Aspects of Technical Reliability of Navigation Systems and Human Element in Case of Collision Avoidance

Michael Baldauf[1] and Knud Benedict[1]; Florian Motz[2]
[1]Hochschule Wismar, Department of Maritime Studies, Germany
[2] FGAN-FKIE, Bonn-Wachtberg, Germany

Keywords:
Integrated Navigation Systems, Bridge Alert Management, Collision Avoidance, Human Element, Technical Reliability

Especially with respect to the level of integration of the sensors, equipment, displays and assistance systems installed on ships navigational bridges they can be defined as high complex man-machine systems undoubtedly. Safety and efficiency of ship operations are dependent, as all other human-machine systems, on the communication between humans and machines during the accomplishment of the tasks. In order to support the mariner effectively onboard the representation of information has to be based on sufficient acquisition and processing of reliable data.

To approach the problem field studies are performed on board of ships to investigate the situation with respect to the occurrence of alarms and their handling by the bridge team. These studies are added by detailed case studies of accident and traffic scenarios regarding the integrity and reliability of data as counterpart to the "human element". Based on the outcome of these studies lacks and shortcomings of navigation systems presently in use were identified. Within this paper the methods used and selected results for samples of the investigations are presented.

The investigations belong to the framework of the RTD-project to further develop Maritime Navigation and Information Services (MarNIS) funded by the European Commission, DG Transport and Energy and of national Research and Development projects funded by German Ministries. The results of the studies are used to directly support the work of the International Maritime Organization regarding the development of new performance standards for Bridge Alert Management and to enhance existing systems.

1 Introduction

In February 2008 the Norwegian classification society Det Norske Veritas published new statistical figures on sea accidents. The figures clearly showed that the number of accidents has doubled over the last five years. DNV concluded that this is caused mainly by the continued growth of the world fleet and a shortage of officers with right skills. The majority of total losses in shipping is due to collisions, groundings and contacts although there are highly automated systems installed onboard seagoing vessels to support the Officer of the Watch (OOW) on the ships navigational bridge.

According to statistics recently published by LMIU also the number of heavy accidents has almost increased threefold since 1998 (less than 250 to nearly 700 in 2006). Simultaneously the part of collisions grew from 17% (1997 – 2001) to 22% (2002 – 2006). Also the national institutions (as e.g. German BSU’s) accident statistics proof these tendencies. In the year book of this institution it was stated last year, that there is a constant increase of the absolute number of reported and investigated accidents. One third of the total number is collisions between ships and collisions between ships and other objects.

As a main reason of fatal events often the “human error” or “human factor” is mentioned. Since BLANDING (1987) in his publication on “Automation of ships and the Human Factor” indicated that the number of human factor caused accidents is 86%, this number was and still is often quoted. BAKER AND MCCAFFERTY for example did so in 2005. Often the intention of the quotations is to indicate the human operator as the most critical element of the navigation process onboard. However, for a long time human factor related research has recognized, those sea accidents are not only caused by human errors of captains, pilots or navigation officers. LÜTZHÖFT requires for a more detailed specification and subdivision of the human error categories to get a more realistic and more objective image about the real reasons of groundings and collisions.

However, human behaviour is not the main subject of this paper – but it is the technology which might lead to human failures. Within this paper selected aspects of the bridge equipment's technical reliability will be studied. The investigations are performed addressing the newly introduced AIS exemplarily. AIS should provide officers of the watch (OOW) onboard with additional and partly redundant information on objects in the vicinity. In this way the system should improve collision avoidance according to the IMO's Performance Standards. This effect should be realised mainly by integration of AIS and the provided data into the existing installed navigation systems as e.g. Radar and ECDIS. Therefore AIS is one of the core elements of ongoing integration processes and further technical developments.

Latest publications dealing with AIS are dedicated to investigations into operational aspects and user acceptance. Beside others NORRIS (2007) delivered detailed summary and critical views. Among others he mentioned the missing mandatory training course as a main lack, but also reflects samples of negative user experiences, which are mainly based on false or doubtful data. First systematic investigations into technical reliability of AIS were performed during the introduction phase of the mandatory installation of the system. First of all these investigations were focussed on data’s plausibility. Among others in the frame of the European EMBARC project static and voyage related AIS data were investigated. VAN DER HEIJDEN delivered a huge collection of wrong data samples. Statistical analysis based on a spotlight from a field study were delivered by BALDAUF & HARTMANN (2004) and provides statistical values for the reliability of ETA-, Port of Destination- as well as Draught-data. The following investigations into the reliability of dynamic AIS data supplement these investigations.

