specific time period. Further analysis is needed to verify the accuracy of the hindcast data for other locations and time periods.

4. CONCLUSIONS

The results can further help in the development of better, more accurate and robust measurement techniques for collecting sea state data on board ships to improve the accuracy and reliability of the measured data.

For future research, the impact of climate change on sea state data and the reliability of hindcast wave databases should be investigated, as changes in wind patterns and ocean currents can significantly affect wave conditions. The impact of different ship types and sizes on sea state data measurements and the agreement with hindcast wave data should also be investigated and considered. The potential of using machine learning techniques to improve the accuracy of sea state data from ships and hindcast wave databases can also be explored.

Acknowledgments: This work has been supported by the Croatian Science Foundation under the project project IP-2018-01-3739 and uniri-tehnic-18-18 1146.

REFERENCES

[1] Lu, L., Sasa, K., Sasaki, W., Terada, D., Kano, T. and Mizojiri, T. (2017). Rough weather wave simulation and validation using onboard ship motion data in the Southern Hemisphere to enhance ship weather routing. *Ocean Engineering,* 144, pp. 61–77. doi: 10.1016/j.oceaneng.2017.08.037.

[2] Chen, C., Sasa, K., Oshawa, T., Kashiwagi, M., Prpić-Oršić, J. and Mizojiri, T. (2020). Comparative assessment of NCEP and ECMWF global datasets and numerical approaches on rough sea ship navigation based on numerical simulation and shipboard measurements. *Applied Ocean Research,* 101. doi: 10.1016/j.apor.2020.102219.

[3] Chen, C., Sasa, K., Prpić-Oršić, J. and Mizojiri T. (2021). Statistical analysis of waves' effects on ship navigation using high-resolution numerical wave simulation and shipboard measurements. *Ocean Engineering,* 229. doi: 10.1016/j.oceaneng.2021.108757.

[4] Bitner-Gregersen, E. M., Ewans, K. C. and Johnson M. C. (2014). Some uncertainties associated with wind and wave description and their importance for engineering applications. *Ocean Engineering,* 86, pp. 11–25. doi: 10.1016/j.oceaneng.2014.05.002

[5] De Hauteclocque, G., Vitali Maretic, N. and Derbanne, Q. (2023). Hindcast based global wave statistics. *Applied Ocean Research,* 130. doi: 10.1016/j.apor.2022.103438.

OCEAN WAVE ESTIMATION AND COMPARISON BY SHIP RADAR

Kenji Sasa[1*], Sang-Won Lee[1], Takuma Kita[1], Keiichi Hirayama[2]

Abstract. *The measurement of ocean waves is one of the most important technologies for ship operation, and many methods have been studied. However, there are few studies on the measuring waves in rough seas. In this study, measurements were made in actual seas using a wave radar analyser. Several cases of rough seas were conducted for a 63,000-DWT bulk carrier in real seas. The measured wave period and wavelength agreed well with the reanalysis of the meteorological data. It is necessary to determine the wave height coefficients from reliable information. They were obtained from the reanalysis data and compared with each other.*

Keywords: *ocean wave estimation; optimum ship routing; wave radar analyzer*

[1] Kobe University, Kobe, Japan
[2] Japan Radio Co., Ltd., Tokyo, Japan
Corresponding author: Kenji Sasa (sasa@maritime.kobe-u.ac.jp)

1. INTRODUCTION

Optimal ship routing has become crucial for the safe operation of ships [6]. This is further emphasized by greener transport [5]. Many studies have attempted to estimate ocean waves [2-4], and wave radar is one of main measurement methods [1]. In this study, ocean waves in the Indian Ocean were monitored using a wave radar analyser. The results analysed are summarized here.

2. WAVE MONITORING IN ACTUAL SEAS

The wave radar analyser was installed in a 63,000-DWT class bulk carrier, as shown in **Figure 1**.

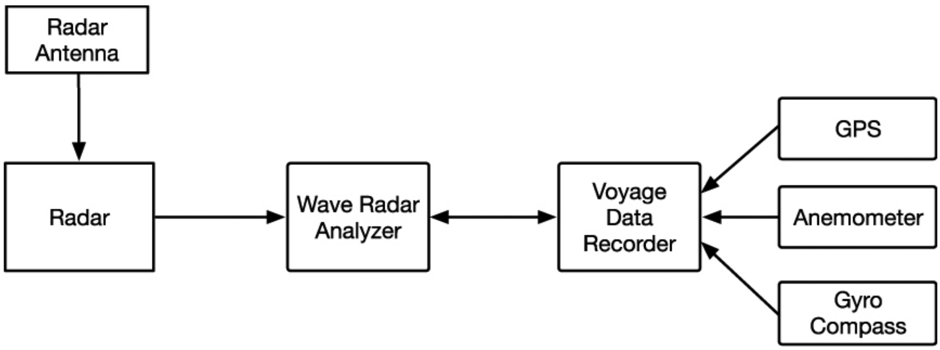


Figure 1. Measurement system of ocean waves in 63,000DWT bulk carrier.

