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University of Rijeka, Croatia

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Royal Institute of Navigation
Science Technology Practice

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8th Annual Baška GNSS Conference

PROCEEDINGS

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DEVELOPING A CRITICAL ATTITUDE TOWARDS THE USE OF GNSS AMONG TODAY'S NAUTICAL STUDENTS

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ABSTRACT. *The paper is motivated by the over-reliance of maritime mates on Global Navigation Satellite Systems (GNSS). An approach designed over the last three years seeking to balance navigational approaches is presented. In accordance with the SOLAS and STCW conventions, the main goal is to raise the threshold of awareness and the confidence of students for the benefit of safety at sea, using the elements of GNSS-reliant navigation in combination with other means. Further, in the context of mariners' syllabi regarding e-navigation, we want to improve our approach through a critical discussion of the presented examples with interested users' communities and also to seize the pace with GNSS standardization activities.*

KEY WORDS: *GNSS use, data reliability, error expansion, situational awareness*

1 INTRODUCTION

> *Your presentation about your concerns reminded me of those days when I was riding ships for days, weeks, months and years, in order to learn about the needs of navigators. I think what happened over these years is that a ship's navigator previously understood the process of establishing a position by getting ranges and bearings, which all made some sort of sense. But once microwave transponders and GPS came into the picture and they no longer understood the process, some navigators assumed that it was all failure-proof "magic" that they did not understand and they automatically assumed it was perfect.* [H. Lanziner, private correspondence]

Acknowledging Mr. Lanziner's early notices from the times of the introduction of ECDIS we believe that the observed basic response to technical advances remains more or less the same. Facing the reality that at times instrumentation's measurement results distributions excess the uncertainty, seafarers should always be aware of the dilemma as to which navigation aid or system is the most accurate regarding vessel's position and velocity in certain specific situations. This dilemma extends to what is more important in order to establish situational awareness – a more rapid navigational solution or longer but reliable accurate solution. Certainly, when there is sufficient time, optimally both should be used.

It is normal that a navigator under pressure would choose to rely on the most rapid automatic solution, which is currently delivered by the GNSS receiver. The less experienced operator does not suspect that information from the integrated electronic chart system (ECDIS) may become biased due to erroneous information from the GNSS receiver. Yet one must be aware that in the case of poor reception or the disruption of GNSS signals the severity of resulting events, including potentially adverse effects on SOLAS applications, are unpredictable — which even the developers of various GNSS dependent services and GNSS receivers themselves would attest to [RoyAcEng, 2011].

Some of the reasons for misinterpretation of position, navigation and timing (PNT) sensor output data are the limited capabilities of the single frequency GNSS receiver for the adaptation to certain circumstances such as sudden ionosphere changes; the error of an operator in inserting inaccurate geodetic datum [Skuld, 2014]; even power supply discontinuities. In addition, the GNSS receiver is not impervious to ill-intentioned human intervention (an attack on GNSS signals may completely degrade a less competent operator's awareness regarding the own position or the vessel's course).

2 DOCUMENTS TO BE FOLLOWED

Let us review the mandatory recommendations for seafarers regarding the use of navigation instruments and check how these documents treat GNSS.

The SOLAS Convention (International Convention for the Safety of Life at Sea, 1974) covers all aspects of the safety of the ship, its people and the environment in which the ship is located. In one of the most important chapters, IX, Management for the Safe Operation of Ships, which is also defined by the ISM (International Safety Management) Code one can find that the shipping company is responsible for the safety of the ship in all aspects. This means that the ship and the shipping company are linked through the SMS – Safety Management System – which dictates that the officer of the watch (OOW), among other responsibilities, is responsible for continuous monitoring of the ship's position.

Despite the accuracy and of today's satellite navigation systems, SMS and SOLAS point out that the ship's position must be verified using alternative methods. For safety critical applications SOLAS regulates the use of satellite navigation aids. Caution is demanded especially when the response time is crucial, such as during search and rescue missions or navigation in populated waterways under poor visibility.

The STCW Convention (Standards of Training, Certification and Watchkeeping) also dictates that seafarers should not rely solely on the position fix obtained by using GNSS. The IMO model course 7.03 (see [IMC703 2014]) emphasizes that "a position obtained from GPS is not the primary source of information for position determination and identifiable terrestrial landed objects should be the main priority as sources of position fixing references." In this manner different GNSS independent maritime navigation methods are defined as: terrestrial, celestial and hyperbolic.