2 Conduction and results of field studies

2.1 Investigations into the Alarm situation onboard ships focussing on AIS data

A series of field studies were conducted on board of ships to investigate the situation with respect to the occurrence of alarms and their handling by the bridge team. As the management and presentation of alarms is influenced by the type of ship, the year of construction, the installed equipment and grade of integration, the sea area, the training and education of the crew as well as by the safety standards of the shipping company (BALDAUF & MOTZ, 2006), these factors were taken into account to obtain a profound database.

These ongoing investigations aim at several technical, operational and human factor related aspects of the situation onboard with respect to the alert occurrence and handling. Within the context of the technical reliability discussed here, the focus will be laid on the AIS related results gained so far.

The field studies were carried out on board of six vessels, which were two ferries operating in the Baltic Sea, three container vessels (with container capacities of 4.200 TEU, 5.500 TEU and 7.500 TEU) and a cruise vessel operating in the Mediterranean Sea. All vessels were built or reconstructed within the time span from 2001 until 2007. The ships' bridges were equipped differently, the equipment (among others AIS devices) was integrated on a medium or high integration level.

The investigations were conducted during voyages in the Baltic Sea, in the Western Mediterranean Sea, in the North Sea and in the English Channel. The average time of observation was 19,0 hours, with a minimum of 11 hours and a maximum of 27 hours. Even though the investigations took place on different times of the year, usually good weather conditions were experienced with low winds and calm sea. During one voyage temporary rain showers were encountered during the night. Another vessel was sailing through fog banks with restricted visibility up to 200m for two hours of its voyage. Detailed analysis of alarm recordings were performed and are recently described in more detail by MOTZ, BALDAUF & HÖCKEL (2008).

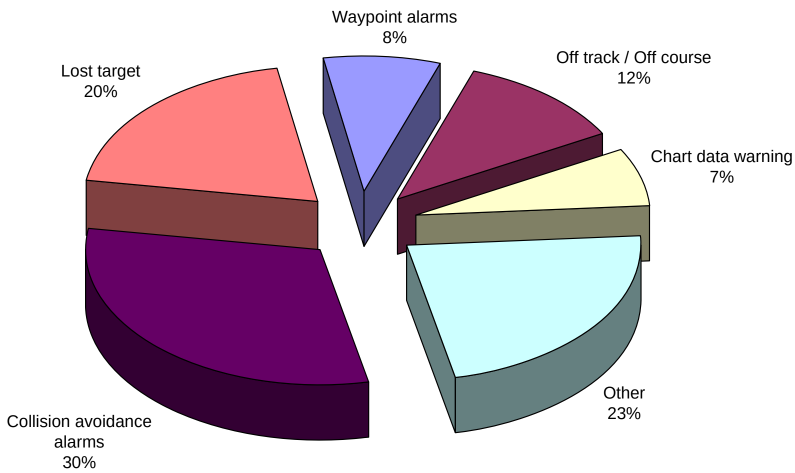

Figure 1: Average percentage for types of alarms for all six vessels

In this chapter only the integration aspects are highlighted using selected results regarding AIS caused alarms. Figure 1 depicts the average percentage of the types of alarms registered for the six vessels. For all vessels investigated the majorities of alarms are collision avoidance alarms and lost target alarms.

