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Comparative Analysis of the Usefulness of AIS and ARPA for Anti-collision Purposes

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ABSTRACT: The article discusses the principles of presenting data available from AIS and radar tracking on ship's radar display units and describes the results of comparative studies of the accuracy of their indications on sea-going vessels in real meeting situations in various hydro meteorological conditions.

1 INTRODUCTION

In accordance with the current international recommendations set out in the Resolution MSC.192(79) "Adoption of the revised performance standards for radar equipment" adopted by the International Maritime Organisation (IMO) on 6th of December 2004, each radar installed on or after 1st of July 2008 on ships subject to the requirements of SOLAS regulation V / 19 should present data from radar tracking and on board automatic identification system (AIS) [4]. Radar tracking aids (automatic radar plotting aid - ARPA and automatic tracking aid - ATA) calculate true vector, the passing distance with detected and tracked object and time to pass it, called respectively closest point of approach (CPA) and time to the closest point of approach (TCPA) on the basis of radar measurements of its distance and bearing. AIS at given time intervals and in pulling mode automatically transmits, receives and displays, inter alia, indications of connected to it gyrocompass, speed and distance measuring device and Global Navigational Satellite System (GNSS), currently mainly GPS, ship's receiver. Additionally, it can calculate and indicate CPA and TCPA on the basis of knowledge of the geographical positions and true motion vectors of the own ship and the opposite vessel transmitting AIS messages. Relatively low accuracy of radar measurements means that the data from radar tracking can be presented with lower accuracy than data from AIS. Due to that, when the target data from AIS and radar tracking are both available and the association criteria (position, motion, etc.) are fulfilled, i.e. the AIS and radar information is considered as concerning one physical target, then the AIS target symbol and the alphanumerical AIS target data should be automatically selected and presented on the radar display as a default condition [4].

However, the radar remains the only independent technical source of information about surface objects around own ship. For this reason, according to the recommendations of the Resolution A.1106(29) "Revised guidelines for the operational use of shipborne automatic identification systems (AIS)" adopted by IMO on 2nd of December 2015, the AIS may be recommended as an anti-collision device in due time and its introduction has not impact on the Rule 19 "Conduct of vessels in restricted visibility" of the International Regulations for Preventing Collisions at Sea (COLREG) and its interpretation. The ship's master and watch keeping officers (OOW) should not rely on AIS as the sole information system,

but should make use of all safety-relevant information available. In general, AIS may be used to assist in collision avoidance decision-making as an additional source of information which supports radar and radar tracking aids to calculate true and relative vectors of the detected and tracked echoes on the basis of radar measurements of their distances and bearings, by assisting in [3,13]:
– identification of targets by name, call sign, ship type and navigational status;
– presentation of targets heading;
– immediate identification of manoeuvres performed by targets; and
– more accurate presentation of courses, speed over ground and rate of turn of the targets.

IEC Standard 61993-2 presenting performance standards for AIS required that if AIS display equipment provides facilities for the calculation of CPA and TCPA then these facilities should comply with the relevant clauses of the IEC Standard 62388 "Shipborne radar - Performance requirements, methods of testing and required test results" [1]. The said standard specifies the minimal requirements for radar conforming to performance standards not inferior to those adopted by IMO in the Resolution MSC.192(79) [2]. According to both standards, accuracy of radar tracking shall be as presented in Table 1 [2,4]. Mentioned in this table time of steady state tracking means radar tracking a target in the steady phase of movement [2,4]:
– after completion of the acquisition process; or
– without a manoeuvre of target or own ship; or
– without target swap or any disturbance.

In maritime navigation nautical miles (NM) and knots (kn) are officially used as the units of distance and speed. ARPA and AIS present values of distance, CPA and speed in these units. Therefore, in this paper they are presented in nautical miles and kilometres and in knots and m/s (1 NM = 1852 m; 1 kn = 1 NM/h ≈ 0.514 m/s) respectively.

Resolution MSC.192(79) informs additionally that automatic tracking accuracy [4]:
– should be achieved assuming the sensor errors allowed by the relevant IMO performance standards (range and bearing accuracy should be within 50 m (or +/-1% of target range) and 2°); and
– may be significantly reduced during or shortly after acquisition, own ship manoeuvre, a manoeuvre of the target, or any tracking disturbance and is also dependent on own ship's motion and sensor accuracy.

The testing standard should comprise detailed target simulation tests as a means to confirm the accuracy of targets with relative speeds of up to 100 kn. The operating instructions should contain a qualified explanation and/or description of information required by the user to operate the radar system correctly, including limitations of the display and tracking process and accuracy, including any delays [4].

The Standard IEC 62388 requires that the tracking accuracy be checked using simulated targets generated by a target simulator in a noise-free and clutter-free environment. Table 1 provides an indication of typical tracking accuracy, averaged over five tracking scenarios and with minimal sensor errors as described in Annex E to that standard. The individual scenarios are as follows [2]:
– scenario 1 applies the sensor errors as defined in Annex E in this standard;
– scenarios 2 and 3 test own ship turns in both directions, without sensor errors;
– scenario 4 tests for target swap, without sensor errors; and
– scenario 5 provides 10 targets, including one having a 50 % visibility; no sensor errors are applied.

The test scenarios differentiate standard and high speed craft by the parameters used. They simulate own ship travelling at up to 30 kn (or up to 70 kn for high speed craft), whilst tracking targets with a speed of up to 70 kn. High rate of turn, own ship and target manoeuvring, target swap, multiple targets on a bearing, acceleration and fading are simulated. The simulator assumes a 2.0° antenna (–3 dB point) horizontal beam width, an antenna rotation rate compatible with the category of equipment, and at a pulse length and pulse repetition frequency as specified by the manufacturer [2].

Additionally, the tracking system shall demonstrate tracking capability in noisy and clutter environments. This requirement shall be checked by visual observation. It is fulfilled if the observer confirms that when [2]:
– the test targets in scenario 5 are set to 10 dB above peak noise level, they are tracked without degradation of the tracking performance; and
– the tracking system is operated in a typical clutter environment and using targets of opportunity (targets of different sizes, speeds and trajectories), continue to be tracked with minimal degradation to tracking performance.

All of the information provided shows that presented in Table 1 radar tracking accuracy and accuracy of the CPA and TCPA values presented by AIS apply only to conditions simulated in the absence of noise and clutters. The issue requiring research is the accuracy of the analyzed indications on seagoing ships of different sizes in real conditions of their exploitation and in real meeting situations.

The measurements reported in this article were carried out to determine;
– the mean values and mean square errors of data presented by AIS and ARPA;
– the influence of the stability of the observed and tracked ship's motion on the accuracy of determining its true motion vector by ARPA and CPA by ARPA and AIS as a function of time; and
– the relationship between the accuracy of AIS and ARPA indications and the current state of the sea.

They were carried out over several years and some of their results have already been partly presented in publications [12-15].

Table 1. Tracked target accuracy (95% probability figures) [2,4]

Time of steady state tracking [min]	Relative course [°]	Relative speed [kn / m/s]	CPA [NM / km]	TCPA [min]	True course [°]	True speed [kn / m/s]
1 min: trend	11	1.5 / 0.8 or 10% (whichever is greater)	1.0 / 1.85	-	-	-
3 min: motion	3	0.8 / 0.4 or 1% (whichever is greater)	0.3 / 0.56	0.5	5	0.5 / 0.3 or 1% (whichever is greater)

Table 2. Ships on which tests were carried out with the indication of their size category and on board AIS and radar equipment [5,6,7,8,9,10,11,16,17,18]

Ship					Used equipment / manufacturer	
Size	Type	Gross tonnage	Length [m]	Service speed [kn / m/s]	Radar / ARPA	AIS
V	Bulk carrier	106884	299.9 1	5.6 / 8.0	JMA-9132-SA, JMA-9122-9XA / JRC	JHS-183 / JRC
L	LPG tanker	46789	226.0	16.7 / 8.6	JMA-9172-SA, JMA-9122-9XA / JRC	JHS-183 / JRC
L	Multipurpose ship	30469	199.8	16.8 / 8.6	Radar Vision Master FT X, S bands, ARPA 340/25X, 340/30S / Sperry Marine	Nauticast X-Pack DS / Nauticast GmbH
M	Multipurpose ship	11864	143.0	13.2 / 6.8	GR3017 (X-Band), GR3018 (S-Band), ARPA Multipilot 1100 / SAM Electronics GmbH	DEBEG 3400 / SAM Electronics GmbH
M	Liqufied gas carrier	22941	174.2	15.5 / 8.0	JMA-9932-SA, JMA-9922-6X / JRC	JHS-182 / JRC
M	Bulk carrier	20603	190	14.0 / 7.2	FAR-21X7(-BB) (X & S BAND), Furuno	FA-150 / Furuno
M	Container	16801	184.1	19.7 / 10.1	X & S Sperry Marine / Northtop Grumman	R4 / SAAB
S	Bulk carrier	2735	89.4	11.0 / 5.7	FAR-28x7 model FAR-21x7 (-BB) / Furuno	R4 / SAAB SAAB Transponder Tech AB
S	Oil/chemical tanker	4667	97.4	13.6 / 6.7	Vision Master FT CAT 2 / Sperry Marine	R4 / SAAB Transponder Tech AB
S	General cargo	3443	93.42	12.0 / 6.2	Bridge Master E (S) / Sperry Marine	JHS-182/ JRC

V- very large; L - large; M - medium; S - small

2 DESCRIPTION OF THE MEASUREMENTS

The measurements were conducted by students of the Faculty of Navigation of the Gdynia Maritime University as part of their engineering thesis listed in bibliography [5,6,7,8,9,10,11,16,17,18], written under the supervision of the author of this article. They were done in real (not simulated) conditions during the sea voyages of ten different ships presented in Table 2, using AIS and radar equipment installed on these vessels and mentioned in this table too. The division of vessels into size categories was made conventionally by the author of the paper. For the analyses presented in this article, only measurement series were selected, during which both the own ship and the tracked vessel were proceeding with a steady course and constant speed without performing any manoeuvres. Any instabilities and errors of CPA and true vector indications were therefore caused only by inaccuracies in radar measurements and the influence of the current hydro meteorological conditions, mainly sea state, on the ship's movement.

Table 3 presents information on all ships tracked during measurements, their names, type, length, speed and distance to the own ship. They are grouped according to the type of meeting situation with own ship (parallel courses – overtaking, reciprocal courses and crossing courses) and to the size of the vessel from which the measurements were taken. The results of measurements during which both ships (own and observed) were at anchors are presented separately at the end of the Table 3. The state of the sea, expressed in degrees of the Douglas scale in the last column of this table, describes weather conditions during the test. Part of the measurements presented in this table is a repetition of information presented in the earlier publications mentioned in the bibliography [12-15].

During each test were recorded, simultaneously every 30 seconds, following parameters of the observed vessel indicated by AIS and ARPA: true bearing, distance, true course, true speed, CPA and time to reach CPA (TCPA). In order to meet the conditions of steady state tracking set out in the IMO resolution and the IEC standard, observed ships were tracked by ARPAs for at least 5 minutes before the beginning of registration and both vessels (own and opposite) did not take any manoeuvres at this time and later during the registration.

The terms and abbreviations used in Table 3 mean:

- Distance - distance between the ships (own and observed) during the measurement;
- L - the length of the observed vessel presented on the web-site;
- No/size category - consecutive number of the measurement series / ship size category;
- T - type of the ship indicated by AIS: B - bulk carrier, C - container vessel, CS – cargo ship, D - dredger, F - ferry boat, FV - fishing vessel, P -

passenger ship, RO – ro-ro vessel, SP – special purpose ship, T – tanker; and

– Sea state - state of the sea expressed in degrees of the Douglas scale, sw means swell.