Terrestrial Navigation

The position in two dimensions in coastal navigation can be determined in several ways. Two of the most common methods are:

- By measuring bearing from two observed objects (terrestrial theta-theta) – the accuracy of this method depends on the precision of the compass used to measure the direction (Figure 1),

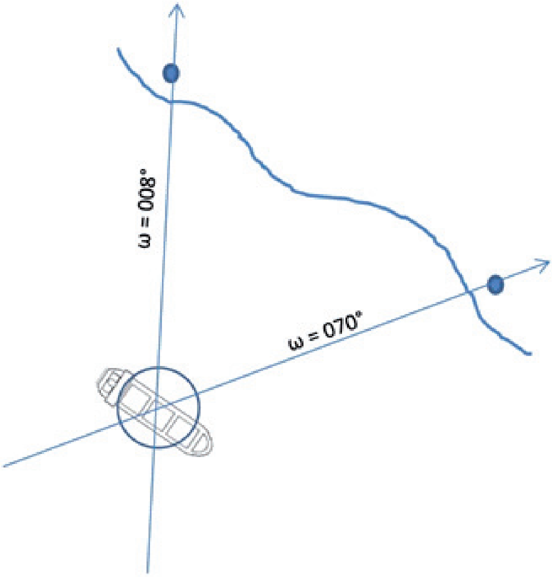

Figure 1 Position fix with two bearings on conspicuous objects

- The measurement of distance to one or more objects and the bearing (rho-theta) – the measurement of the distance is carried out by radar (Figure 2).

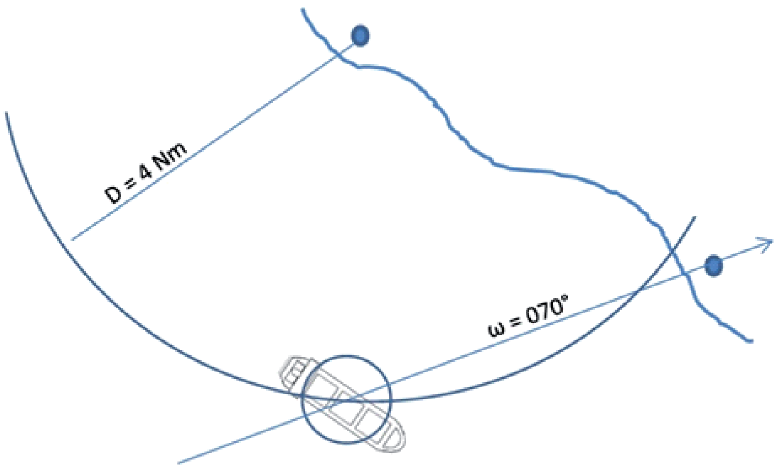

Figure 2 Position fix with a bearing on and the distance to two conspicuous objects

Celestial Navigation

In the era before GNSS, determination of the position of the ship on the open sea was reinforced using celestial bodies, the most widely accepted method being Azimuth intercept or the so called Marcq St. Hilaire method (celestial theta-theta).

Hyperbolic Navigation

Within terrestrial hyperbolic sea-surface positioning systems hyperboloids are determined by the measurements of:

- Time and phase differences of signals' as received by an observer's station from at least a triplet of dedicated transmitters, which gives the vessel's position through the cross sections of distance differences of hyperboloids' on-surface projections (eg., the LORAN-C system, still in function, partially dismounted),
- Phase differences only (e.g., the British DECCA system, obsolete).

Although the GNSS system is essentially also a hyperbolic system, due to its global character and higher performances the GPS itself (helped by GLONASS) has almost completely dislodged the terrestrial hyperbolic radio navigation during the last two decades. In spite of all lacks GNSS dominates positioning at sea. Nowadays terrestrial hyperbolic systems are coming back into use, mainly in Europe, redeveloped as a back-up to satellite systems under the name of e-Loran, eDLoran, etc. Due to the higher exposure of the space based critical navigation infrastructure, especially to variable solar activity but also modern artificial terrestrial signal attacks governments were compelled to *think about baking resiliency into enhancement the PNT architectures and designs*. They want *to preserve the sufficient continuity of operations of the critical infrastructure if a disruption was to occur, with planning a self-healing PNT system that bends in the face of a disruption, rather than breaks* [R. Crane, Baška 2014]. In Canada, an additional function of a ship's radar is called RadarFix, as the GNSS backup at harbour approach and dockings in reduced visibility conditions.

For the education of future vessel navigation executives it is clearly written in Model course 7.01 that the student (trainee) must be encouraged to develop a critical attitude towards possible errors, limitations in precision positioning and the need for constant checking of position (Model course 7.01, 2014 – Master and Chief Mate in Section 1.2, Determine Position and the accuracy of resultant position fix by any means).