It is connected with the X-band radar and the radar image is analysed using a two-dimensional Fourier transformation. Since ships have a forward speed, the position, ship speed, ship heading, wind speed and direction are used to analyse the radar image. When the sea state is rough, sea clutter appears in the image. The amount of sea clutter is converted into a signal-to-noise ratio (S/N). From the analysed radar images, it is possible to determine the wave direction and length. However, the coefficients for wave height were determined by the relationship between the S/N and the reliable wave height. Thus, the wave height was determined by the following equation:

$$H_{1/3} = a \times SN + b, \quad (1)$$

where $H_{1/3}$ is the significant wave height, *SN* is the S/N ratio, and *a* and *b* are the wave height coefficients. An inertial measurement unit, NAV440, was also installed on the ship's bridge. The navigation and machinery information was recorded on the PCs. The wave conditions in rough seas are summarised in the sum total.

3. COMPARISON OF OCEAN WAVES IN OPEN SEAS

The wave height coefficients were obtained from measurement results during a voyage from Canada to China in April 2018. The voyage included five rough sea conditions. A reliable wave height was obtained from reanalysis of meteorological wave data in the NOAA. **Figure 2** shows the ship track from 1 to 31 July 2018.

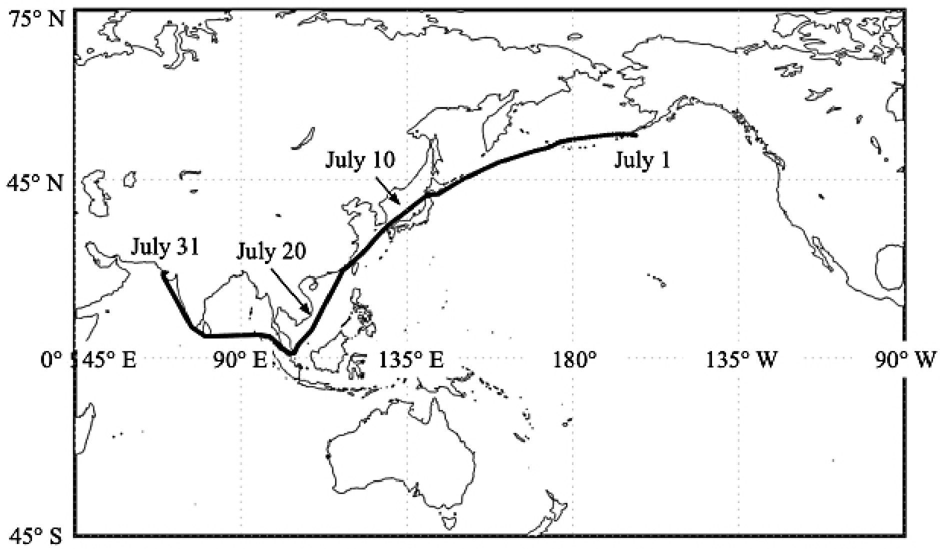


Figure 2. Measured ship track of 63,000DWT bulk carrier (July 1-31, 2018).

Figure 3 shows the variation in rolling and pitching from 1 to 31 July 2018. **Figure 4** shows a comparison of wave height, wave period and wave direction from 1 to 31 July 2018.

The ship left from North America in late June 2018 and headed towards West Asia via Korea, China, the Strait of Malacca, India, etc. From 1 to 8 July it was in the Pacific Ocean and from 25 to 31 July it was in the Indian Ocean after passing through the Strait of Malacca. This shows that the roll and pitch motions increased sixfold, while the ship motions remained larger in the Indian Ocean. As can be seen in **Figure 4**, the radar wave height exceeds 3 m, and that of NOAA shows different patterns. The maximum value of 4.7 m was reached on 8 July. However, ship motion was very small at that time. This means that the radar tends to agree with the measured ship motions.

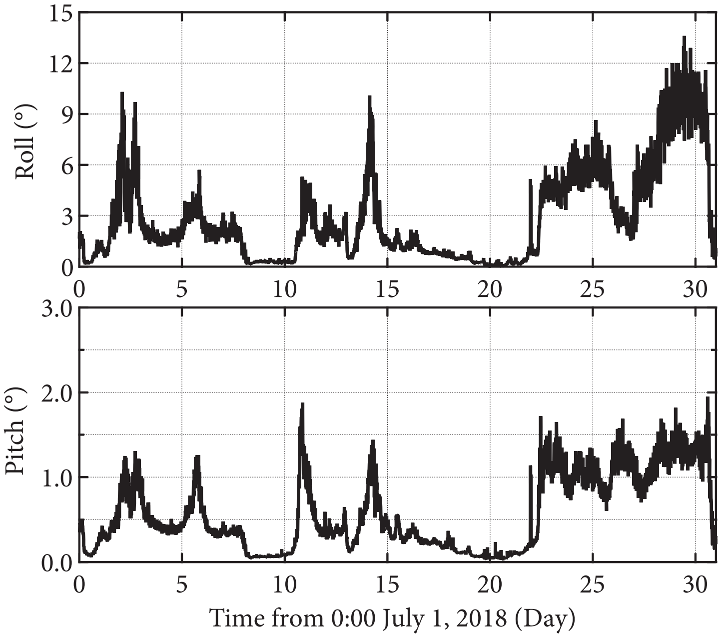


Figure 3. Variation of roll and pitch motions (1-31 July 2018).