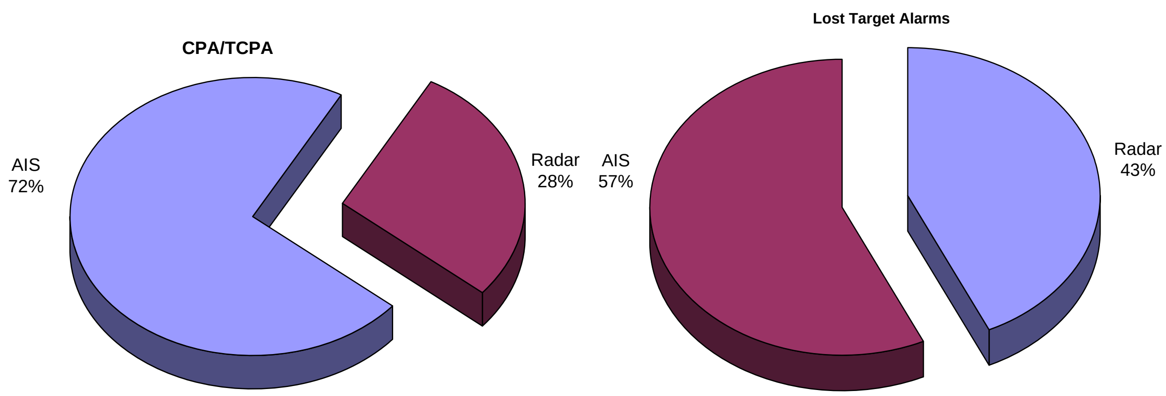

Figure 2: Sources of CPA/TCPA and lost target alarms for all six vessels

Additionally Figure 2 shows the average percentages of the sources initiating the CPA/TCPA and lost target alarms for all vessels investigated. Both kinds of alarms were predominantly caused by AIS information. This percentage could have been even higher, if the bridge team of one of the container vessel had not chosen a radar setting without integration of AIS information, which caused all CPA/TCPA and lost target alarms to be initiated by radar information.

This result is to be expected because of the technical configuration and the use of the automatic alarm functions. For AIS, according to IMO regulations, the same limit values were applied as for tracked radar targets and the option for CPA/TCPA calculation was switched on to sleeping AIS targets by default. On the other hand a critical fact is that 20% of all registered alarms are "Lost target alarms", mainly caused by AIS.

2.2 Onboard Investigations into dynamic AIS data and update rates onboard

In the context of investigations into the process of data fusion of AIS- and ARPA-Radar targets visualized in onboard collision avoidance displays, another series of measurements have been performed onboard of the Swedish RoRo-passenger ferry "Stena Germanica" in the western Baltic Sea (WILSKE, GRUNDEVIK & BALDAUF (2007)). For this studies the onboard installed ECDIS Navisailor 3000, the Radar NUCLEUS 6000A and the AIS unit of SAAB R4 AIS have been used.

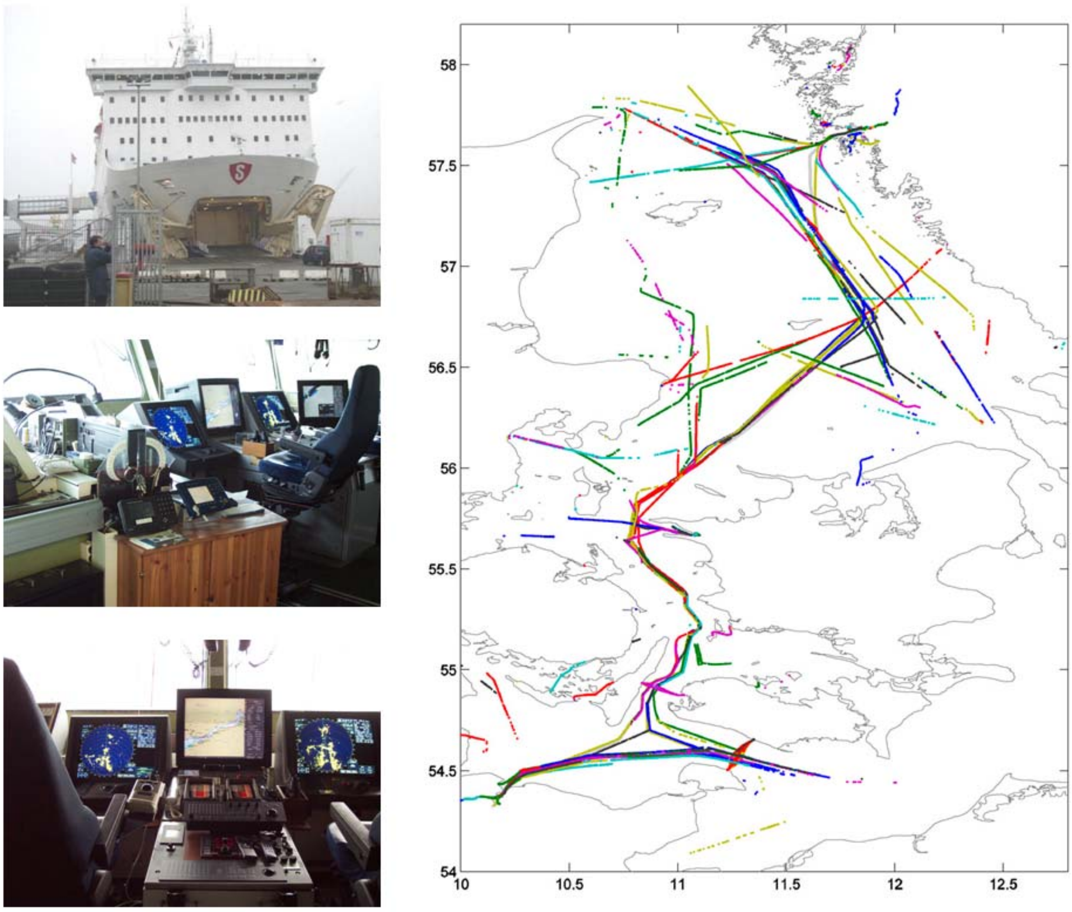

Figure 3: RoRo-Passenger ferry and bridge configuration (left) as well as example of plotted targets during one of the voyages between Gothenburg and Kiel