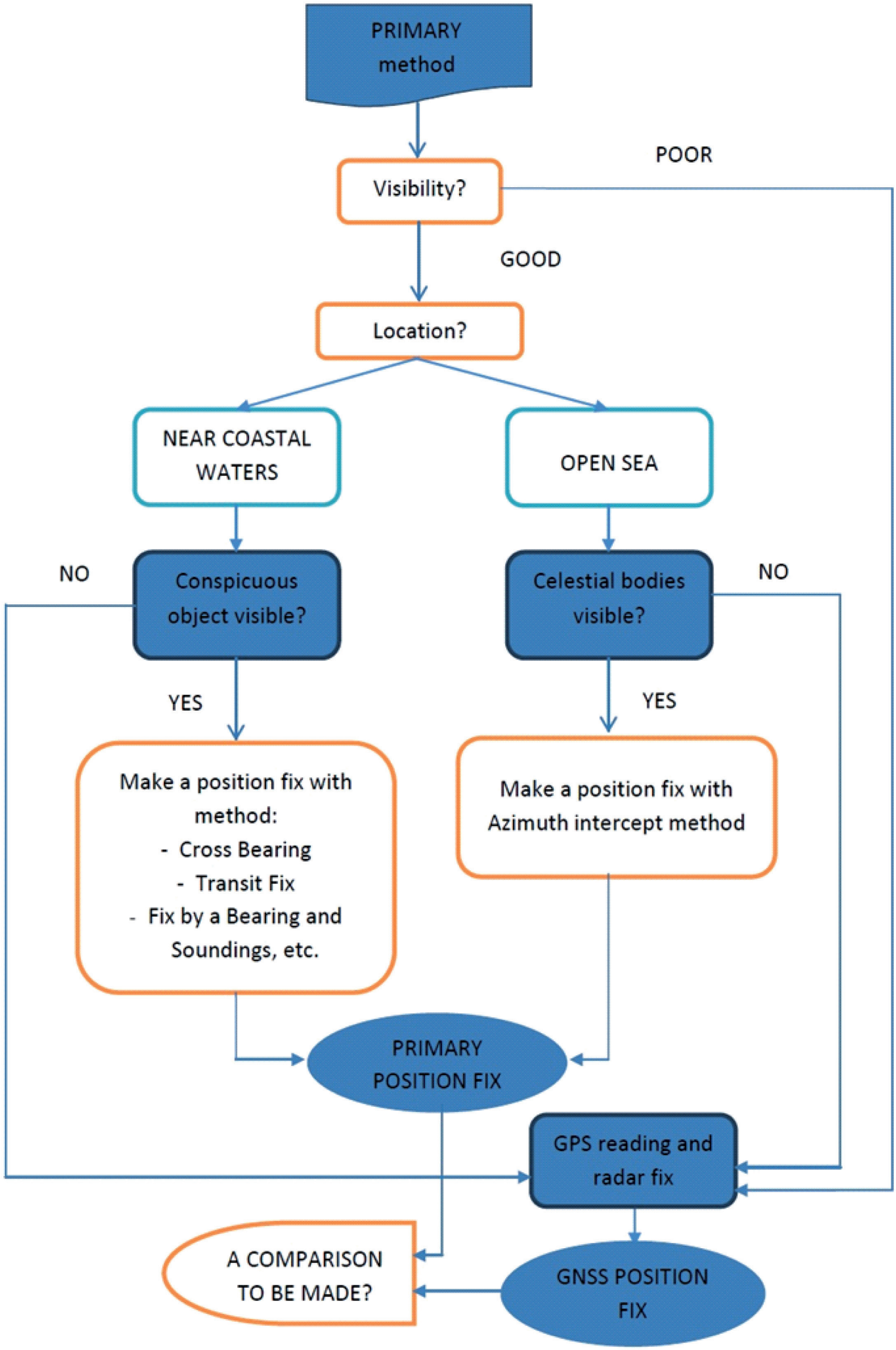

Figure 3 The position getting algorithm – the safe way

Further learning materials which warn mariners of the possible unreliability of the GNSS system (or of human error when using a GNSS) are the books “Bridge Team Management” [Swift, 2004] and “Bridge Procedures Guide” [ICS, 2007]. Swift [Swift, 2004] points out that electronic system for the determination of the position (e.g., LORAN or GNSS) may act as a reliable instrument, but the operator “must be familiar with the principles and shortcomings of it in order to avoid a false sense of safety.” The same author stressed that “the diligent seamen always check the position obtained by GNSS with another independent method for determining a ship’s position, even if would be the most simple, such as dead reckoning” (see Fig. 3).