Table 3. Ships observed during tests divided according to the meeting situation and size category of the vessel from which the measurements were conducted [5-18]

No/size category	Ship's name	T	L [m]	Speed [kn/m/s]	Distance [M/km]	Sea state
			Parallel courses - overtaking			
1/V	Belgian Express	C	180	13.0 / 6.7	1.0-0.7 / 1.9-1.3	4
2/V	China Peace	B	289	0 / 0	16.8-14.5 / 31.1-26.9	3
3/V	Lena River	T	290	0 / 0	6.7-3.4 / 12.4-6.3	2
4/V	Ocean Trader	CS	180	11.1 / 5.7	19.8-19.6 / 36.7-36.3	4
5/V	Regio Mar	FV	21	8.0 / 4.1	6.5-3.0 / 12.0-5.6	2
6/V	Tian Zhu Feng	B	225	10.8 / 5.6	16.8-16.4 / 31.1-30.4	7
7/L	F.D. Gennaro Aurilia	B	225	12.0 / 6.2	14.1-13.2 / 26.1-24.4	3
8/L	Hyundai Unity	C	294	13.3 / 6.8	9.3 / 17.2	3
9/L	Suez Vasilis	T	274	14.0 / 7.2	2.0-1.8 / 3.7-3.3	4
10/L	Thorco Raffles	CS	161.5	11.8 / 6.1	6.8-6.7 / 12.6-12.4	3
11/L	Creole Spirit	T	295	11.5 / 5.9	12.5-10.6 / 23.2-19.6	2
12/L	Lake Kivu	CS	182	15.5 / 8.0	8.7-8.2 / 16.1-15.2	2
13/M	Alexandra	CS	270	17.5 / 9.0	2.5-2.2 / 4.6-4.1	2
14/M	Celtic Ambasador	CS	88	9.1 / 4.7	13.4-12.4 / 24.8-23.0	5
15/M	Christopher	CS	171	15.1 / 7.8	1.8-1.6 / 3.3-3.0	5
16/M	Coral Meandra	T	91	11.1 / 5.7	1.5-1.4 / 2.8-2.6	4
17/M	Corcovado	CS	207	0.5 / 0.3	18.9-15.8 / 35.0-29.3	1
18/M	CSCL Jupiter	CS	366	18.2 / 9.4	3.6-2.6 / 6.7-4.8	3
19/M	Flinter Aland	CS	132	10.7 / 5.5	7.9-7.1 / 14.6-13.1	4
20/M	Heinrich	T	114	11.9 / 6.1	18.6-18.1 / 34.4-33.5	2
21/M	Histria Ivory	T	179	10.8 / 5.6	17.1-17.0 / 31.7-31.5	6
22/M	Navin Kestrel	CS	116	10.2 / 5.3	5.2-4.4 / 9.6-8.1	3
23/M	Pacific Heron	SP	88	4.8 / 2.5	9.0-7.8 / 16.7-14.4	1
24/M	Panther	CS	207	16.1 / 8.3	11.4-10.9 / 21.1-20.2	3
25/M	Union Ranger	CS	185	11.7 / 6.0	18.7-18.4 / 34.6-34.1	1
26/M	Varvara	CS	225	11.2 / 5.8	5.7-5.1 / 10.6-9.4	3
27/M	MSC India	CS	278	18.0 / 9.3	4.4-3.6 / 8.2-6.7	2
28/M	Grande Cotonou	CS	236	14.6 / 7.5	15.0-14.8 / 27.8-27.4	2
29/M	Lacerta	T	183	14.2 / 7.3	6.7-6.1 / 12.4-11.3	3
30/M	Anne	T	333	0.5 / 0.3	17.8-14.8 / 33.0-27.4	3
31/M	Mosvik	CS	82	5.7 / 2.9	1.2-0.7 / 2.2-1.3	5
32/M	SFC Don	T	183	11.9 / 6.1	1.0-0.9 / 1.9-1.7	5
33/M	Nordica Hav	CS	83	6.2 / 3.2	1.8-0.9 / 3.3-1.7	5
34/M	Sca Ortviken	RO	170	13.6 / 7.0	1.1-0.5 / 2.0-0.9	4
35/M	Iron Kovdor	B	225	11.3 / 5.8	4.1-3.9 / 7.6-7.2	4
36/M	Alexandra	FV	24	2.8 / 1.4	4.8-3.8 / 8.9-7.0	2
37/M	Shiosai	B	289	9.0 / 4.6	9.4-3.5 / 17.4-6.5	5
38/M	Maersk Columbus	C	299	17.0 / 8.7	20.4-18.9 / 37.8-35.0	1
39/M	Iver Bitumen	T	109	4.8 / 2.5	3.3-3.0 / 6.1-5.6	7
40/M	Oceana	P	261	18.2 / 9.4	24.4-23.8 / 45.2-44.1	1
41/M	Fuji Bay	CS	148	16.7 / 8.6	17.7-14.1 / 32.8-26.1	1
42/S	Britannia	P	329	17.0 / 8.7	4.1-2.2 / 7.6-4.1	1
43/S	Finnstar	P	219	22.7 / 11.7	6.4-0.5 / 11.9-0.9	4
44/S	Gilingham	CS	190	13.0 / 6.7	5.7-4.7 / 10.6-8.7	4
45/S	Hafnia Sea	CS	187	18.5 / 9.5	6.0-2.6 / 11.1-4.8	2
46/S	Kompozitor Rakhmaninov	CS	126	9.6 / 4.9	2.2-2.1 / 4.0-3.9	1
47/S	Navi Star	CS	110	11.5 / 5.9	1.8-1.7 / 3.3-3.1	1
48/S	Sea Explorer	CS	110	11.5 / 5.9	0.9-0.8 / 1.7-1.5	2
49/S	Beaumonde	CS	89	4.4 / 2.3	5.8-5.7 / 10.7-10.6	3
50/S	Ogino Park	CS	145	12.2 / 6.3	4.8-4.5 / 8.9-8.3	3
51/S	SSI Pride	CS	190	10.5 / 5.4	4.2-4.1 / 7.8-7.6	6
52/S	Pinnau	CS	88	10 / 5.1	2.8-2.7 / 5.2-5.0	3
53/S	John Friedrich K	CS	89	10.5 / 5.4	1.1-0.7 / 2.0-1.3	2
54/S	Abidjan EXpress	CS	222	18.5 / 9.5	5.2-5.0 / 9.6-9.3	3
55/S	Muflao	FV	16	0.9 / 0.5	3.5-2.0 / 6.5-3.7	2
56/S	Varkan Marmara	CS	100	5.7 / 2.9	1.1-0.7 / 2.0-1.3	5
57/S	Aldebaran	CS	90	9.2 / 4.7	1.0-0,7 / 1.8-1.3	2
58/S	Belmar	T	249	5.0 / 2.6	4.1-2.8 / 7.6-5.2	3
59/S	Fortuna	CS	87	9.0 / 4.6	0.7-0.5 / 1.3-0.9	3
60/S	Maersk Privilege	T	240	1.6 / 0.8	4.1-2.1 / 7.6-3.9	4
61/S	Stone	Tug	37	7.8 / 4.0	1.1-0.5 /2.0-0.9	3
			Reciprocal courses			
62/V	APL Vancuver	C	328	19.2 / 9.9	18.4-13.1 / 34.1-24.3	4
63/V	Jacamar Arrow	B	199	14.0 / 7.2	5.5-1.3 / 10.2-2.4	5
64/L	Cosco Jinggangshan	B	177	10.0 / 5.1	13.1-6.6 / 24.3-12.2	5
65/L	HSC	B	289	11.6 / 6.0	7.6-5.7 / 14.1-10.6	3