During the measurement campaign navigating officers have been instructed to plot targets as much as practicable. Typically the log from one voyage (11.5 hours) has contained 15-30 targets tracked for more than four minutes. In Figure 3 the tracks of targets plotted during one voyage can be seen exemplarily. All in all, data records of 616 targets were used for several statistical analyses.

A main point in the analysis was the differences of the dynamic parameters (position, heading, velocity), that are pertinent to the fusion of target displays during conditions of real ship operations. For the reflection on reliability of the AIS-data exchange further analyses of transmission schemes and heading information have been undertaken. To check the received AIS-heading-information the AIS-data were simply compared with the course-over-ground-data of AIS und the complementary ARPA-object. For example: A received AIS-heading data set was estimated as incorrect, if an AIS-target with more than 8 kts on a constant course (turning rate = 0 and standard deviation of the heading data < 0,01°) deviates from the COG (Course Over Ground)-data with more than 10°. Under these circumstances about a fifth (a total of 18%) of the tracked AIS-objects sent incorrect heading dates.

Furthermore, to proof the standard conformable transmission and receiving schemes, the update rates of the time difference between two consecutive AIS-messages were determined and compared with the update rates, which are required according to the relevant specifications of ITU and IMO. The statistical analysis of all gained update rates of every crossing AIS-vessel resulted to an average update rate of 23 seconds. This result is clearly above the expected rate of 6 to 10 seconds. The received maxima time span between two consecutive AIS-messages of an object was 33 seconds. This is more than three times of the defined limit value of the update rate for vessels with a maximum velocity of 14 kts. The results of the fusion process of AIS- and ARPA-Radar-target information, which was mainly investigated, were found critical. Under favourable conditions AIS-target information is estimated as qualitatively superior information to radar. That's why target merging should only display AIS-data. However, situation changes due to higher update rates and blackouts and target loss or rather de-fusion of displayed merged ARPA/AIS target symbols may occur often. A more reliable equipment and software to guarantee the required update-intervals would also clearly improve the process of target merging.

2.3 Shore-based measurement for a spotlight study

In order to investigate the reliability of AIS data exchange and its use for collision avoidance under conditions of real operation a further case study was conducted on the basis of a stochastic spotlight from continuously recorded AIS data transmissions in the area of southern Baltic Sea (see figure 4 following page).

The spotlight contains the course of a real collisions situation. This situation was selected for a more detailed scenario study. The evaluation of the AIS data exchange reliability is performed by a comparison of the real update rates with those rates required by the relevant IMO standards. Secondly the plausibility of AIS data content is analysed by comparing the values with other time synchronised sources.

All data used for the analysis were recorded with a certified standard AIS mobile station. A detailed description of measurement installation is given by BALDAUF & HARTMANN (2004). The distance of antenna position (with a height of 25,5 m) to the area where the collision situation happened is approximately 14 nm. There is no obstacle blocking of the optical view. At the scenario when the selected collision scenario happened there were conditions of good visibility and weak south-westerly winds, calm sea with wave heights of around 0,5 m.