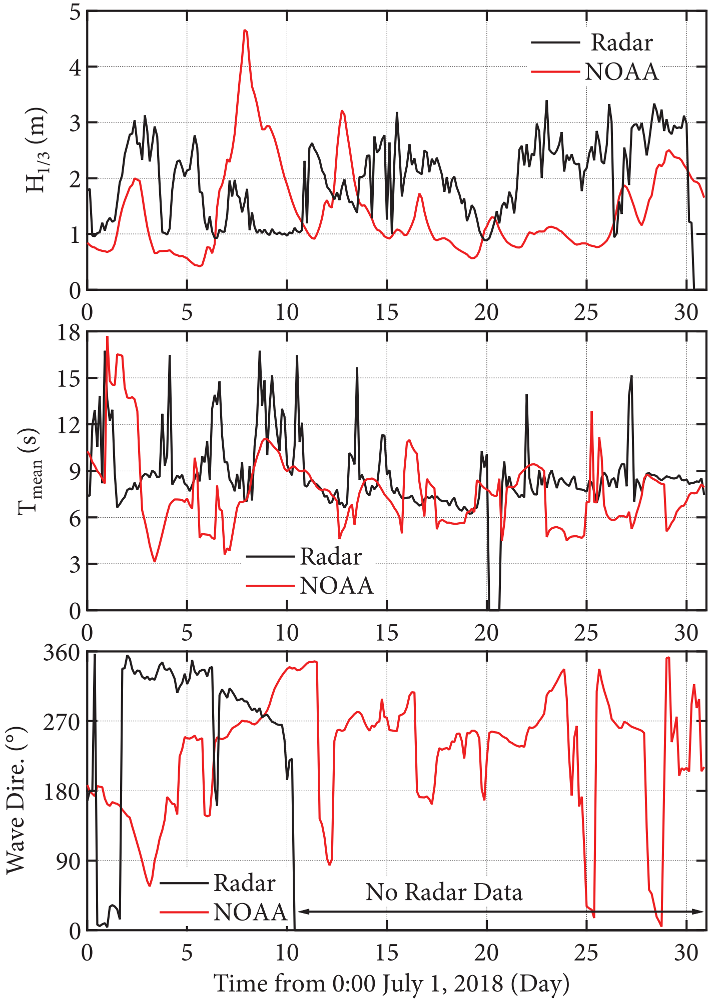


Figure 4. Comparison of wave conditions (1-31 July 2018).

It is also obvious that the wave period is almost the same as that in the NOAA. The wave direction of the radar could not be accurately determined from 10 July. Further comparisons are needed to clarify this issue.

4. CONCLUSIONS

This study investigated the accuracy of wave estimation for rough seas in the Indian and Pacific Oceans for 63,000-DWT bulk carriers using a wave radar analyser. Wave height coefficients were defined and the data from April 2018 were reanalysed. Wave heights in July 2018 were compared with those from the NOAA data. Although not similar, the wave height determined by the radar appears to be reasonable as it is synchronised with the variation in rolling and pitching. The wave period was almost consistent, while the wave direction needed to be checked in the other cases.

Acknowledgments: The authors wish to extend their gratitude to Shoei Kisen Kaisha, Ltd., for their cooperation in conducting the onboard measurements of the 63,000-DWT bulk carrier. This study was financially supported by Scientific Research (B) (Project No. 20H02398, 2020–2024, represented by Kenji Sasa) and Fostering Joint International Research (B) (Project No. 18KK0131, 2018–2022, represented by Kenji Sasa) under Grants-in-Aid for Scientific Research, Japan Society for the Promotion of Science.

REFERENCES

[1] Hirayama, K., Oka, K. and Baba, M. (2010). Marine Wave Observation System with Radar, *Technical Report of Japan Radio Co., Ltd.*, No. 59, pp. 30–33. *Japan Radio Co., Ltd.* (in Japanese).

[2] Iseki, T. and Terada, D. (2002). Bayesian Estimation of Directional Wave Spectra for Ship Guidance Systems, *International Journal of Offshore and Polar Engineering*, Vol. 12, No. 1, pp. 25–30. ISSN: 1053-5381.

[3] Nielsen, U.D. (2006). Estimations of On-site Directional Wave Spectra from Measured Ship Responses, *Marine Structures*, No. 19, pp. 33–69. doi: 10.1016/j.marstruc.2006.06.001.

[4] Pascoal, R., Guedes Soares, C. and Sorensen, A.J. (2007). Ocean Wave Spectral Estimation Using Vessel Wave Frequency Motions, *Journal of Offshore Mechanic and Arctic Engineering*, Vol. 129, No. 2, pp. 90–96. doi: 10.1115/1.2426896.

[5] Prpić-Oršić, J. and Faltinsen, O.M. (2012). Estimation of Speed Loss and Associated CO_2 Emissions in a Seaway, *Ocean Engineering*, Vol. 44, pp. 1–10. doi: 10.1016/j.oceaneng.2012.01.028.