66/L	Maersk Cape Coast	C	249	15.0 / 7.7	6.5-2.6 / 12.0-4.8	1
67/L	NYK Altair	C	333	14.1 / 7.3	12.5 / 23.2	4
68/L	Port Shanghai	B	190	10.0 / 5.1	7.7-2.5 / 14.3-4.6	5
69/L	Varamo	C	166	25.3 / 13.0	6.9-1.2 / 12.8-2.2	4
70/L	Kota Buana	CS	180	11.1 / 5.7	11.6-5.3 / 21.5-9.8	3
71/L	Militos	T	274	12.4 / 6.4	5.4-2.7 / 10.0-5.0	3
72/M	Ara Antwerpen	CS	145	11.2 / 5.8	9.2-3.0 / 17.0-5.6	4
73/M	Beatriz B	CS	159	12.9 / 6.6	19.0-12.9 / 35.2-24.0	6
74/M	Bomar Resolute	CS	232	15.4 / 7.9	7.0-1.8 / 13.0-3.3	1
75/M	Eken	T	135	12 / 6,2	4.7-2.0 / 8.7-3.7	2
76/M	Gas Pasha	CS	96	9.3 / 4.8	14.1-8.4 / 26.1-15.6	3
77/M	Hoegh Shanghai	CS	229	9.2 / 4.7	17.1-11.3 / 31.7-20.9	2
78/M	Rome Trader	CS	179	14.4 / 7.4	19.5-12.6 / 36.1-23.3	2
79/M	Rome Trader	CS	179	14.4 / 7.4	10.1-3.4 / 18.7-6.3	2
80/M	Thorco Legion	CS	132	12.35 / 6.4	13.5-6.8 / 25.0-12.6	3
81/M	Cape Esmeralda	CS	127	11.3 / 5.8	14.2-10.6 / 26.3-19.6	3
82/M	Capella	T	185	13.2 / 6.8	4.4-3.0 / 8.1-5.6	3
83/M	Stena Germanica	F	240	16.6 / 8.5	7.4-0.9 / 13.7-1.7	5
84/M	Minerva Lisa	T	243	13.4 / 6.9	7.5-1.3 / 13.9-2.4	5
85/M	Arklov Brave	CS	120	12.3 / 6.3	6.7-4.6 / 12.4-8.5	4
86/M	Jing Lu Hai	B	225	12.5 / 6.4	5.7-4.3 / 10.6-8.0	4
87/M	Hong Yu	B	225	10.9/ 5.6	6.0-0.9 / 11.1-1.7	6
88/M	Luzon Strait	C	167	20.5 / 10.5	9.1-1.8 / 16.9-3.3	4
89/M	Aknoul	RO	122	13.5 / 6.9	6.2-4.6 / 11.5-8.5	1
90/M	LPG Barouda	T	115	9.8 / 5.0	11.0-4.2 / 20.4-7.8	2
91/M	Reggedijk	CS	90	10.0 / 5.1	9.3-7.4 / 17.2-13.7	2
92/S	Baltic Advance	T	182	11.1 / 5.7	10.9-1.4 / 20.2-2.6	3
93/S	Genco Thunder	CS	225	10.2 / 5.2	10.3-3.5 / 19.1-6.5	4
94/S	Seabourn Ovation	P	211	16.9 / 8.7	11.0-4.9 / 20.4-9.1	2
95/S	Tidan	CS	88	10.5 / 5.4	9.8-1.8 / 18.1-3.3	2
96/S	Clipper Point	CS	142	17.0 / 8.7	10.6-3.3 / 19.6-6.1	5
97/S	Emek S	CS	112	14.2 / 7.3	9.1-5.3 / 16.9-9.8	2
98/S	Sider Amy	CS	136	13.1 / 6.7	7.5-4.7 / 13.9-12.4	4
99/S	Tramaro Paris	CS	154	12.2 / 6.3	7.7-4.6 / 14.3-8.5	6
100/S	Drenec	CS	336	12.3 / 6.3	7.2-3.9 / 13.3-7.2	5
101/S	Anneleen Knutsen	T	187	6.7 / 3.4	4.9-1.0 / 9.1-1.9	1
102/S	Carten Elina	CS	102	10.2 / 5.2	6.3-1.7 / 11.7-3.1	4
103/S	Corinne	CS	74	9.5 / 4.9	5.8-1.0 / 10.7-1.9	1
104/S	Edmy	CS	86	9.9 / 5.1	8.6-3.7 / 15.9-6.9	2
105/S	Pluto	T	184	10.2 / 5.2	7.4-2.7 / 13.7-5.0	3
106/S	Samskip Frost	CS	86	13.2 / 6.8	5.2-1.1 / 9.6-2.0	2
107/S	Seapike	T	200	12.8 / 6.6	5.9-0.6 / 10.9-1.1	3
108/S	Stavangerfjord	P	170	14.5 / 7.5	8.7-2.6 / 16.1-4.8	4
			Crossing courses			
109/V	Bulk Switzerland	B	289	9.5 / 4.9	20.0-18.0 / 37.0-33.3	5
110/V	Free Neptune	CS	185	11.5 / 5.9	14.2-11.5 / 26.2-21.3	2
111/V	MSC Rachele	C	334	19.5 / 10.0	23.4-17.5 / 43.3-32.4	5
112/V	NCC Danah	T	183	13.5 / 6.9	5.6-3.3 / 10.4-6.1	7
113/V	OOCL Korea	C	366	15.8 / 8.1	5.7-1.6 / 10.6-3.0	7 sw
114/V	Spirit of Britain	F	213	23.5 / 12.1	9.1-8.3 / 16.9-22.4	3
115/L	Cap San Marco	C	333	20.0 / 10.3	4.3-2.7 / 8.0-5.0	4
116/L	Carnival Valor	P	292	18.2 / 9.4	3.4-2.9 / 6.3-5.4	4
117/L	Horncap	C	153	14.5 / 7.5	5.6-2.9 / 10.4-5.4	3
118/L	JS Columbia	B	199	14.4 / 7.4	16.7-12.8 / 30.9-23.7	2
119/L	Gpo Grace	CS	225	2.4 / 1.2	9.1-5.5 / 16.9-10.2	4sw
120/L	Rix Spring	D	82	2.3 / 1.2	3.9-2.4 / 7.2-4.4	3sw
121/M	Abis Calais	CS	115	9.4 / 4.8	16-13.7 / 29.6-25.4	4
122/M	Arklow Cadet	CS	87	10.6 / 5.4	6.7-4.3 / 12.4-8.0	3
123/M	Coral Lophelia	T	109	13.4 / 6.9	17.1-16.3 / 31.7-30.2	5
124/M	Ilyas Efendiyev	CS	140	8.4 / 4.3	9.6-4.9 / 17.8-9.1	2
125/M	Rio de Janeiro Express	CS	260	13.4 / 7.4	19.5-15.4 / 36.1-28.5	2
126/M	Sea Faith	T	182	12.8 / 6.6	10.9-7.7 / 20.2-14.3	3
127/M	Leon Poseidon	T	149	13.5 / 6.9	16.0-12.5 / 29.6-23.2	3
128/M	Lolland	F	100	12.3 / 6.3	2.8-0.9 / 5.2-1.7	8
129/M	Thun Gazelle	T	116	9.9 / 5.1	6.7-5.4 / 12.4-10.0	5
130/M	Washington Express	C	243	14.2 / 7.3	12.2-7.8 / 22.6-14.4	3
131/M	Sakura	B	196	11.2 / 5.8	10.9-10.1 / 20.2-18.7	3
132/M	Vienna Wood N	B	190	10.6 / 5.4	8.1-6.2 / 15.0-11.5	3
133/M	Arklow Vanguard	CS	87	11.3 / 5.8	6.9-3.1 / 12.8-5.7	2
134/M	Seastar Trojan	CS	179	12.3 / 6.3	15.9-14.3 / 29.4-26.5	6
135/M	Med Baltic	T	123	13.6 / 7.0	5.8-4.6 / 10.7-8.5	1
136/M	Nave Equinox	T	184	13.5 / 6.9	10.6-7.5 / 19.6-13.9	1
137/M	Pac Athena	CS	179	13.8 / 7.1	10.5-6.0 / 19.5-11.1	2
138/M	Melody Fair	CS	200	12.9 / 6.6	15.9-12.8 / 29.4-23.7	1
139/M	Nissos Schinoussa	T	254	7.9 / 4.1	9.5-7.5 / 17.6-13.9	1

140/M	Bomar Victory	C	179	7.2 / 3.7	21.8-20.5 / 40.4-38.0	2
141/M	Ocean Tianchen	B	199	2.2 / 1.1	6.1-5.1 / 11.3-9.4	7
142/M	Apl Le Havre	C	354	16.4 / 8.4	21.2-19.5 / 39.3-36.1	6
143/M	Salahuddi N	C	368	17.2 / 8.8	15.3-14.7 / 28.3-27.2	6
144/M	Bulk Beothuk	B	190	10.7 / 5.5	18.7-15.7 34.6-29.1	6
145/M	Atlantic Geneva	C	148	10.8 / 5.6	24.3-18.3 / 45.0-33.9	5
146/M	Green Ocean	CS	108	11.3 / 5.8	18.9-15.6 / 35.0-28.9	5
147/M	Am Gijon	B	292	10.6 / 5.5	20.0-19.1 / 37.0-35.4	5
148/M	Hestia Leader	RO	199	16.5 / 8.5	16.8-15.1 / 31.1-28.0	2
149/M	Volcan de Tijarafe	P	154	23.6 / 12.1	11.7-9.1 / 21.7-16.9	2
150/M	Brotonne Bridge	C	268	13.5 / 6.9	7.7-0.9 / 14.3-1.7	4
151/M	Genoa Express	C	228	11.1 / 5.7	10.3-9.7 / 19.1-18.0	5
152/S	Ekfjord	T	144	11.7 / 6.0	8.6-2.4 / 15.9-4.4	3
153/S	Freya	CS	118	17.5 / 9.0	8.8-5.8 / 16.3-10.7	1
154/S	John August Essberger	T	120	12.2 / 6.3	10.3-5.5 / 19.1-10.2	1
155/S	King Gregory	T	183	11.7 / 6.0	8.6-3.1 / 15.9-5.7	3
156/S	Jade	CS	190	12.6 / 6.5	5.2-1.5 / 9.6-2.8	3sw
157/S	Navion Stavanger	CS	277	13.5 / 6.9	11.9-6.1 / 22.0-11.3	5
158/S	Ionis	P	96	15.6 / 8.0	2.9-2.3 / 5.4-4.3	3
159/S	Tamara	CS	117	12.4 / 6.4	16.6-15.9 / 30.7-29.4	2
160/S	Floto SG 244	FV	18	2.8 / 1.4	2.9-0.5 / 5.4-0.9	3
161/S	Superspeed 1	P	26	25.5 / 13.1	4.0-1.8 / 7.4-3.3	3
Both ships at anchor						
162/M	Despina Angel	CS	169	0	1.2 / 2.2	3
163/M	Lacerta	T	183	0	1.7 / 3.2	3
164/M	Ridgebury Maryselena	T	274	0	1.0 / 1.8	3
165/M	Dylan	T	180	0	1.9 / 3.5	3

3 RESULTS OF THE MEASUREMENTS

Tables 4 and 5 present results of tests listed in Table 3 and conducted on ships mentioned in the Table 2. They contain information about mean values (M) and standard deviations (σ) of true motion vectors (true courses and true speeds) and CPA of observed vessels presented by AIS and ARPA in particular measurement series. Values of standard deviations exceeding their limits specified in Table 1 are printed in these tables in bold and are underlined.

Table 4. Results of tests conducted on ships. True course and true speed (95% probability figures) [own study]

No/size category	ARPA True course (TC)		True speed (TSp)		AIS True course (TC)		True speed (TSp)	
	M [°]	2σ [°]	M [kn / m/s]	2σ [kn / m/s]	M [°]	2σ [°]	M [kn / m/s]	2σ [kn / m/s]
Parallel courses – overtaking								
1/V	255.0	2.7	13.12 / 6.74	0,28 / 0.14	254.5	3.0	12.96 / 6.66	0.12 / 0.06
2/V	252.6	**142.7**	0.43 / 0.22	**1.30 /0.67**	265.3	**67.8**	0.00	0.00
3/V	202.5	**196.4**	0.00	0.00	353.7	3.2	0.06 / 0.03	0.10 / 0.05
4/V	026.7	**15.9**	11.36./ 5.84	**2.32 / 1.19**	026.0	**9.6**	11.14 / 5.73	0.28 / 0.14
5/V	248.7	3.3	8.34 / 4.29	0.16 / 0,08	246.0	4.1	8.06 / 4.14	0.34 / 0.17
6/V	264.5	**23.0**	11.06 / 5.68	**0.96 / 0.49**	264.1	**12.3**	10.86 / 5.58	0.44 / 0.23
7/L	094.3	**12.7**	11.96 / 6.15	**1.20 / 0.62**	092.9	4.1	11.96 / 6.15	0.10 / 0.05
8/L	086.0	1.9	13.38 / 6.88	**0.66 / 0.34**	085.4	1.4	13.31 / 6.84	0.08 / 0.04
9/L	084.4	1.5	14.98 / 7.70	0.22 / 0.11	082.5	1.3	14.05 / 7.22	0.10 / 0.05
10/L	160.7	1.9	11.65 / 5.99	0.26 / 0.13	161.7	**8.8**	11.8 / 6.07	0.44 / 0.23
11/L	187.1	**12.9**	11.48 / 5.90	**6.20 / 3.12**	188.3	**5.1**	11.51 / 5.92	**1.50 / 0.77**
12/L	023.5	**68.7**	19.01 / 9.77	**11.12 / 5.72**	039.0	0.3	15.46 / 7.95	0.10 / 0.05
13/M	029.6	1.0	17.44 / 8.96	0,30 / 0.15	029.4	1.0	17.48 / 8.98	0.34 / 0.17
14/M	206.9	**8.4**	9.17 / 4,71	0,28 /0.14	208.6	4.2	9.08 / 4.67	0.16 / 0.08
15/M	051.4	2.4	15.07 / 7.75	0,18 /0.09	051.1	4.5	15.09 / 7.76	0.28 / 0.14
16/M	061.1	0.5	11.10 / 5.71	0,12 / 0.06	060.9	0.9	11.10 / 5.71	0.10 / 0.05
17/M	189.3	**23.3**	0.50 / 0.26	0,16 / 0.08	149.7	**13.3**	0.52 / 0.27	0.10 / 0.05
18/M	035.2	4.3	18.22 / 9.37	**0,54 / 0.28**	034.7	2.9	18.19 / 9.35	0.16 / 0.08
19/M	211.2	2.0	10.73 / 5.52	0,38 / 0.20	210.9	1.1	10.69 / 5.49	0.22 / 0.11
20/M	347.1	3.8	12.06 / 6.20	**1.44 / 0.74**	346.9	3.3	11.87 / 6.10	0.42 / 0.22
21/M	194.6	4.6	10.69 / 5.49	**0.68 / 0.35**	194.2	4.5	10.86 / 5.58	0.46 / 0.24
22/M	242.6	2.8	10.24 / 5.26	0.30 / 0.15	242.7	1.1	10.25 / 5.27	0.12 / 0.06
23/M	250.8	3.4	4.72 / 2.43	0.30 / 0.15	249.2	1.9	4.78 / 2.46	0.08 / 0.04
24/M	179.3	2.7	16.18 / 8.32	0.42 / 0.22	179.4	1.9	16.13 / 8.29	0.22 / 0.11
25/M	140.7	4.0	11.79 / 6.06	**0.80 / 0.41**	139.2	1.8	11.65 / 5.99	0.20 / 0.10
26/M	252.9	1.3	11.30 / 5.81	**0.58 / 0.30**	253.6	1.2	11.21 / 5.76	0.08 / 0.04
27/M	244.8	1.8	17.96 / 9.23	**1.34 / 0.69**	247.3	0.9	18.00 / 9.25	0.10 / 0.05
28/M	072.2	0.6	14.51 / 7.46	**0.64 / 0.33**	072.5	1.1	14.57 / 7.49	0.16 / 0.08
29/M	236.5	1.0	14.15 / 27.53	0.38 / 0.20	236.9	0.7	14.23 / 7.31	0.16 / 0.08
30/M	062.6	**229.9**	0.49 / 0.25	0.48 / 0.25	060.2	**8.1**	0.48 / 0.25	**0.65 / 0.33**
31/M	247.3	3.1	5.65 / 2.90	**0.59 / 0.30**	248.7	**6.2**	5.66 / 2.91	**0.62 / 0.32**
32/M	248.9	1.2	11.88 / 6.11	0.31 / 0.16	248.9	2.0	11.81 / 6.07	0.15 / 0.08