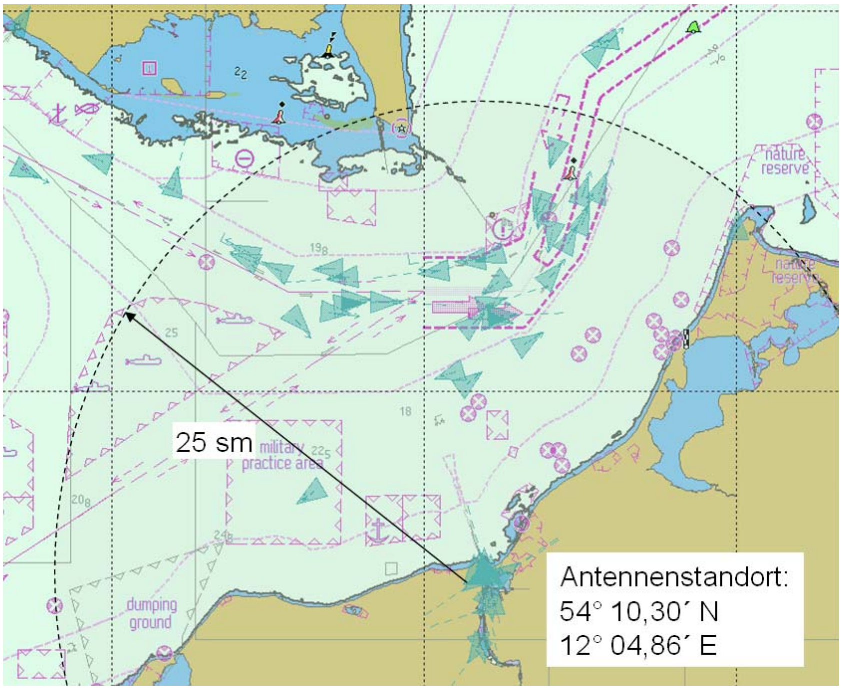

Figure 4: ECDIS-snapshot including the selected observation area and the initial positions the AIS objects in the overall traffic scenario

From the continuous data logging of the complete AIS data exchange in this area the data stream of 20 minutes length was filtered. For the scenario study of the collision situation the data sets of the four involved ships were extracted and processed for the purposes of the exemplarily statistical analysis. The focus of this analysis were mainly laid on the dynamic data contained in the AIS position reports (message 1, and 3 according to the ITU-definitions) and received via channel A and B. However, for competition of the investigations also the static voyage related AIS data were analysed additionally.

The spotlight of the 20 min time period contains 11.160 binary data sets in total. They were received from 62 AIS mobile stations and 3 shore-based IAS base stations. The recorded raw data were converted into NMEA- and ASCII-formats respectively. Each the data sets were identified by means of the MMSI number, which is included in the position reports. For the detailed scenario study of the collision situation finally 832 AIS messages were available and used. After a verification of the completeness of the spotlight the data analysis was performed using self developed, partially ECDIS-based software modules. The completeness of the spotlight's AIS transmissions and the correct work of the used AIS equipment were carefully checked.

2.4 General Statements concerning the overall traffic situation

In total 7.449 Position reports (including repeated messages) were received from the targets involved in the scenario of concern. According to the analysed speed and navigational status information and their correlation with the MMSI-numbers of the messages, there were 13 objects "moored" or "at anchor" in a harbour permanently. All other objects were vessels under way with speeds greater than 3 kts.

Within the spotlight only one case of invalid position, course and speed data occurred. However, in total 10 targets, representing 16% of the spotlight, transmitted invalid values for heading and another group of further 10 targets were registered sending invalid rate of turn information. Invalid data content means wrong characters or figures were inserted in the data field or the content of the relevant data field stands for "invalid input". The figures registered here do not mean false or doubtful values, as e.g. differences between COG and heading.

2.5 Case study of a collision situation

Some situations were investigated to further analyse the situation with respect to the reliability of the AIS data exchange and especially the updating of the data under aspects of collision avoidance. One example is given here. The tracks depicted in Figure 5 belong to the overall traffic scenario described and analysed above. This specific situation happened in the open sea area with a traffic separation scheme during night time and conditions of good to moderate visibility.