[6] Sasa, K., Chen, C., Fujimatsu, T., Shoji, R., and Maki, A. (2021). Speed Loss Analysis and Rough Wave Avoidance Algorithms for Optimal Ship Routing Simulation of 28,000-DWT Bulk Carrier, *Ocean Engineering*, Vol. 228, p. 108800. doi: 10.1016/j.oceaneng.2021.108800.

UNCERTAINTIES IN SEAKEEPING CALCULATIONS FOR TWO RESEARCH VESSELS IN THE ADRIATIC SEA

Joško Parunov[1*], Marko Katalinić[2], Petar Matić[2], Ivan Ćatipović[1], Ivana Gledić[1], Tamara Petranović[1], Srđan Vujičić[3]

Abstract. *A comparison is presented between seakeeping analysis and full-scale measurements of the vertical motions of two research vessels in rough seas. The experiments were conducted in the Adriatic Sea, near the coast of Split and Dubrovnik. Seakeeping calculations were performed with the 3D panel seakeeping method in the frequency domain and spectral analysis using measured wave spectra. While the agreement between the calculations and the measurements of ship motion amplitudes was quite good, large discrepancies were found in the mean zero-crossing response times in stern and quartering seas. The likely reason for these uncertainties is ambiguities in the calculation of the encountered response spectra for ship with forward speed. This is discussed in the presentation and suggestions are made for improving the accuracy of seakeeping calculations.*

Keywords: *Adriatic Sea; full-scale measurements; seakeeping analysis; uncertainties*

[1] Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Croatia
[2] Faculty of Maritime Transportation, University of Split, Croatia
[3] Maritime Department, University of Dubrovnik, Croatia
Corresponding author: Joško Parunov (jparunov@fsb.hr)

1. INTRODUCTION

Accurately predicting ship responses in a fairway is important for variety of applications, such as seakeeping-based ship operability analysis and improving safety and operational efficiency through weather routing. Uncertainties in the seakeeping analysis of wave-induced motions and loads for ship design and analysis are therefore the subject of much interest in the international shipbuilding research community [1]. Comparison of seakeeping computations and full-scale measurements is considered essential for uncertainty assessment. Recently, two experimental campaigns have been carried out in the Adriatic Sea to improve the understanding of uncertainties [2-4]. Measured heave and pitching responses from two research vessels were compared with the seakeeping computation performed by state-of-the art software, measuring waves in the vicinity of ships. Since large discrepancies were found in the mean zero-crossing response periods in the stern and following seas, an in-depth analysis is carried out, showing that ambiguities in the calculation of the encountered response spectrum could be the main reason for this phenomenon.

2. COMPARISON OF FULL-SCALE MEASUREMENTS AND SEAKEEPING CALCULATIONS

Full-scale measurements of waves and vertical ship motions were made on two research vessels: Bios dva (owned by the Institute of Oceanography and Fisheries, Split, Croatia) and Naše more (owned by the University of Dubrovnik, Croatia). Sea trials were conducted at "choppy seas" on 10 February 2021 near Split and on 5 November 2021 near Dubrovnik, for Bios dva and Naše More, respectively [5], [6]. Seakeeping calculations were performed using the state-of-the-art software HydroSTAR, which is based on a 3D diffraction/radiation potential theory. The agreement between calculations and measurements was quite good for the amplitudes of the ship motions, but large discrepancies were found for the response times in following and quartering waves [3]. Thus, the ratio of predicted and measured average response period was found to be close to, or in some cases even above 2.

3. ENCOUNTERED WAVE SPECTRA

The uncertainty described in the previous section is caused by the fact that the response spectrum, encountered at following and stern quartering seas, draws energy from three different absolute wave frequencies. Theoretically, the encountered response spectrum concentrates at a certain encounter frequency with a corresponding extremely high value of energy density and then suddenly drops to almost zero. However, the measured response spectrum shows that the energy is more evenly distributed across the encountered wave frequencies. It is therefore proposed to use new methods (ANN) to improve the accuracy of seakeeping predictions and to carry out additional full-scale measurements.

4. CONCLUSIONS

The paper deals with the comparison of full-scale measurements and seakeeping calculations of two research vessels in the Adriatic Sea. The agreement between measurements and calculations was quite good, although large discrepancies were found in the response times in following and stern quartering waves. The reason for these discrepancies is the ambiguity in the calculation of the response spectra in following waves. New methods are needed to solve this problem.

Acknowledgement: This work was fully supported by the Croatian Science Foundation under the project lP-2019-04-2085.

REFERENCES

[1] Parunov, J., Guedes Soares, C., Hirdaris, S. & Wang, X. (2022). Uncertainties in modelling the low-frequency wave-induced global loads in ships. Marine Structures, 86, p. 103307, 21. doi:10.1016/j.marstruc.2022.103307.

[2] Gledić, I., Petranović, T., Katalinić, M., Vujičić, S., Matić, P., Ćatipović, I. & Parunov, J. (2022). Comparison of full-scale measurements and seakeeping calculations for two research vessels in the Adriatic Sea. Ocean Engineering, 266, p. 113135.