33/M	251.6	2.0	6.18 / 3.18	**0.54 / 0.28**	251.3	**5.3**	6.19 / 3.18	0.40 / 0.21
34/M	253.7	3.4	13.60 / 6.99	0.41 / 0.21	252.7	2.8	13.50 / 6.94	0.21 / 0.11
35/M	210.7	1.7	11.25 / 5.78	0.39 / 0.20	210.6	3.1	11.21 / 5.76	0.22 / 0.11
36/M	097.6	4.1	2.81 / 1.44	0.15 / 0.08	094.5	**7.6**	2.89 / 1.49	0.20 / 0.10
37/M	024.4	4.0	9.09 / 4.68	0.47 / 0.24	033.0	1.0	8.95 / 4.60	0.10 / 0.05
38/M	111.9	**12.8**	17.71 / 9.10	**2.62 / 1.35**	108.6	1.6	16.96 / 8.72	0.10 / 0.05
39/M	256.6	**10.1**	4.83 / 2.48	**1.18 / 0.61**	254.4	**14.3**	4.79 / 2.46	**0.95 / 0.49**
40/M	076.5	3.1	21.21 / 10.90	**7.80 / 4.01**	078.7	1.3	18.24 / 9.38	0.26 / 0.13
41/M	262.6	**6.5**	16.79 / 8.63	**1.61 / 0.83**	263.9	2.9	16.72 / 8.59	0.27 / 0.14
42/S	037.1	3.1	17.00 / 8.74	0.18 / 0.09	037.5	2.0	17.00 / 8.74	0.16 / 0.08
43/S	249.8	0.6	22.80 / 11.7	0.36 / 0.19	249.6	1.1	22.70 / 11.67	0.16 / 0.08
44/S	034.3	1.8	13.0 / 6.68	0.16 / 0.08	033.9	1.8	13.00 / 6.68	0.12 / 0.06
45/S	051.1	0.8	18.5 / 9.51	0.34 / 0.17	051.1	1.0	18.40 / 9.46	0.34 / 0.17
46/S	231.5	0.3	9.71 / 4.99	**1.2 / 0.62**	231.6	0.9	9.60 / 4.93	0.14 / 0.07
47/S	034.8	1.8	11.50 / 5.91	**1.5 / 0.78**	034.8	2.0	11.50 / 5.91	0.18 / 0.09
48/S	061.0	2.4	11.60 / 5.96	0.40 / 0.21	060.9	1.8	12.00 / 6.17	0.18 / 0.09
49/S	085.7	4.1	4.33 / 2.23	**0.64 / 0.33**	085.5	2.0	4.38 / 2.25	0.09 / 0.05
50/S	359.4	1.3	12.20 / 6.27	0.26 / 0.13	000.1	1.0	12.17 / 6.26	0.14 / 0.07
51/S	029.0	2.8	10.61 / 5.45	**0.60 / 0.31**	028.7	5.0	10.46 / 5.38	0.45 / 0.23
52/S	289.6	1.1	10.00 / 5.14	0.28 / 0.15	289.6	1.3	10.00 / 5.14	0.12 / 0.06
53/S	250.5	0.7	10.65 / 5.47	0.41 / 0.21	250.8	1.7	10.49 / 5.39	0.38 / 0.20
54/S	208.0	0.8	18.38 / 9.45	**0.76 / 0.39**	207.7	1.4	18.44 / 9.48	0.21 / 0.11
55/S	Variable	-	0.88 / 0.45	**0.86 / 0.44**	Variable	-	0.54 / 0.28	0.42 / 0.22
56/S	102.6	2.7	5.70 / 2.93	**1.37 / 0.70**	103.3	3.0	5.66 / 2.91	**1.70 / 0.87**
57/S	083.3	1.3	9.20 / 4.73	0.20 / 0.10	082.9	1.4	9.19 / 4.72	0.12 / 0.06
58/S	159.3	**13.1**	5.03 / 2.59	**3.40 / 1.75**	160.1	3.7	4.97 / 2.55	0.15 / 0.08
59/S	166.9	**18.2**	9.11 / 4.68	**0.63 / 0.32**	166.9	**18.0**	9.03 / 4.64	0.29 / 0.15
60/S	155.4	**147.0**	0.53 / 0.27	0.45 / 0.23	120.6	**125.7**	0.17 / 0.09	0.18 / 0.09
61/S	158.7	3.5	7.80 / 4.01	0.28 / 0.14	158.9	2.7	7.78 / 4.00	0.23 / 0.12
				Reciprocal courses				
62/V	068.4	**7.1**	19.26 / 9.90	**2.98 / 1.53**	068.7	1.4	19.17 / 9.85	0.22 / 0.11
63/V	207.8	1.2	14.03 / 7.21	0.28 / 0.14	204.9	1.1	13.99 / 7.19	0.14 / 0.07
64/L	232.2	**5.3**	11.16 / 5,74	0.22 / 0.11	232.7	2.4	11.14 / 5.73	0.12 / 0.06
65/L	040.7	1.3	11.73 / 6.03	0.38 / 0.20	042.6	1.2	11.52 / 5.92	0.16 / 0.08
66/L	236.6	1.2	15.54 / 7.99	0.50 / 0.26	237.1	1.0	15.43 / 7.93	0.18 / 0,09
67/L	054.2	3.1	14.62 / 7.51	**0.72 / 0.37**	052.1	1.0	14.11 / 7.25	0.08 / 0.04
68/L	229.6	1.5	10.39 / 5.34	0.24 / 0.12	234.5	1.8	10.18 / 5.23	0.12 / 0.06
69/L	321.3	1.4	13.10 / 6.73	0.30 / 0.15	322.5	2.2	13.07 / 6.72	0.44 / 0.23
70/L	163.0	**17.7**	11.91 /6.12	**1.18 / 0.61**	160.3	**10.2**	11.12 / 5.72	0.28 / 0.14
71/L	139.6	2.1	12.38 /6.36	0.48 / 0.25	139.5	2.1	12.42 / 6.38	0.13 / 0.07
72/M	232.9	2.4	11.28 / 5.80	**0.64 / 0.33**	231.4	1.6	11.20 / 5.76	0.16 / 0.08
73/M	009.2	4.4	13.06 / 6.71	**1.00 / 0.51**	011.1	1.3	12.78 / 6.57	0.26 / 0.13
74/M	312.5	**6.1**	15.57 / 8.00	**0.58 / 0.30**	314.6	1.9	15.43 / 7.93	0.16 / 0.08
75/M	221.1	0.9	12.57 / 6.46	**1.50 / 0.77**	220.4	1.1	12.12 / 6.23	0.16 / 0.08
76/M	207.2	2.5	9.31 / 4.79	**0.54 / 0.28**	209.1	1.3	9.30 / 4.78	0.16 / 0.08
77/M	180.9	**7.4**	9.33 / 4.80	0.46 / 0.24	181.2	1.5	9.23 / 4.74	0.08 /0.04
78/M	179.2	4.1	14.47 / 7.44	0.48 / 0.25	181.6	1.6	14.34 / 7.37	0.16 / 0.08
79/M	178.9	2.8	14.39 / 7.40	0.26 / 0.13	181.7	1.4	14.25 / 7.32	0.12 / 0.06
80/M	032.2	**7.8**	12.39 / 6.37	0.22 / 0.11	032.0	1.2	12.39 / 6.37	0.10 / 0.05
81/M	326.8	3.8	11.86 / 6.10	**0.65 / 0.33**	329.1	2.5	11.26 / 5.79	0.17 / 0.09
82/M	091.2	3.3	13.47 / 6.92	**0.85 / 0.44**	091.9	0.8	13.20 / 6.78	0
83/M	208.7	1.7	16.60 / 8.53	**0.56 / 0.29**	210.1	1.6	16.41 / 8.43	0.25 / 0.13
84/M	208.8	2.2	13.42 / 6.90	0.45 / 0.23	209.3	1.0	13.30 / 6.84	0.10 / 0.05
85/M	026.0	1.4	12.25 / 6.30	0.49 / 0.25	027.9	3.1	12.10 / 6.22	0.16 / 0.08
86/M	021.1	1.4	12.54 / 6.45	**0.54 / 0.28**	023.3	3.1	12.40 / 6.38	0.21 / 0.11
87/M	030.5	0.7	10.87 / 5.59	0.17 / 0.32	031.7	0.9	10.80 / 5.55	0.13 / 0.24
88/M	071.4	1.7	20.48 / 10.53	0.35 / 0.18	069.7	2.6	20.37 / 10.47	0.46 / 0.24
89/M	037.1	1.9	13.58 / 6.98	**0.66 / 0.34**	043.3	1.8	13.54 / 6.96	0.21 / 0.11
90/M	104.4	1.2	9.83 / 5.05	0.13 / 0.07	109.6	1.8	9.84 / 5.06	0.16 / 0.08
91/M	078.5	1.0	10.40 / 5.35	**1.2 / 0.62**	077.9	4.8	10.0 / 5.14	0.14 / 0.07
92/S	058.7	1.6	11.30 / 5.81	**1.14 / 0.59**	058.3	0.9	11.11 / 5.71	**0.80 / 0.41**
93/S	070.9	0.7	10.30 / 5.29	0.28 / 0.14	070.2	0.4	10.20 / 5.24	0.1 / 0.05
94/S	037.5	1.2	17.05 / 8.76	**0.56 / 0.29**	037.3	0.7	16.90 / 8.69	0.24 / 0.12
95/S	268.1	0.8	10.58 / 5.44	0.28/0.14	268.8	0.6	10.45 / 5.37	0.10 / 0.05
96/S	099.2	2.2	17.00 / 8.74	**0.83/0.43**	098.9	1.7	16.86 / 8.67	**0.63 / 0.32**
97/S	214.7	2.5	14.17 / 7.28	**0.57/0.29**	216.4	1.7	14.20 / 7.30	0.05 / 0.03
98/S	017.9	1.4	12.97 / 6.67	0.48/0.25	016.3	3.6	13.14 / 6.75	0.24 / 0.12
99/S	284.3	2.0	12.05 / 6.19	**0.75/0.39**	285.6	2.0	12.20 / 6.27	0.39 / 0.20
100/S	033.7	2.5	12.21 / 6.28	**1.12/0.58**	035.8	0.5	12.30 / 6.32	0
101/S	270.7	3.5	7.06 / 3.63	**1.28/0.66**	269.5	1.3	6.72 / 3.45	0.10 / 0.05
102/S	045.4	4.3	11.0 / 5.65	**0.74 / 0.38**	043.3	1.7	10.21 / 5.25	**3.43 / 1.76**
103/S	226.3	**5.5**	9.60 / 4.93	0.35 / 0.18	224.8	1.3	9.51 / 4.89	0.18 / 0.09
104/S	053.2	**6.0**	9.88 / 5.08	0.30 / 0.15	050.8	1.1	9.87 / 5.07	0.14 / 0.07
105/S	041.6	4.4	10.38 / 5.34	0.22 / 0.11	034.5	1.0	10.18 / 5.23	0.12 / 0.06
106/S	285.5	4.7	13.27 / 6.82	0.35 / 0.18	284.8	1.5	13.18 / 6.77	0.27 / 0.14