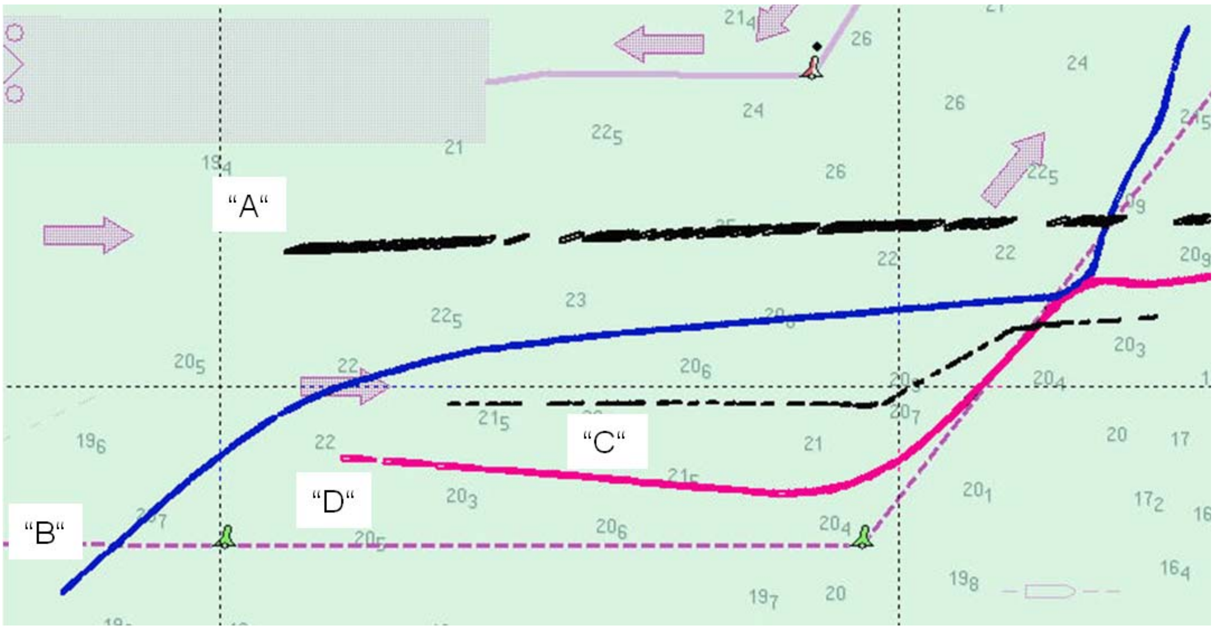

Figure 5: Initial positions and tracks of the four vessels covered by the detailed case study

Each of the four vessels (marked A-D) were equipped with AIS. The ships were involved in the situation that led to a collision between the targets "B" and "D". The main basic data of these vessels are summarised in the following table 1.

The situation happened near the easterly end of the southern traffic lane of the established TSS. After target "B", coming from south, has inserted herself into the easterly bounded traffic, the four vessels were under way inside the dedicated traffic lane on approximately parallel courses. Vessel "B" was the fastest vessel of this group.

Table 1: Target data of the concerned ships involved in the collision situation

Target Id.	Length [m]	Breadth [m]	Draught [m]	Course over Ground	Heading	Speed over Ground [kts]	Port of destination
"A"	190	30	6,5	88°	73°	14,3	Skt. Petersburg
"B"	157	24	6,8	50°	50°	18,0	Malmoe
"C"	81	12	4,3	89,8°	87°	9,6	Szczecin
"D"	199	28	6,8	94,4°	95°	13,4	Ventspils

The traffic lane's direction changes south westerly off a bank to north-easterly direction. According to the description given by SMI (2006) only "B" and "D" intended to follow the traffic lane whereas the two other vessels intended to leave the TSS on easterly courses. During the course of the scenario approximately at 03:46 UTC "B" and "D" collided, after "B" had initiated a course change from 94° to 45° some minutes before. Approximately 45 seconds before the collision vessel "B" started a hard to port manoeuvre but it was obviously to late and could therefore not avoid the accident.

The following examples of data analysis belong to the data exchange of the vessels involved in this situation described above. For the analysis the same methodology was applied as for the aforementioned field studies. The focus was laid on the comparison of the real update rates with those required by the regulations. The involved vessels were firstly on constant speed with required update rates of 6 and 10 seconds. During course change manoeuvres the update rates should be increasing automatically to 3 1/3 and 6 seconds respectively.

Table 2: Overview of results related to the analysis of the AIS transmission scheme in the concerned scenario

Target	**Position Reports (Msg.-Id. 1 and/or 3)**			**faulty reception intervals**	**Update rate (Reception intervals)**	
	Total number	Total without repetitions	expected number		Mean value	Maxima
"A"	115	101	200	42	9,34 s	82 s
"B"	286	178	280	47	4,27 s	22 s
"C"	90	62	165	43	13,42 s	56 s
"D"	153	101	215	41	7,78 s	30 s

The values especially for the number of position reports shows clearly that there is a lack between the number of expected reports according to the rates required by the standards and the really received ones. If the number of repeated messages will be taken into account additionally, then a significant deficit has to be stated with respect to the required update rates.

The figures in column "faulty reception intervals" cover the number of intervals that were more than 2 seconds above the required time period. Whereas this number differs with each of the vessel, the portion is relatively high with respect to the overall number of required messages. As e.g. for target "C" 48% of the received position reports were too late with respect to the required update rates. The detected maximum value of the times between two consecutive reports was more than one minute (target "A" 1:22 min) and was probably connected to a "lost target" alarm at the dedicated display unit.