[3] Katalinić, M., Matić, P., Petranović, T. & Parunov, J. (2022). Full-scale measurements of ship motion in rough seas in the Adriatic Sea. Trends in Maritime Technology and Engineering Volume 1, pp. 365–371.

[4] Vujičić, S., Petranović, T., Parunov, J. & Katalinić, M. (2022). The Seaworthiness of a Training Ship "NAŠE MORE" in Heavy Seas. In: Sviličić, B. & Kurshubadze, N. (edts.) A publication of the International Association of Maritime Universities.

CFD STUDY ON PROPULSION CHARACTERISTICS OF SHIPS SUBJECTED TO WAVES

Ivan Sulovsky*, Jasna Prpić-Oršić, Roko Dejhalla

Abstract. *Predicting the propulsion characteristics of ships with conventional propellers is the most fundamental and enduring problem associated with ship hydrodynamics, whether the ship is a newbuild or a retrofit. The problem is becoming increasingly important in the maritime industry and these predictions are particularly difficult when the ship is exposed to real weather conditions, i.e., waves, wind, and currents. The study is carried out using Computational Fluid Dynamics (CFD) and focuses on thrust in regular head and oblique waves for a passenger ferry of a double-ended type. Prior to this, a one-dimensional actuator disk (AD) used in this study is validated by a self-propulsion configuration in calm water of a KRISO container ship, a widely used hull model for benchmarking in ship hydrodynamics.*

Keywords: *actuator disk; CFD; KCS containership; passenger ferry; ship propulsion*

University of Rijeka, Faculty of Engineering, Croatia
Corresponding author: Ivan Sulovsky (isulovsky@riteh.hr)

University of Zadar

1. INTRODUCTION

In maritime traffic, the need for fully electric ferries is becoming increasingly clear. Accordingly, the design of the complete propulsion unit must be engineered efficiently. In general, the overall performance of the propulsion system is the result of a complex interaction between ship motions, engine workload and consequently propeller output. In this paper, the focus is on the latter. For a passenger ferry, originating from [**1**], self-propulsion calculation using *CFD* tool is conducted. The propulsion force, i.e. the thrust, is modelled using an ideal actuator disk, which eliminates the high computational needs for a fully discretised propeller geometry. All calculations are performed with OpenFOAM® [**2**], a viscous flow solver based on a finite volume method. First, an estimate of the thrust in calm water is made. Then, the vessel is subjected head and oblique waves. An integral quantity of the propulsion is observed, namely the thrust, which can provide valuable information for the specific engineering needed for a fully electric propulsion for ships.

2. METHODOLOGY

The research presented in this article is based on numerical simulation. Experimental data for the KRISO container ship, described in detail in [**3**], are used to validate AD, a common modelling strategy for ship propulsion in computational marine hydrodynamics. For the passenger ferry, the propulsion is also idealised with the disc but with the fully discretised geometry of the azimuth thruster to obtain more accurate estimate of the inflow properties to the disc (**Fig. 1**). The green circle represents the AD surface. Data required for the numerical modelling of AD include the basic geometric characteristics of the propeller and the properties from the open water test. In the context of the finite volume framework and consequently the Navier-Stokes equations, AD is treated as the volumetric source term on the right-hand side of the momentum equation.

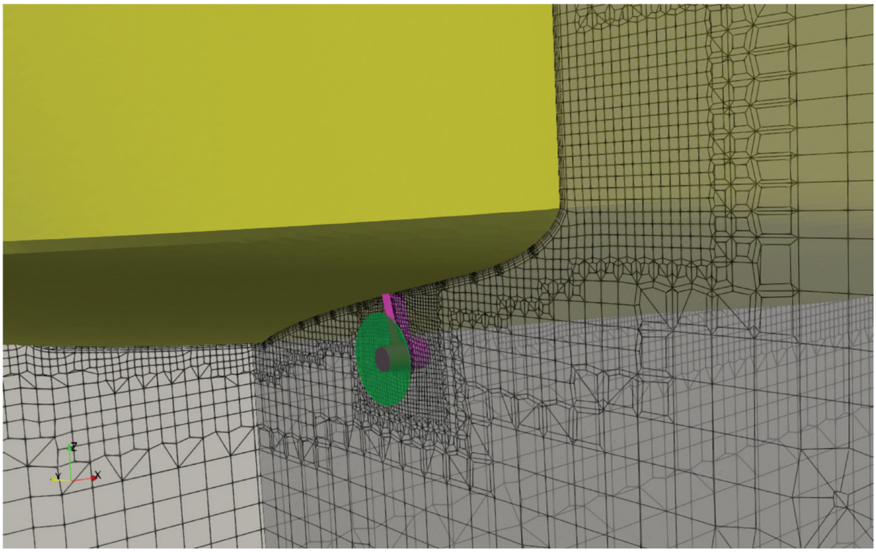


Figure 1. Discretisation of idealized actuator disk.