107/S	148.8	4.1	12.80 / 6.58	**0.82 / 0.42**	147.1	2.4	12.77 / 6.56	0.26 / 0.13
108/S	132.6	3.6	14.40 / 7.40	**0.60 / 0.31**	130.7	3.3	14.46 / 7.43	0.30 / 0.15
Crossing courses								
109/V	084.6	**12.5**	9.62 / 4.94	**3.94 / 2.03**	084.2	**8.7**	9.53 / 4.90	0.22 / 0.11
110/V	025.9	**11.4**	11.49 / 5.91	**0.56 / 0.29**	024.8	1.2	11.48 / 5.90	0.20 / 0.10
111/V	289.4	**16.4**	20.11 / 10.34	**7.82 / 4.02**	289.7	1.4	19.72 / 10.14	0.14 / 0.07
112/V	087.5	3.1	13.69 / 7.04	0.38 / 0.20	087.8	**7.6**	13.56 / 6.97	0.40 / 0.21
113/V	270.5	1.3	15.97 / 8.21	**0.60 / 0.31**	270.5	2.2	15.96 / 8.20	0.38 / 0.20
114/V	118.4	**5.8**	23.14 / 11.89	**0.90 / 0.46**	114.7	**7.3**	23.50 / 12.01	0.48 / 0.25
115/L	198.8	0.5	20.43 / 10.50	0.36 / 0.19	202.0	0.5	20.05 / 10.31	0.14 / 0.07
116/L	130.0	1.3	18.38 / 9.45	**0.52 / 0.27**	130.0	1.1	18.16 / 9.33	0.12 / 0.06
117/L	017.8	1.1	14.32 / 7.36	0.32 / 0.16	019.6	1.6	14.60 / 7.50	0.12 / 0.06
118/L	033.1	2.5	13.84 / 7.11	**0.70 / 0.36**	034.4	3.1	14.29 / 7.35	0.16 / 0.08
119/L	158.8	**16.2**	2.56 / 1.32	**0.72 / 0.37**	161.2	**6.6**	2.44 /1.25	**0.52 / 0.27**
120/L	030.9	**16.9**	9.58 / 4.92	**2.11 / 1.08**	028.3	2.1	9.48 /4.87	0.30 / 0.15
121/M	166.9	1.9	9.55 / 4.91	**0.92 / 0.47**	165.9	2.5	9.40 / 4.83	0.22 / 0.11
122/M	298.0	2.5	10.62 / 5.46	0.28 / 0.14	297.4	3.8	10.49 / 5.39	0.18 / 0.09
123/M	215.4	**9.4**	13.12 / 6.74	**2.40 / 1.23**	216.9	1.9	13.45 / 6.91	0.20 / 0.10
124/M	269.0	**5.8**	8.55 / 4.39	**0.84 / 0.43**	268.8	2.0	8.44 / 4.34	0.12 / 0.06
125/M	083.5	2.3	14.56 / 7.48	**0.70 / 0.36**	083.6	0.8	14.46 / 7.43	0.10 / 0.05
126/M	310.6	0.6	12.83 / 6.59	0.42 / 0.22	311.2	1.4	12.80 / 6.58	0.17 / 0.09
127/M	324.9	3.5	13.55 / 6.96	**0.59 / 0.30**	324.6	3.8	13.52 / 6.95	0.07 / 0.04
128/M	126.7	**6.2**	12.27 / 6.31	**1.17 / 0.60**	125.1	3.9	11.84 / 6.09	0.21 / 0.11
129/M	349.7	1.3	9.86 / 5.09	0.14 / 0.07	351.3	1.3	9.74 / 5.01	0.20 / 0.10
130/M	290.4	2.0	14.16 / 7.29	**0.76 / 0.39**	290.9	1.3	14.43 / 7.42	0.34 / 0.17
131/M	116.4	1.5	11.20 / 6.27	0.37 /0.19	116.1	1.5	11.21 / 5.76	0.08 / 0.04
132/M	107.8	1.6	10.56 / 5.43	0.31 /0.16	108.6	0.9	10.78 / 5.54	0.07 / 0.04
133/M	200.5	1.9	11.32 / 5.82	0.44 / 023	202.4	0.9	10.96 / 5.63	0.11 / 0.06
134/M	116.6	**6.3**	12.63 / 6.49	**2.08 / 1.10**	117.6	1.7	12.27 / 6.31	0.40 / 0.21
135/M	005.7	**6.3**	14.03 / 7.21	**0.66 / 0.34**	009.6	**6.5**	13.57 / 6.97	0.09 / 0.05
136/M	074.3	**9.1**	13.60 / 6.99	**0.65 / 0.33**	075.1	1.0	13.48 / 6.93	0.18/ 0.09
137/M	266.2	2.3	13.52 / 6.95	**0.83 / 0.43**	270.3	1.8	13.77 / 7.08	0.10 / 0.05
138/M	253.1	**9.6**	11.95 / 6.14	**3.04 / 1.56**	263.1	1.0	12.92 / 6.64	**0.56 / 0.29**
139/M	290.3	4.2	6.63 / 3.41	**2.08 / 1.07**	294.0	1.3	7.87 / 4.05	**0.76 / 0.39**
140/M	129.5	2,0	7.36 / 3.78	0.10 / 0.05	123.7	2.6	7.15 / 3.68	0.13 / 0.07
141/M	201.4	**89.52**	2.44 / 1.25	**1.79 / 0.92**	210.9	**51.9**	2.23 / 1.15	**1.67 / 0.86**
142/M	265.8	**38.8**	17.49 / 8.99	**11.66 / 5.99**	257.8	**34.3**	16.37 / 8.41	**10.16 / 5.22**
143/M	076.1	**17.1**	17.63 / 9.06	**8.51 / 4.37**	080.4	4.0	17.18 / 8.83	**0.64 / 0.33**
144/M	088.9	**54.1**	10.47 / 5.38	**5.91 / 3.04**	079.8	**9.1**	10.69 / 5.49	0.42 / 0.22
145/M	059.7	**122.3**	13.40 / 6.89	**10.50 / 5.40**	033.8	**9.62**	10.83 / 5.57	**1.69 / 0.87**
146/M	086.2	**34.7**	12.16 / 6.25	**14.47 / 7.44**	085.4	**5.5**	11.32 / 5.82	0.33 / 0.17
147/M	093.7	**101.2**	10.59 / 5.44	**16.23 / 8.34**	081.7	**9.4**	10.55 / 5.42	0.40 / 0.21
148/M	208.9	5	16.33 / 8.39	**2.98 / 1.53**	210.4	4.0	16.47 / 8.47	0.13 / 0.07
149/M	097.0	3.1	23.72 / 12.19	**1.00 / 0.51**	099.2	2.7	23.62 / 12.14	0.29 / 0.15
150/M	252.6	3.3	13.35 / 6.86	0.29 / 0.15	256.0	3.2	13.47 / 6.92	0.13 / 0.07
151/M	105.6	4.8	11.56 / 5.94	**0.56 / 0.29**	107.1	1.4	11.14 / 5.73	0.15 / 0.08
152/S	237.7	1.0	11.86 / 6.10	0.22 / 0.11	238.5	1.1	11.62 / 5.97	0.08 / 0.04
153/S	017.3	2.4	17.60 / 9.05	**0.60 / 0.31**	017.7	0.1	17.50 / 9.00	0.16 / 0.08
154/S	015.8	3.2	12.20 / 6.27	0.44 / 0.23	016.6	0.9	12.17 / 6.27	0.18 / 0.09
155/S	254.2	2.4	11.90 / 6.12	**1.58 / 0.81**	255.2	0.8	11.70 / 6.01	0.28 / 0.14
156/S	066.5	**8.5**	12.84 / 6.60	**0.53 / 0.27**	064.9	**6.5**	12.69 / 6.52	0.19 / 0.10
157/S	252.2	2.4	13.58 / 6.98	**0.73 / 0.38**	251.0	2.8	13.70 / 7.04	0.41 / 0.21
158/S	050.6	**140.8**	16.03 / 8.24	**12.15 / 6.25**	032.3	**10.7**	15.60 / 8.02	0.13 / 0.07
159/S	313.7	**15.6**	12.39 / 6.37	**1.73 / 0.89**	314.5	1.5	12.38 / 6.36	0.13 / 0.07
160/S	205.9	2.3	2.91 / 1.50	**1.03 / 0.53**	206.4	**6.7**	2.79 / 1.43	0.08 / 0.04
161/S	183.5	1.3	25.12 / 12.91	**0.60 / 0.31**	182.3	0.5	25.5 / 13.11	0.21 / 0.11
Both ships at anchor								
162/M	1.21/2.24	0.01/0.02	0.12 / 0.06	0.12 / 0.06	1.23 / 2.28	0.01/0.02	0	0
163/M	1.72/3.19	0.02/0.04	0.25 / 0.13	0.35 / 0.18	1.69 / 3.13	0.07/0.13	0.06 / 0.04	0.09 / 0.05
164/M	0.99/1.83	0.02/0.04	0.28 / 0.14	0.21 / 0.11	1.00 / 1.85	0.05/0.09	0.43 / 0.22	0.45 / 0.23
165/M	1.87/3.46	0.01/0.02	0.27 / 0.14	0.33 / 0.17	1.83 / 3.39	0.01/0.02	0	0

Table 5. Results of tests conducted on ship's. CPA (95% probability figures) [own study]

No/size category	CPA (ARPA) Mean value [M / km]	2σ [M / km]	CPA (AIS) Mean value [M / km]	2σ [M / km]
Parallel courses - overtaking				
1/V	0.69 / 1.28	0.04 / 0.07	0.67 / 1.24	0.04 / 0.07
2/V	4.50 / 8.33	**1.74 / 3.22**	4.38 / 8.11	**0.74 / 1.37**
3/V	0.68 / 1.26	0.02 / 0.04	0.69 / 1.28	0.04 / 0.07
4/V	17.18 / 31.82	**5.20 / 9.63**	15.71 / 29.09	**6.12 / 11.33**
5/V	2.65 / 4.91	0.14 / 0.26	2.58 / 4.78	0.12 / 0.22
6/V	11.31 / 20.95	**8.68 / 16.08**	9.99 / 18.50	**7.04 / 13.04**
7/L	6.72 / 12.45	**5.82 / 10.78**	7.66 / 14.19	**1.60 / 2.96**
8/L	9.25 / 17.13	0.06 / 0.11	9.18 / 17.00	0.06 / 0.11