During the scenario four of the three vessels performed all together five course change manoeuvres. However, the required change in the update rates could only be registered in two cases. Especially the 'hard-to-port'-manoeuvre of the target at the southern edge of the traffic lane, which was very important for the course of the collision, was not accompanied by the increased transmission of AIS data. The following figure 6 shows exemplarily the results of the analysis of the real update rates for one target changing from constant steering into "manoeuvring mode".

As can be seen from the graph the update intervals are only stochastically near or below the required intervals (marked by line in magenta). During the phase of the constant course without acceleration the reception interval is in the range of required update rate. Compared to the first manoeuvring phase the increase of the update rate during the second course change manoeuvre is clearly to be seen. In general there seems to be a time shift between the increased turning rate and the increase of the update rate.

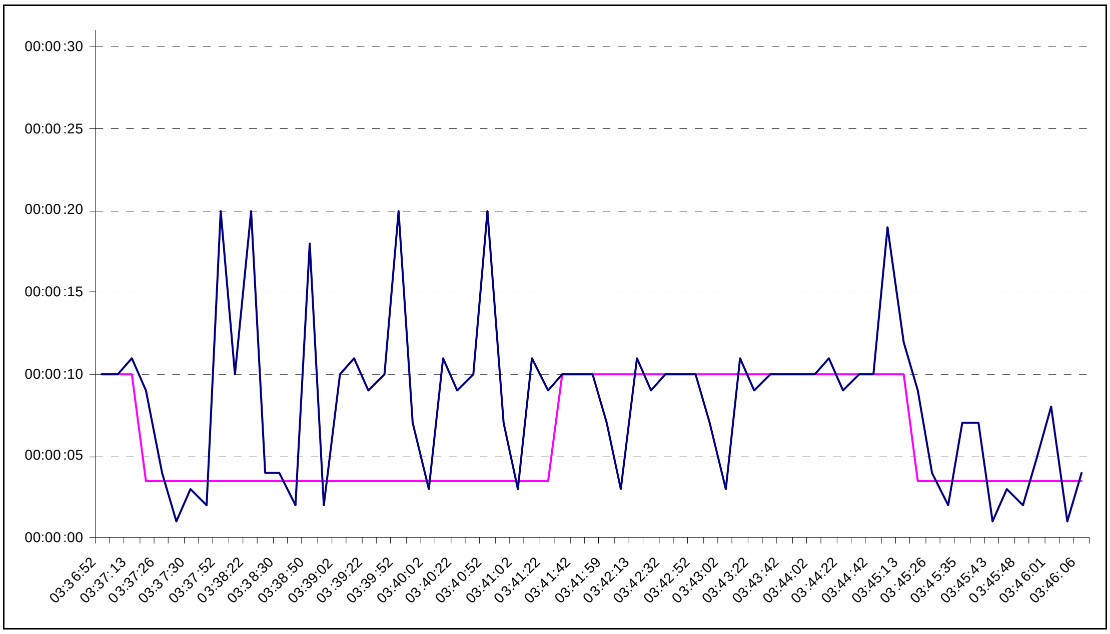

Figure 6: Reception intervals (excerpt) for target under way with course change manoeuvre (target "D" SOG= 13,2 .. 11,8 kn, first course alteration from 95° to 45° and second course alteration from 45° to 90°)

In parallel to the analysis of the update rates also the content of the AIS messages was investigated. As e.g. the analysis of heading information of the most northern target comes up with a great difference of up to 13° to 15° to the COG value. As there were no wind and current influence and furthermore other targets in the vicinity had not sent such deviations between heading and COG it can be concluded, that these heading information were faulty.

An analysis of the Rate of turn (RoT) information shows, that only three of the four vessels send RoT information from a dedicated indicator. The RoT-values alternates significantly although the COG indicated constant course and heading as well. It can be assumed, hat the sensor was configured very sensible. One of the analysed targets sent no RoT information at all during the whole observation period. This result is at least not typically, because RoT information is allowed to be derived internally from the heading information, which is obligatory.

Finally for reasons of completeness also the static voyage related data were studied. For the overall traffic scenario in total 271 faulty messages (invalid data content) were received from 46 targets. Five targets had sent no or invalid ETA data and from two targets invalid draught information were received. Target "A" of the detailed scenario study sent wrong ETA and Port of destination information. These data sets were obviously not updated. It was found, that no vessel of the overall scenario had used the coding of the destination according to the UN/LOCODE as recommended by IMO.