The wave conditions for the ferry are given in **Table 1** where *H* is the wave height, λ is the wave length, L_{pp} is the length between perpendiculars and *T* is the wave period. The value of wave height is chosen to correspond to sea state 4 according to the World Meteorological Organisation. The test matrix is constructed so that the wave steepness is constant while the wave length varies with L_{PP}. As for the direction of the incident wave β, two directions are given. The first considers the pure head wave (β = 180°) and the second the oblique wave (β = 135°). A total of six wave cases are specified for a comprehensive analysis of the propulsion and seakeeping behaviour.

Table 1. Wave conditions for the passenger ferry for β = 180°/135°.

Case n⁰	**H** (*m*)	$\boldsymbol{\lambda/L_{pp}}$	**T** (*s*)
Case 1.	2	1	7.75
Case 2.	2	0.5	5.15
Case 3.	2	0.33	4.42

For the pure head wave cases, the ship model has two degrees of freedom (pitch and heave), while for the oblique wave, the rolling motion is also included, which provides insight into the changes in thrust due to the rotating motion in the transversal plane of the ship. As for the ship loading condition, the design draught is 2.3 m at a design speed of 12 knots.

3. RESULTS AND DISCUSSION

The results of the study are described in this section. **Figure 2** shows the steady convergence of thrust T and calm water resistance R_{sp} at self-propulsion point. The forces are compared with the experimental values, namely *EFD*. The result show that the AD model is accurate enough for large-scale application while the resistance force could be resolved more accurately with a finer computational grid. Also, skin friction coefficient *SFC,* which is required for model scale testing, is an additional source of uncertainty, which means that the results could be slightly more accurate for the full-scale calculation.

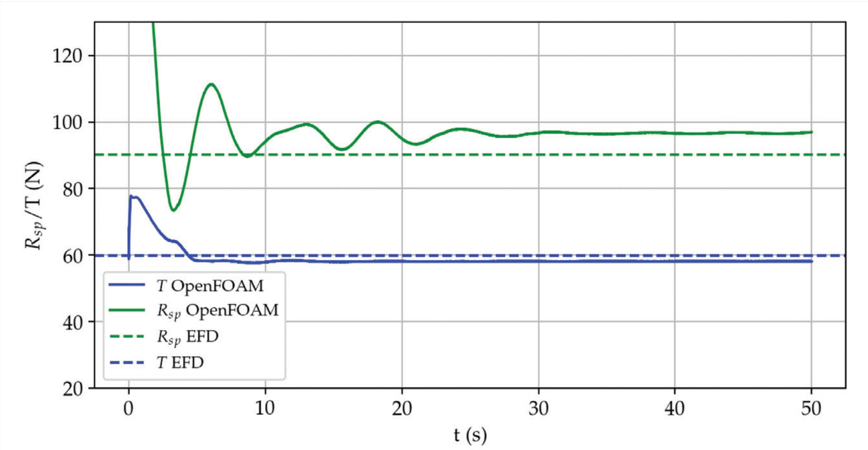


Figure 2. Thrust and total resistance convergence from the numerical simulation.

Table 2 shows the comparison of bare hull resistance coefficient $C_{T,}$ resistance coefficient at self-propulsion point $C_{T(sp)}$ and thrust coefficient K_T with experiment.

Table 2. Comparison of the results with experiment (*EFD*) for KRISO containership.

R_e=1,40·10^7	C_T	$C_{T(sp)}$	K_T
CFD	4.041	4.278	0.164
EFD	3.835	3.966	0.170
(EFD/CFD)·100%	5.37	7.87	3.06

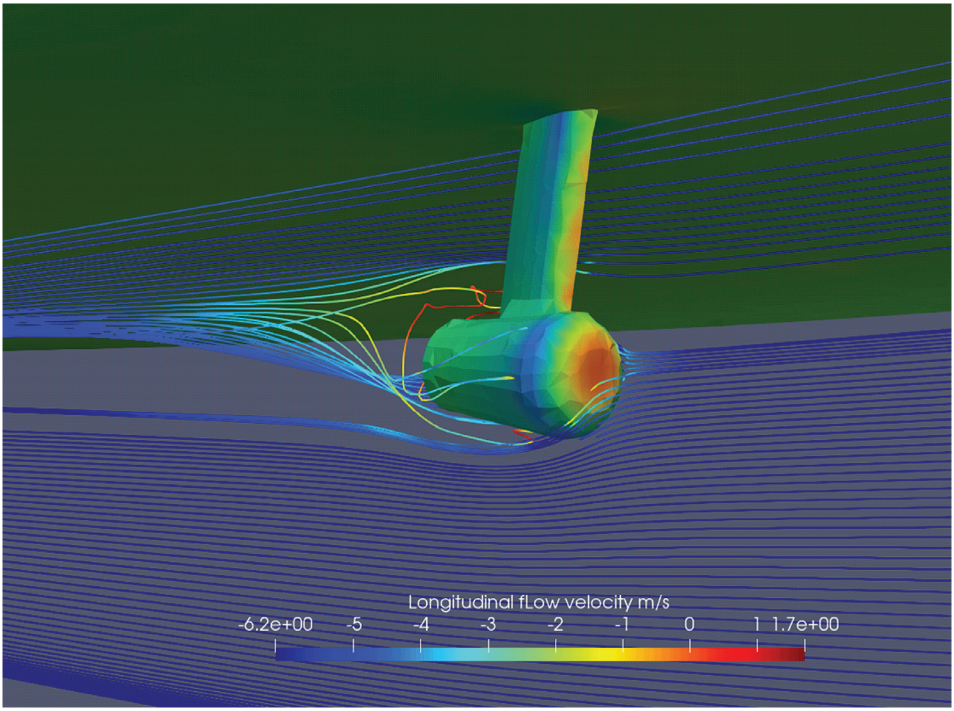


Figure 3. Velocity streamlines around azimuth thruster body.