9/L	1.64 / 3.04	0.18 / 0.33	1.45 / 2.69	0.16 / 0.30
10/L	6.27 / 11.61	**2.35 / 4.35**	6.33 / 11.72	0.27 / 0.50
11/L	7.79 / 14.43	**3.93 / 7.28**	8.38 / 15.52	**0.99 / 1.83**
12/L	6.01 / 11.13	**5.73 / 10.62**	1.38 / 2.56	**0.94 / 1.74**
13/M	2.11 / 3.91	0.16 / 030	2.07 / 3.83	0.18 / 0.33
14/M	2.29 / 4.24	**3.04 / 5.63**	2.15 / 3.98	**1.42 / 2.63**
15/M	1.54 / 2.85	0.24 / 0.44	1.44 / 2.67	**0.42 / 0.78**
16/M	1.17 / 2.17	0.20 / 0.37	1.21 / 2.24	0.20 / 0.37
17/M	2.70 / 5.00	**0.42 / 0.78**	2.65 / 4.91	**0.36 / 0.67**
18/M	1.62 / 3.00	**0.48 / 0.89**	1.56 / 2.89	**0.56 / 1.04**
19/M	2.65 / 4.91	**1.20 / 2.22**	2.83 / 5.24	**0.70 / 1.30**
20/M	11.31 / 20.95	**5.24 / 9.70**	11.17 / 20.69	**3.94 / 7.30**
21/M	15.71 / 29.09	**4.64 / 8.59**	15.27 / 28.28	**4.52 / 8.37**
22/M	2.39 / 4.43	**0.64 / 1.19**	2.41 / 4.46	0.28 / 0.52
23/M	6.81 / 12.61	0.22 / 0.41	6.79 / 2.58	0.16 / 0.30
24/M	4.70 / 8.70	**3.42 / 6.33**	4.68 / 8.67	**2.54 / 4.70**
25/M	8.47 / 15.69	**7.52 / 13.93**	9.21 / 17.06	**9.32 / 17.26**
26/M	0.47 / 0.87	**0.82 / 1.52**	0.32 / 0.59	**0.34 / 0.63**
27/M	1.57 / 2.91	**0.63 / 1.17**	1.71 / 3.17	**0.31 / 0.57**
28/M	12.46 / 23.08	**2.19 / 4.06**	11.85 / 21.95	**1.68 / 3.11**
29/M	3.89 / 7.20	**0.68 / 1.26**	3.87 / 7.17	0.28 / 0.52
30/M	8.99 / 16.65	**0.75 / 1.39**	8.94 / 16.56	**0.61 / 1.13**
31/M	0.72 / 1.33	0.02 / 0.04	0.70 / 1.30	0.06 / 0.11
32/M	0.98 / 1.81	0.05 / 0.09	0.92 / 1.70	0.10 / 0.18
33/M	0.81 / 1.50	0.18 / 0.33	0.75 / 1.40	0.21 / 0.39
34/M	0.55 / 1.02	0.21 / 0.39	0.49 / 091	0.18 / 0.33
35/M	2.46 / 4.56	**1.32 / 2.44**	2.38 / 4.41	**1.54 / 0.79**
36/M	3.44 / 6.37	0.07 / 0.13	3.34 / 6.19	0.16 / 0.30
37/M	1.84 / 3.41	0.27 / 0.50	1.90 / 3.52	0.17 / 0.31
38/M	6.22 / 11.52	**7.42 / 13.74**	1.86 / 3.44	**2.26 / 4.19**
39/M	1.68 / 3.11	**2.10 / 3.89**	1.81 / 3.35	**2.22 / 4.11**
40/M	23.84 / 44.15	0.22 / 0.41	23.90 / 44 26	0.14 / 0.26
41/M	11.13 / 20.61	**1.47 / 2.72**	11.25 / 20.84	**0.71 / 1.32**
42/S	1.94 / 3.59	**0.36 / 0.67**	1.90 / 3.52	0.22 / 0.41
43/S	0.46 / 0.85	0.11 / 0.20	0.45 / 0.83	0.14 / 0.30
44/S	1.11 / 2.06	**0.64 / 1.19**	0.63 / 1.17	**0.92 / 1.70**
45/S	0.53 / 0.98	0.02 / 0.04	0.80 / 1.48	0,16 / 0.30
46/S	1.08 / 2.00	**1.89 / 3.50**	1.36 / 2.52	**0.96 / 1.78**
47/S	0.85 / 1.57	**1.43 / 2.65**	0.92 / 1.70	**1.24 / 2.30**
48/S	0.77 / 1.43	0.02 / 0.04	0.80 / 1.48	0.14 / 0.26
49/S	5.65 / 10.46	0.04 / 0.07	5.66 / 10.48	0.03 / 0.06
50/S	2.37 / 4.39	**2.32 / 4.30**	2.77 / 5.13	**1.64 / 3.04**
51/S	3.72 / 6.89	**0.78 / 1.45**	3.64 / 6.74	**0.90 / 1.67**
52/S	2.66 / 4.93	0.03 /0.06	2.68 / 4.96	0.02 / 0.04
53/S	0.63 / 1.17	0.11 / 0.20	0.64 / 1.19	0.11 / 0.20
54/S	5.02 / 9.30	0.07 / 0.13	5.02 / 9.30	0.09 / 0.17
55/S	1.93 / 3.57	0.14 / 0.26	1.92 / 3.56	0.17 / 0.32
56/S	0.65 / 1.20	0.06 / 0.11	0.66 / 1.22	0.13 / 0.24
57/S	0.67 / 1.24	0.30 / 0.56	0.71 / 1.31	0.19 / 0.35
58/S	0.61 / 1.13	**0.64 / 1.19**	0.52 / 0.96	**0.40 / 0.74**
59/S	0.57 / 1.06	0.22 / 0.41	0.55 / 1.02	0.22 / 0.41
60/S	1.60 / 2.96	**0.32 / 0.59**	1.59 / 2.94	0.23 / 0.43
61/S	0.30 / 0.56	0.20 /0.37	0.29 / 0.54	0.16 / 0.30
Reciprocal courses				
62/V	9.76 / 18.08	**1.14 / 2.11**	9.81 / 18.17	0.20 / 0.37
63/V	1.11 / 2.06	0.04 / 0.07	1.11 / 2.06	0.08 / 0.15
65/L	3.34 / 6.19	**0.38/ 0.70**	2.95 / 5.46	0.22 / 0.41
65/L	5.55 / 10.28	0.12 / 0.22	5.48 / 10.15	0.08 / 0.15
66/L	2.13 / 3.94	0.10 / 0.19	2.05 / 3.80	0.08 / 0.15
67/L	11.13 / 20.61	**4.54 / 8.41**	6.13 / 11.35	**6.48 / 12.00**
68/L	2.38 / 4.41	0.04 / 0.07	2.19 / 4.06	0.18 / 0.33
69/L	1.15 / 2.13	0.04 / 0.07	1.28 / 2.37	0.16 / 0.30
70/L	1.16 / 2.15	**1.11 / 2.06**	1.09 / 2.02	**0.63 / 1.17**
71/L	2.67 / 4.94	0.08 / 0.15	2.70 / 5.00	0.09 / 0.17
72/M	1.22 / 2.26	0.18 / 0.33	1.17 / 2.17	0.16 / 0.30
73/M	3.38 / 6.26	**0.94 / 1.74**	3.35 / 6.20	0.26 / 0.48
74/M	1.64 / 3.04	**0.42 / 0.78**	1.64 / 3.04	0.12 / 0.22
75/M	0.36 / 0.67	0.06 / 0.11	0.36 / .67	0.04 / 0.07
76/M	1.45 / 2.69	0.22 / 0.41	1.54 / 2.85	0.16 / 0.30
77/M	1.83 / 3.39	**0.82 / 1.52**	1.98 / 3.67	0.28 / 0.52
78/M	1.36 / 2.52	**0.60 / 1.11**	1.36 / 2.52	**0.42 / 0.78**
79/M	1.36 / 2.52	**0.32 / 0.59**	1.37 / 2.54	0.10 / 0.19
80/M	2.27 / 4.20	**0.64 / 1.19**	2.39 / 4.43	0.12 / 0.22
81/M	9.30 / 17.22	0.19 / 0.35	9.63 / 17.83	0.14 / 0.26
82/M	1.75 / 3.24	0.09 / 0.17	1.74 / 3.22	0.03 / 0.06