3 Summary and Outlook

Based on several series of field studies into the integration of AIS with onboard based alarm recordings and onboard measurements of AIS parameters another detailed scenario study with shore-based AIS-measurements has been performed in order to gain information concerning the real update rates and the plausibility of received dynamic AIS data.

For that purpose especially AIS communication in the southern Baltic Sea was investigated by means of a spotlight study. The analysed scenarios also include a real collision. Besides statistical results concerning the overall situation, the scenario of the accident was investigated in a more detailed analysis.

To get more knowledge about the update rates of AIS-data, actual receiving-intervals were determined and compared to intervals required by international standards. The plausibility of the data's content was compared sample wise with other data sources. The most important results from this scenario study and the onboard field studies are:

- The update rate of AIS data, in both the onboard- and the shore-based measurements was slower as demanded by the standards. The AIS-data exchange showed wide variations both to the top and to the bottom border of the arrogated broadcast regime. Some of the receiving-intervals were above the demanded intervals. The amount of messages detected with enlarged time intervals have target specific a share of up to 67%.
- The amount of repeatedly received position messages with the same content is quite high, target specific there were up to 35% doubled messages.
- The required increase of broadcast intervals was only registered in three of five course changing situations that were analysed and part of the detailed scenario study.
- The amount of AIS-targets transmitting invalid heading information is enormous. In the specific traffic situation investigated with 62 AIS-targets its amount was about 16%. This proofs the results of the onboard measurements.
- Also the static, voyage-related data are still often invalid or contain errors. The information about port of destination is not coded according to the IMO recommendations.

Summarising these facts, under the global aspect of collision avoidance it has to be concluded, that the human factor discussed in the introduction chapter, of course plays a major role in safety critical situations without any doubt. However, the results gained during the studies and described here have clearly shown that the technical reliability of the systems has to be addressed very carefully.

On one hand the studies showed that AIS is still not yet as good and reliable as it is required by the defined Performance standards set into force by IMO. The actual state is obviously apart from contributing significantly to a reduction of dangerous encounters and reduction of the number of collisions respectively. Moreover the present situation is more or less characterised by the role of the officer of the watch as an observer of the navigational equipment instead of the vision that the installed navigational equipment support the officers, as e.g. stated by SHERWOOD JONES et al (2006).

The ongoing development of AIS based applications for the purposes of collision avoidance and the integration of this information for more enhanced assistance functions of modern decision support systems of modern INS requires urgently an enhancement of the reliability of the AIS data input. It is the authors hope, that this can be realised soon.

4 References

Baldauf, M. & Motz, F. (2006). *Operational Aspects of future Alert Management to support ship navigation. (in German)* In: Morten Grandt (ed.): *Cognitive Systems Engineering in der Fahrzeug- und Prozessführung.* DGLR-Bericht 2006-02, Bonn, ISBN 3-932182-51-0.

Lützhöft, M. (2004). *Maritime Technology and Human Integration on the Ship's bridge.* Dissertation No. 907, Linköpping Studies in Science and Technology. Sweden, ISBN 91-85295-78-7.

Motz, F., Baldauf, M. & Höckel, S.(2008). *Field Studies Onboard Regarding Bridge Alert Management.* Proceedings of the International Symposium Information on Ships. 18-19 September 2008 Hamburg, Germany.

Baker, C.C., McCafferty, D. B. (2005). *Accident database review of human element concerns: What do the results mean for classification?* in: Proceedings of the International Conference on Human Factors in Ship Design and Operation. London: RINA, 2005.

Baldauf, M.; Hartmann, F. (2004). *Investigations into the use of AIS voyage related AIS data.* In: Proceedings - International Symposium "Information on Ships – ISIS 2004", Hamburg, September 2004

Blanding, H. C. (1987): *Automation of ships and the human factor*. Paper presented at the Ship technology and research symposium of the society of naval architects and marine engineers, Philadelphia, PA.

Norris, A. (2007). *AIS Implementation – Success or Failure?* The Journal of Navigation, 60, (S. 1-10), London, January 2007

Sherwood Jones, B.M., Earthy, J.V.; Fort, E.; Gould, D. (2006). *Improving the design and management of alarm systems.* Proceedings of the World Maritime Technology Conference, London, March 2006

SMSI (Swedish Maritime Safety Inspectorate) (2006). *Sjöfartsverkets rapportserie B 2006-7.* Swedish Maritime Administration, Norrköping, March 2006

Wilske, E.; Grundevik, P.; Baldauf, M. (2007). *Overlapping Radar, AIS and ECDIS.* MarNIS Task Report SWP 2.4.1, Gothenburg, March 2007