As expected, the thrust force for the passenger ferry shows strong oscillations in the wave environment that correlate with the amplitudes of the ship motion. Velocity streamlines around azimuth thruster body are shown in **Fig. 3**. The hydrodynamic pressure on the thruster body is colour coded. Knowing the changes in thrust ina given condition provides a twofold advantage. Firstly, for the ship designer who gets an early overview of the effective wake field under real conditions, which allows a more efficient design of the propeller geometry. The second advantage is for the ship master and helmsman, especially if the ship is battery-powered. Adjusting the ship's direction relative to incident waves or changing the ship's speed can affect the efficiency of the electric propulsion system throughout its lifetime.

4. CONCLUSIONS

The main objective of this study is to shed light on the thrust behaviour of a typical Ro-Ro passenger ferry in regular head and oblique waves. The research is carried out exclusively with numerical simulations using the *CFD* tool, where the propeller is simplified by an ideal actuator disk. As the research is conducted for a full-scale ship, the validation of the actuator disk is done on a model-scale arrangement of a KRISO container ship. Further research is aimed at incorporating torque estimation into the actuator disk and evaluating the propulsion characteristics for different loading conditions of the ferry, as its operating profile is highly variable.

Acknowledgments: This work has been supported by the Croatian Science Foundation under the project IP-2018-01-3739 and uniri-tehnic-18-18 1146.

REFERENCES

[1] A Computational Fluid Dynamics Analysis of a Double-Ended Ferry, report, Interreg Italy-Croatia project METRO, University of Rijeka – Faculty of Engineering.

[2] Weller HG, Tabor G, Jasak H, Fureby C (1998). A tensorial approach to computational continuum mechanics using object-oriented techniques. Comput Phys 12:620.

[3] Kim WJ, Van SH, Kim DH (2001). Measurement of flows around modern commercial ship models. Exp Fluids 31:567–578.

ANALYSIS OF THE SHIP'S PROPELLER-INDUCED VIBRATIONS

Josip Orović*, Marko Valčić, Jelena Čulin, Josip Mijatov

Abstract. *Shipboard vibrations have a detrimental effect on propulsion and auxiliary systems and also on the habitability of ships. The project "Improving the ship propulsion efficiency by propeller optimization" aims, among other things, to explore and further explain how propeller optimisation procedures can reduce fuel consumption and ship vibrations and improve the overall efficiency of ship propulsion. The results show that different propeller designs, manufacturing processes and damage during operation affect ship vibration, fuel consumption, habitability, and consequently ship speed.*

Keywords: *fuel oil consumption; habitability of ships; propulsion efficiency; ship's propeller modification; vibration analysis*

University of Zadar, Maritime Department, Zadar, Croatia
Corresponding author: Josip Orović (jorovic@unizd.hr)

1. INTRODUCTION

The measurement, analysis, diagnostic evaluation, and reporting of a vessel's vibrations are very useful to improve the efficiency of the propulsion plant [1], [2], reduce maintenance costs, and reduce the long-term high-intensity vibrations of the human body [3]. The research results presented shed light on fuel consumption and vibration reduction through propeller optimisation and modification.

2. METHODOLOGY

During the research activities of the project, the propellers on different ship types were modified during dry dock period to achieve a better class, i.e. a tolerance and a deviation of the propeller pitch close to the theoretical one. Vibration measurements were carried out before and after drydocking to assess the impact on fuel consumption, habitability, and ship speed. So far, measurements and data collection have been carried out before and after drydocking on several ships (up to the current phase of the project). The onboard measurements were carried out with the Acoem Falcon vibration measuring device [4]. All other data for the analysis of the ship parameters before and after the propeller optimisation process were collected on board with existing/installed instruments. The measured and recorded values were used for the data analysis and comparison. The data and vibration analyses were carried out using the computer software programmes Nest Analyst (**Figure 1**) [5], vib-Graph (**Figure 2**) and dBFA [6].