83/M	0.66 / 1.22	0.11 / 0.20	0.66 / 1.22	0.10 / 0.19
84/M	0.70 / 1.30	0.12 / 0.22	0.69 / 1.28	0.08 / 0.15
85/M	4.66 / 8.63	0.05 / 0.09	4.61 / 8.54	0.10 / 0.19
86/M	4.36 / 8.08	0.04 / 0.07	4.31 / 7.98	0.06 / 0.11
87/M	0.73 / 1.35	0.06 / 0.11	0.74 / 1.37	0.08 / 0.15
88/M	1.24 / 2.30	0.20 / 0.37	1.24 / 2.30	0.30 / 0.56
89/M	3.66 / 6.78	0.12 / 0.22	3.66 / 6.78	0.11 / 0.20
90/M	1.80 / 3.33	0.17 / 0.31	1.91 / 3.54	0.14 / 0.26
91/M	7.38 / 13.67	0.18 / 0.33	7.39 / 13.69	0.10 / 0.19
92/S	1.37 / 2.54	0.19 / 0.36	1.2 / 2.22	0.06 / 0.11
93/S	3.50 / 6.48	0.04 / 0.07	3.50 / 6.48	0.08 / 0.15
94/S	5.02/ 9.30	0.08 / 0.15	5.01 / 9.28	0.24 / 0.44
95/S	1.81 / 3.35	**0.94 / 1.74**	1.69 / 3.13	0.01 / 0.02
96/S	1.42 / 2.63	0.19 / 0.35	1.41 / 2.61	0.16 / 0.30
97/S	5.26 / 9.74	0.13 / 0.24	5.62 / 10.41	0.11 / 0.20
98/S	4.69 / 8.69	0.13 / 0.24	4.69 / 8.69	0.14 / 0.26
99/S	4.52 / 8.37	0.10 / 0.19	4.56/ 8.45	0.11 / 0.20
100/S	3.86 / 7.15	0.12 / 0.22	3.88 / 7.19	0.08 / 0.15
101/S	0.67 / 1.24	0.17 / 0.31	0.71 / 1.31	0.09 /0.17
102/S	0.56 / 1.04	0.24 / 0.44	0.53 / 0.98	0.14 / 0.26
103/S	0.50 / 0.93	0.26 / 0.48	0.49 / 0.91	0.05 / 0.09
104/S	1.02 / 1.89	**0.38 / 0.70**	1.07 / 1.98	0.06 / 0.11
105/S	1.01 / 1.87	0.28 / 0.52	0.91 / 1.69	0.13 / 0.24
106/S	0.53 / 0.98	0.25 / 0.46	0.55 / 1.11	0.05 / 0.09
107/S	0.61 / 1.13	0.12 / 0.22	0.64 / 1.19	0.07 / 0.13
108/S	1.08 / 2.00	0.26 / 0.48	1.07 / 1.98	0.27 / 0.50
Crossing courses				
109/V	17.18 / 31.82	**0.76 / 1.41**	17.19 / 31.84	**0.50 / 0.93**
110/V	9.43 / 17.46	**1.22 / 2.26**	9.48 / 17.56	0.16 / 0.30
111/V	3.85 / 7.13	**4.64 / 8.59**	3.65 / 6.76	0.30 / 0.56
112/V	2.97 / 5.50	0.26 / 0.48	2.92 / 5.41	0.22 / 0.41
113/V	1.51 / 2.80	0.12 / 0.22	1.47 / 2.72	0.16 / 0.30
114/V	8.28 / 15.33	0.06 / 0.11	8.25 /15.28	0.06 / 0.11
115/L	2.60 / 4.82	0.04 / 0.07	2.54 / 4.70	0.10 / 01.9
116/L	2.90 / 5.37	0.02 / 0.04	2.79 / 5.17	0.04 / 0.07
117/L	2.84 / 5.26	0.04 / 0.07	2.70 / 5.00	0.12 / 0.22
118/L	5.92 / 10.96	**0.52 / 0.96**	5.30 / 9.82	**0.32 / 0.59**
119/L	2.05 / 3.80	0.29 / 0.54	2.06 / 3.82	**0.34 / 0.63**
120/L	2.17 / 4.02	**1.03 / 1.91**	2.27 / 4.20	**0.33 / 0.61**
121M	4.43 / 8.20	**1.86 / 3.44**	4.33 / 8.02	**0.42 / 0.78**
122/M	3.72 / 6.89	0.14 / 0.26	3.71 / 6.87	014 / 0.26
123/M	13.12 / 24.30	**6.44 / 11.93**	14.30 / 26.48	**0.32 / 0.59**
124/M	2.44 / 4.52	**0.58 / 1.07**	2.41 / 4.46	0.20 / 0.37
125/M	0.76 / 1.41	**0.66 / 1.22**	0.77 / 1.43	**0.32 / 0.59**
126/M	3.73 / 6,91	**0.32 / 0.59**	3.72 / 6.89	0.22 / 0.41
127/M	7.89 / 14.61	0.25 / 0.46	8.00 / 14.82	**0.40 / 0.74**
128/M	0.98 / 1.81	0.07 / 0.13	0.92 / 1.70	0.03 / 0.06
129/M	4.11 / 7.61	0.18 / 0.33	3.94 / 7.30	0.22 / 0.41
130/M	5.23 / 9.69	0.29 / 0.54	5.32 / 9.85	0.14 / 0.26
131/M	9.26 / 17.15	0.22 / 0.41	9.21 / 17.06	0.11 / 020
132/M	3.29 / 6.09	**0.34 / 0.63**	3.08 / 5.70	0.10 / 0.19
133/M	2.59 / 4.80	0.09 / 0.17	2.53 / 4.69	0.03 / 0.06
134/M	13.04 / 24.2	**1,05 / 1.94**	12.90 / 23.89	**0.88 / 1.63**
135/M	3.36 / 6.22	0.10 / 0.19	3.37 / 6.24	0.09 / 0.17
136/M	5.84 / 10.82	**0.52 / 0.96**	5.89 / 10.91	0.16 / 0.30
137/M	5.85 / 10.83	0.25 / 0.46	5.81 / 10.76	0.21 / 0.39
138/M	15.58 / 28.85	0.14 / 0.26	15.60 / 28.89	0.04 / 0.07
139/M	7.42 / 13.74	0.17 / 0.31	7.28 / 13.48	0.17 / 0.31
140/M	1.87 / 3.46	**2.65 / 4.91**	0.91 / 1.69	**1.27 / 2.35**
141/M	4.41 / 8.17	**1.60 / 2.96**	-	-
142/M	12.73 / 23.58	**9.57 / 17.72**	14.32 / 26.52	**9.85 / 18.24**
143/M	14.88 / 27.56	0.27 / 0.50	14.88 / 27.56	**0.38 / 0.70**
144/M	13.52 / 25.04	**5.76 / 10.67**	14.48 / 26.82	**1.19 / 2.20**
145/M	7.15 / 13.24	**10.32 19.11**	2.67 / 4.94	**2.23 / 4.13**
146/M	15.95 / 29.54	**2.08 / 3.85**	16.24 / 30.08	**0.57 / 1.06**
147/M	18.50 / 34.26	**3.33 / 6.17**	19.06 / 35.30	**0.43 / 0.80**
148/M	15.14 / 28.04	0.25 / 0.46	15.12 / 28.00	0.17 / 0.31
149/M	9.08 / 16.82	0.11 / 0.20	9.13 / 16.91	0.16 / 0.30
150/M	0.83 / 1.54	0.23 / 0.43	0.84 / 1.56	0.15 / 0.28
151/M	9.69 / 17.95	**0.33 / 0.61**	9.69 / 17.95	0.20 / 0.37
152/S	2.39 / 4.43	0.04 / 0.07	2.37 / 4.39	0.10 / 0.19
153/S	5.38 / 9.96	**0.32 / 0.59**	5.67 / 10.50	0.18 / 0.33
154/S	5.50 / 10.19	0.12 / 0.22	5.41 / 10.02	0.10 / 0.18
155/S	3.20 / 5.93	0.04 / 0.07	3.13 / 5.80	0.16 / 0.30
156/S	1.36 / 2.52	**0.34 / 0.63**	1.36 / 2.52	0.26 / 0.48

157/S	2.47 / 4.57	0.29 / 0.54	2.47 / 4.57	0.30 / 0.56
158/S	1.63 / 3.02	**0.99 / 1.83**	1.70 / 3.15	0.20 / 0.37
159/S	14.28 / 26.5	**3.33 / 6.17**	14.63 / 27.10	**0.41 / 0.76**
160/S	0.46 / 0.85	0.13 / 0.24	0.45 / 0.83	0.07 / 0.13
161/S	1.74 / 3.22	0.12 / 0.22	1.74 / 3.22	0.02 / 0.03
Both ships at anchor				
162/M	0.55 / 1.02	**0.58 / 1.07**	0.92 / 1.70	**0.56 / 1.04**
163/M	1.19 / 2.20	**0.96 / 1.78**	0.39 / 0.72	**0.56 / 1.04**
164/M	0.60 / 1.11	**0.62 / 1.15**	0.95 / 1.80	0.26 /0.48
165/M	1.51 / 2.80	**0.89 / 1.65**	1.37 / 2.54	**0.44 / 0.81**

4 DISCUSSION OF THE TESTS RESULTS

Table 6 summarizes the information presented in Tables 4 and 5 and shows the number of particular types of investigated meeting situations of two ships where errors (for 95% probability) of the presented data were greater than their values specified in the international standards and shown in Table 1.

Table 6. The number of meeting situations where errors of data presented by AIS and ARPA (CPA, true course and / or true speed) were greater than their values presented in Table 1 (for 95% probability figures, excluding both ships at anchor) [own study]

Data	Number of meeting situations with data errors greater than their values presented in Table 1 / total number of meeting situation ARPA				AIS			
	1	2	3	All	1	2	3	All
TC	1	1	0	2	6	0	6	12
TSp	7	19	12	38	1	3	2	6
TC & TSp	2	0	6	8	1	0	0	1
CPA	9	3	3	15	23	2	9	34
CPA & TC	4	4	0	8	4	1	4	9
CPA & TSp	10	2	5	17	0	0	0	0
All data	10	3	17	30	3	0	5	8
Σ/Σ_T	43/ 61	32/ 47	43/ 53	118/ 161	38/ 61	6/ 47	26/ 53	70/ 161

Abbreviations used in Table 6 mean:
1 - parallel courses – overtaking;
2 - reciprocal courses;
3 - crossing courses;
All - all meeting situations;
TC - true course;
TSp - true speed; and
Σ/Σ_T - number of meeting situations of a given type with data errors greater than presented in Table 1 / total number of all meeting situations of this type.

Table 7 presents correlation between the errors of the results of ARPA calculation and errors of the true course, true speed and/or CPA indications by AIS for the same ships' meeting situations.

The analysis of the data contained in Tables 4 and 5 shows that the differences between the average values of the true course (ΔTC), true speed (ΔTSp) and/or CPA (ΔCPA) indicated by the AIS and ARPA for particular observed and tracked vessels exceeded errors defined in the IMO Resolution MSC.192(79) and IEC Standard 61993-2 in 40 measurement series (24% of all of them). It should be noted that they exceeded these errors in 29.5% of measurements for ships overtaking on parallel courses, 24.5% for ships at crossing courses, and 19% for vessels sailing on reciprocal courses. Detailed information on these meeting situations is presented in Table 8.

Table 7. Correlation between errors of the results of ARPA calculation and errors of the true course, true speed and/or CPA indications by AIS for the same meeting situation (excluding both ships at anchor, abbreviations as in Table 7) [own study]

Data presented by ARPA with errors greater than presented in Table 1	Meeting situation		The number of meeting situations in which AIS simultaneously presented particular data with errors greater than presented in Table 1							
	Type	No	TC	TSp	TC & TSp	CPA	CPA & TC	CPA & TSp	All data	OK
TC	1	1	-	-	-	-	-	-	-	1
	2	1	-	-	-	-	-	-	-	1
	3	-	-	-	-	-	-	-	-	-
	Σ	2	-	-	-	-	-	-	-	2
TSp	1	7	1	1	1	-	-	-	-	4
	2	19	-	3	-	-	-	-	-	16
	3	12	1	1	-	1	-	-	-	9
	Σ	38	2	5	1	1	-	-	-	29
TC & TSp	1	2	2	-	-	-	-	-	-	-
	2	-	-	-	-	-	-	-	-	-
	3	6	2	1	-	-	-	-	2	1
	Σ	8	4	1	-	-	-	-	2	1
CPA	1	9	1	-	-	6	-	-	-	2
	2	3	-	-	-	1	-	-	-	2
	3	3	-	-	-	1	-	-	-	2
	Σ	15	1	-	-	8	-	-	-	6
CPA & TC	1	4	1	-	-	1	1	-	1	-
	2	4	-	-	-	-	-	-	-	4
	3	-	-	-	-	-	-	-	-	-
	Σ	8	1	-	-	1	1	-	1	4
CPA & TSp	1	10	-	-	-	10	-	-	-	-
	2	2	-	-	-	1	-	-	-	1
	3	5	-	-	-	3	-	-	-	2
	Σ	17	-	-	-	14	-	-	-	3
All data	1	10	-	-	-	5	3	-	2	-

	2	3	-	-	-	-	1	-	-	2
	3	17	2	-	-	4	4	-	3	4
	Σ	30	2	-	-	9	8	-	5	6
OK	1	18	1	-	-	1	-	-	-	16
	2	15	-	-	-	-	-	-	-	15
	3	10	1	-	-	-	-	-	-	9
	Σ	43	2	-	-	1	-	-	-	40

Abbreviations used in Table 7 mean:
Type 1, 2 3 - see Table 6;
OK - data presented by AIS without unacceptable errors;
TC - true course;
TSp - true speed; and
Σ - all meeting situations.