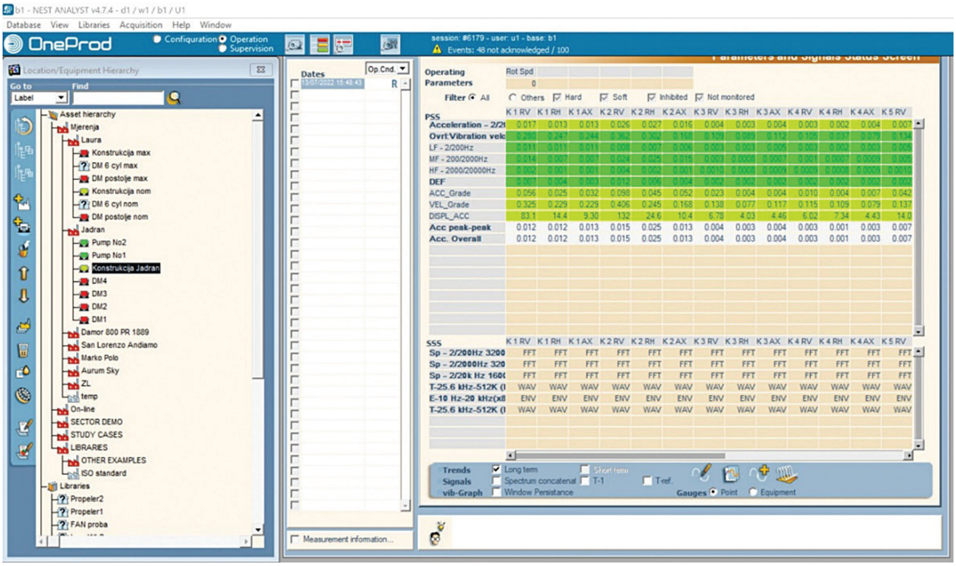


Figure 1. Predictive maintenance software platform Nest Analyst.

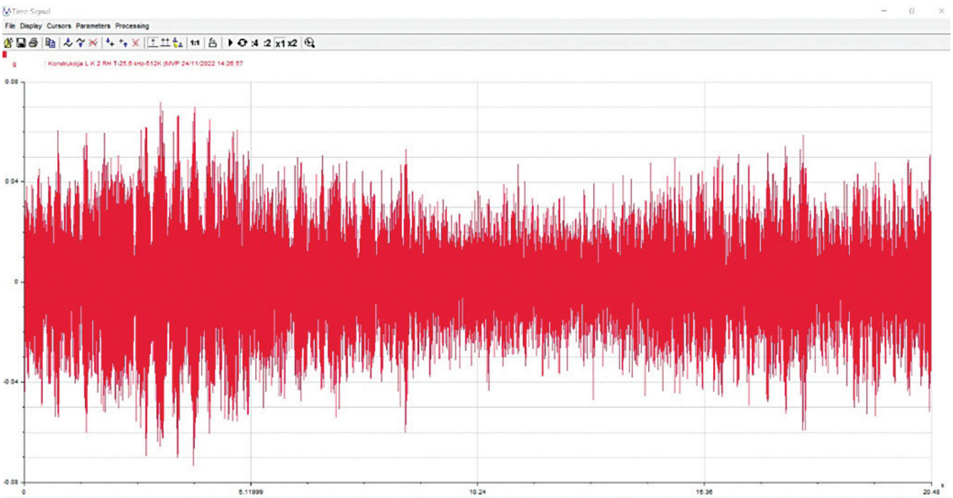


Figure 2. Vib-Graph software used for vibration analysis.

3. RESULTS

The analysed vibration data show certain deficiencies in the propulsion systems of the investigated vessels. By optimising the current parameters and modifying the propeller, it is possible to reduce fuel consumption and thus maintenance costs and to reduce the long-term high-intensity vibrations of the human body. During the duration of the project, data measurements will be carried out on several different ships in order to have a sufficiently large database of measurement data from ships to enable high-quality optimisation of the propeller and selection of the best solution in terms of predictive diagnostics of the propulsion system.

4. CONCLUSION

The results presented show that different propeller designs, manufacturing processes, and damage during operation affect the ship vibration, fuel consumption, ship speed, propulsion efficiency, and consequently the habitability on board ships. The results of this research could be very useful for shipowners, ship operators, propeller manufacturers, and all other interested parties in increasing propulsion efficiency and reducing of maintenance costs.

Acknowledgments: This research is funded by the European Regional Development Fund. This work was also supported by the Croatian Science Foundation under the project IP-2018-01-3739.

REFERENCES

[1] Carlton, J.S. (2019). *Marine Propellers and Propulsion*. 4th Ed. Butterworth-Heinemann, Elsevier, Oxford, UK.

[2] Schneekluth, H., Bertram, V. (2004). *Ship Design for Efficiency and Economy*, 2nd Ed. Butterworth-Heinemann, Elsevier, Oxford, UK.

[3] ISO 20283-5 (2016). *Mechanical vibration – Measurement of vibration on ships – Part 5: Guidelines for measurement, evaluation and reporting of vibration with regard to habitability on passenger and merchant ships*. ISO Copyright Office, Geneva, Switzerland.

[4] FALCON Acoem. (2023). *Vibration analyser*. Available from: https://www.acoem.com/en/products/predictive-maintenance/handheld-vibration-measurement/falcon/, accessed on 25 February 2023.

[5] NESTi4.0. (2023). *Predictive maintenance software platform*. Available from: https://www.acoem.com/en/products/predictive-maintenance/predictive-maintenance-platform/nesti-4-0/, accessed on 25 February 2023.

[6] dBFA software suite. (2023). dBFA software suite USER MANUAL. Available from: https://manualzz.com/doc/4158443/dbfa-software-suite-user-manual, accessed on 25 February 2023.