Table 8. Meeting situations in which the differences in the indications of average values of true course, true speed and CPA by ARPA and AIS are less than the error of determining these parameters presented in the IMO Resolution MSC.192(79) and IEC Standard 61993-2 [own study]

No	NOMS	ΔTC	ΔTSp	ΔCPA	L	D	V	Sea state
				Parallel courses - overtaking				
1	2V	**No**	Yes	Yes	289	16.8-14.5 / 31.1-26.9	0 / 0	3
2	3V	**No**	Yes	Yes	290	6.7-3.4 / 12.4-6.3	0 / 0	2
3	4V	Yes	Yes	**No**	180	19.8-19.6 / 36.7-36.3	11.1 / 5.7	4
4	6V	Yes	Yes	**No**	225	16.8-16.4 / 31.1-30.4	10.8 / 5.6	7
5	7L	Yes	Yes	**No**	225	14.1-13.2 / 26.1-24.4	12.0 / 6.2	3
6	9L	Yes	**No**	Yes	274	2.0-1.8 / 3.7-3.3	14.0 / 7.2	4
7	11L	Yes	Yes	**No**	295	12.5-10.6 / 23.2-19.6	11.5 / 5.9	2
8	12L	**No**	**No**	**No**	182	8.7-8.2 / 16.1-15.2	15.5 / 8.0	2
9	17M	**No**	Yes	Yes	207	18.9-15.8 / 35.0-29.3	0.5 / 0.3	1
10	21M	Yes	Yes	**No**	179	17.1-17.0 / 31.7-31.5	10.8 / 5.6	6
11	25M	Yes	Yes	**No**	185	18.7-18.4 / 34.6-34.1	11.7 / 6.0	1
12	28M	Yes	Yes	**No**	236	15.0-14.8 / 27.8-27.4	14.6 / 7.5	2
13	37M	**No**	Yes	Yes	289	9.4-3.5 / 17.4-6.5	9.0 / 4.6	5
14	38M	Yes	**No**	**No**	299	20.4-18.9 / 37.8-35.0	17.0 / 8.7	1
15	40M	Yes	**No**	Yes	261	24.4-23.8 / 45.2-44.11	8.2 / 9.4	1
16	44S	Yes	Yes	**No**	190	5.7-4.7 / 10.6-8.7	13.0 / 6.7	4
17	50S	Yes	Yes	**No**	145	4.8-4.5 / 8.9-8.3	12.2 / 6.3	3
18	60S	**No**	Yes	Yes	240	4.1-2.1 / 7.6-3.9	1.6 / 0.8	4
				Reciprocal courses				
19	64L	Yes	Yes	**No**	177	13.1-6.6 / 24.3-12.2	10.0 / 5.1	5
20	67L	Yes	**No**	**No**	333	12.5 / 23.2	14.1 / 7.3	4
21	70L	Yes	**No**	Yes	180	11.6-5.3 / 21.5-9.8	11.1 / 5.7	3
22	81M	Yes	**No**	**No**	127	14.2-10.6 / 26.3-19.6	11.3 / 5.8	3
23	89M	**No**	Yes	Yes	122	6.2-4.6 / 11.5-8.5	13.5 / 6.9	1
24	90M	**No**	Yes	Yes	115	11.0-4.2 / 20.4-7.8	9.8 / 5.0	2
25	97S	Yes	Yes	**No**	112	9.1-5.3 / 16.9-9.8	14.2 / 7.3	2
26	102S	Yes	**No**	Yes	102	6.3-1.7 / 11.7-3.1	10.2 / 5.2	4
27	105S	**No**	Yes	Yes	184	7.4-2.7 / 13.7-5.0	10.2 / 5.2	3
				Crossing courses				
28	118L	Yes	Yes	**No**	199	16.7-12.8 / 30.9-23.7	14.4 / 7.4	2
29	123M	Yes	Yes	**No**	109	17.1-16.3 / 31.7-30.2	13.4 / 6.9	5
30	138M	**No**	**No**	Yes	200	15.9-12.8 / 29.4-23.7	12.9 / 6.6	1
31	139M	Yes	No	Yes	254	9.5-7.5 / 17.6-13.9	7.9 / 4.1	1
32	140M	**No**	Yes	**No**	179	21.8-20.5 / 40.4-38.0	7.2 / 3.7	2
33	141M	**No**	Yes	**No**	199	6.1-5.1 / 11.3-9.4	2.2 / 1.1	7
34	142M	**No**	**No**	**No**	354	21.2-19.5 / 39.3-36.1	16.4 / 8.4	6
35	144M	**No**	Yes	**No**	190	18.7-15.7 34.6-29.1	10.7 / 5.5	6
36	145M	**No**	**No**	**No**	148	24.3-18.3 / 45.0-33.9	10.8 / 5.6	5
37	146M	Yes	**No**	Yes	108	18.9-15.6 / 35.0-28.9	11.3 / 5.8	5
38	147M	**No**	Yes	**No**	292	20.0-19.1 / 37.0-35.4	10.6 / 5.5	5
39	158S	**No**	Yes	Yes	96	2.9-2.3 / 5.4-4.3	15.6 / 8.0	3
40	159S	Yes	Yes	**No**	117	16.6-15.9 / 30.7-29.4	12.4 / 6.4	2
				Both ships at anchor				
41	162M	-	-	**No**	169	1.2 / 2.2	0/ 0	3
42	163M	-	-	**No**	183	1.7 / 3.2	0 / 0	3
43	164M	-	-	**No**	274	1.0 / 1.8	0 / 0	3

Abbreviations used in Table 8 mean:
D - the distance between the ships (own and observed) during the measurement;
L - the length of the observed vessel presented on the web-site;
No - the differences in the indications of average value are greater than errors defined in IMO resolution and IEC standard;
NOMS – number of meeting situation described in the Table 3;
Sea state – the state of the sea during the measurements expressed in degrees of the Douglas scale;
V – the mean value of the true speed of the observed ship;
Yes - the differences in the indications of average value are less than the errors defined in IMO resolution and IEC standard; and
ΔTC, ΔTSp, ΔCPA – differences in the indications of average values of true course (TC), true speed (TSp) and CPA by ARPA and AIS.

The information shown in Table 8 is summarized in Table 9.

Table 9. The number of measurement series with the differences in the indications of the average values of particular parameters by ARPA and AIS exceeding the error values specified in the IMO resolution and the IEC standard [own study]

Parameter	Number of measurement series			
	1	2	3	ΣT
TC	5	3	1	9
TSp	2	2	2	6
TC & TSp	0	0	1	1
CPA	9	2	3	14
CPA & TC	0	0	4	4
CPA & TSp	1	2	0	3
All data	1	0	2	3
ΣT	18	9	13	40

Abbreviations used in Table 9 mean:
- 1, 2 3 see Table 6; and
- ΣT – total number of measurement series with differences in the indications of the average values of particular parameters by ARPA and AIS exceeding the error values specified in the IMO resolution and the IEC standard.

The data presented in Table 8 show the dependence of the differences in AIS and ARPA indications on the true speed of the observed and tracked vessel and on the type of meeting situation. No other correlations could be found. The next Table 10 shows the relationship between the differences in AIS and ARPA indications and the errors in determining the average values of individual parameters by these devices.

Table 10. The number of measurement series in which the average value of the true course, true speed or CPA of the observed object indicated by ARPA and / or AIS had the error greater than its limit defined in the IMO resolution and IEC standard (for meeting situation in which differences in the indications of average true course, true speed or CPA by ARPA and AIS were greater than defined by international regulations [own study]

The average value of the parameter presented with too great error by	The number of measurement series in which the average value had too great error			
	TC	TSp	CPA	Σ_T
AIS & ARPA	9	5	21	35
ARPA	3	7	1	11
AIS	0	0	0	0
Mean value without too great error	5	1	2	8
Σ_T	17	13	24	54

Abbreviations as in the table 9.

The next table provides information on the state of the sea during the measurement series in which errors of the true course, true speed and / or CPA indications by ARPA and AIS on board equipment exceeded the values shown in Table 1.

Table 11. The state of the sea during the measurement series in which errors of the true course, true speed and / or CPA indications by ARPA and AIS on board equipment exceeded the values shown in Table 1 (for 95% probability figures, excluding both ships at anchor) [own study]

Data with errors exceeding the values shown in Table 1	State of the sea expressed in degrees of the Douglas scale								Σ
	1	2	3	4	5	6	7	8	
ARPA indications									
TC	1	1	-	-	-	-	-	-	2
TSp	4	7	13	5	7	1	1		38
TC & TSp	2	1	2	1	-	1	-	1	8
CPA	1	4	7	3	-	-	-	-	15
CPA & TC	1	2	2	1	2	-	-	-	8
CPA & TSp	4	5	2	2	1	3	-	-	17
All data	4	5	7	2	6	3	3	-	30
Σ/Σ_T	17/20	25/35	33/42	14/26	16/23	8/9	4/5	1/1	118/161
AIS indications									
TC	1	2	6	1	1	-	1	-	12
TSp	2	-	1	1	2	-	-	-	6
TC & TSp	-	-	-	-	1	-	-	-	1
CPA	5	9	9	5	3	3	-	-	34
CPA & TC	1	-	2	1	3	1	1	-	9
CPA & TSp	-	-	-	-	-	-	-	-	-
All data	-	1	1	1	1	2	2	-	8
Σ/Σ_T	9/20	12/35	19/42	9/26	11/23	6/9	4/5	-/1	70/161

Collective information on the state of the sea during particular measurement series is presented in Table 12. Too few measurements in storm conditions makes it impossible to draw conclusions about the relationship between the accuracy of ARPA and AIS indications and the state of the sea.

Table 12. State of the sea expressed in degrees of the Douglas scale during the measurement series (including both ships at anchor) [own study]

State of the sea (Douglas scale)	1	2	3	4	5	6	7	8
Number of measurement series	20	35	46^x	26	23	9	5	1

x - including four measurement series, during which both ships were anchored

5 FINAL CONCLUSIONS

Measurements described in this paper were carried out on ten different merchant ships using popular, often used AIS and radar on board equipment but produced by four manufacturers only. Due to that and due to the limited number of conducted tests (161 series of measurements while both ships are underway and 4 when they are at anchors), it is impossible to formulate on their basis general conclusions about the stability and accuracy of the AIS and ARPA indications and their dependence on hydro meteorological conditions. Nevertheless, the performed measurements allow for the formulation of some remarks on these topics.

Table 6 shows that the accuracy of ARPA indications does not depend on the type of ships' meeting situation. ARPA presented all or part of data with the accuracy lower than defined by international recommendations and standard (presented in Table 1) in 73% of the measurement series (118 out of 161). It mainly had a problem with the accuracy of the presentation of the true speed of the tracked vessel (in 24% of meeting situations (38 out of 161)). All ARPA data had too great error in 19% of observations (30 out of 161), CPA, or CPA and true course, or CPA and true speed in 25% (40 out of 161). Generally, ARPA reported a CPA value with an error greater than 0.3 nautical miles in 43% of meetings (70 out of 161). AIS had problems mainly with the accurate presentation of CPA value (in 32% of measurement series (51 out of 161)), especially in the case of overtaking ships on parallel courses (in 49% percent of observations (30 out of 61 measurement series)).

The data presented in Table 7 show that there was no correlation between the inaccuracies in the AIS and ARPA indications for the same object. Out of the total number of 30 measurement series in which ARPA incorrectly presented all recorded data, AIS also showed all data with too great errors in only 5 series (in 9 series the inaccuracy was related to CPA value, in 8 series related to CPA and true course). In 15 meeting situations where ARPA had problems with accurately presenting only CPA values, AIS also incorrectly showed only CPA in 8 tests. In 38 tests, where ARPA showed insufficiently accurate information about the true speed of the tracked vessel, AIS had problems with the accurate presentation of its true speed in 5 tests only and in 29 tests presented all data of this vessel with the required accuracy.

The tests carried out have shown that both ARPA and AIS can indicate distances between two ships at anchors unstable and with significant inaccuracies.

A separate issue are the differences between the AIS and ARPA indications of the average values of the observed and tracked object true course, true speed and CPA. In a significant number of tests (in 24% of the measurement series), they exceeded the values of the presentation errors defined in the IMO Resolution MSC.192(79) and IEC Standard 61993-2. It should be noted that in all these cases, the AIS presented the mean values of individual parameters with acceptable errors. It is interesting that in 8 cases of the discussed differences in the AIS and ARPA indications, both devices showed average values of all parameters with errors smaller than those defined in the international regulations.

The results of the measurements presented in Table 11 do not show a clear relationship between the accuracy of the data presented by AIS and ARPA and the current level of disturbances from the sea surface. The reason for this may be the lack of a comparable number of measurements carried out in individual sea states expressed in the Douglas scale and too small number of tests conducted in storm weather condition (Table 12).

The comments presented in this article should be taken into account when using ARPA and AIS as technical means of observation for anti-collision purposes. They show that the indications of both devices in real conditions may be unstable and have errors greater than those specified in the IMO Resolution MSC.192(79) and IEC Standard 61993-2. Therefore, users should not rely on the instantaneous digital data values of the other vessel presented by ARPA and AIS.

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