When not navigating according to the mandatory recommendations one step before making a decision regarding manoeuvring which guarantees the safety of sea navigation is using a GNSS independent source of PNT information. If possible, the seafarer should verify the position by radar or by visual observation of objects (position obtained by several fixes); along a coast the parallel index technique – marking the boundaries of hazardous areas for navigation on the radar picture or ECDIS and quickly checking the position obtained through GNSS – is very useful.

Naturally, conspicuous objects along the coast must already have been foreseen when planning the passage so that it is possible to implement alternative methods of determining position. ICS [ICS, 2007] also warns that: “The OOW should not become over reliant on automated navigational equipment, including electronic chart systems, thereby failing to make proper navigational use of visual information.”

Keeping in mind progress towards unmanned vessels and the human susceptibility to simplification, we may ask ourselves: What is the attitude of maritime educators toward the plans for unmanned ships? Should we join our forces with those who seek to make advances in artificial intelligence at the expense of losing some time in educating trainees according to current capabilities? The vision of the unmanned vessel aims for increased safety, better energy efficiency and costs, but why beside all technical aids the future officer still needs training of dealing with unexpected from interaction with teachers and through process of getting own experiences?

Many of the actions made by human operators are transferrable to machine and all acts of a good navigator should also be explainable and transferable to software with a machine learning approach, but there always remain a field of unexpected situations which OOW may face and behave better than a machine. Of course this line of thought is necessarily relegated to the future; for the time being, an unmanned vessel remains unthinkable.

3 ORIGINS OF GNSS OVER-RELIANCE

Based on the professional literature mentioned in the previous section it is clear that a seafarer, during the training stage, is advised on the pros and cons of GNSS and should develop a healthily sceptical attitude towards it and while working on board should verify the results of electronic devices by using alternative methods. Despite any applied obligatory IMO content, IMO directives may have a limited impact on trainees. Reasons for the limitations come from the personal attitude of trainee, though they are also initiated from outside.

System Misperceptions

> *My background is primarily in electronic charting (ECDIS) in the early days when ship's officers were often older and less familiar with technology in general…When we introduced our PINS (Precise Integrated Navigation System) in 1983-1984, we noticed a reluctance by users because it looked too much like a computer. We then devised a 'Directed Syntax' concept where they could operate the entire system from 8 special keys at the bottom of the screen, so we could remove and hide the 'computer-like' keyboard.* [H. Lanziner, private correspondence].

The user friendly, reliable device is the holy grail of the modern designers and manufacturers, who attempt to tailor their products such that they are attractive and accepted promoted through the social networks which nowadays channel much of the influence of public opinion. As industry has accommodated the operators' early reluctance to engage computer-like navigation devices by reshaping the terminal and changing the displays this trend has had its influence for example on the current ship's dynamic positioning console. The GNSS applications are tested against many failures through simulation, which is a process similar to and associated technically with 'gaming', which has made advances in comfortable interfacing, yet there is the negative aspect that operator cannot but associate the tool as his disposal with games, thus either leading him to take them less seriously or too casually. This disposal may outbreak as ship's shore close ups for fun.

It seems that a new generation of seafarers trust rather too much in satellite systems, which they are familiar with from early youth, as GPS has become almost ubiquitous in this advanced technological global epoch. It is not surprising, then, that this new generation of young seafarers relies heavily on electronic devices on board, trusts the information provided by these devices and does not reflect on whether the information is credible. A common perception has arisen ([Charette, 2011], [Stewart, 2011], [RoyAcEng, 2011]) that PNT related services are available always and everywhere. A related problem is complacency in regard to the security and perfection of large systems like GPS or GLONASS, which are thought to be completely secured against any disruption, whether natural or artificial.

> *Of course, the other problem was that some officers believed that these systems were failure proof, although at that time, there were many inaccuracies with charts and other problems because it was a new technology. This was all long before GPS, so we had to use expensive and complicated microwave systems for positioning at the start, which also had many problems. In some cases their confidence in our systems scared the hell out of me* [H. Lanziner, private correspondence].

Sustaining the device's reliability while introducing operational simplifications is a technically very challenging task, especially at low cost. Not to mention that in professional use the more expensive device is treated as more reliable, and, in fact, often is in that it is more apt to survive the mistakes of operators.

Technology Progress

GNSS receivers are today an integral part of the ship's e-navigation system, which means that they are integrated in most of the systems on board which comprise bridge team management. Automatic systems (ECDIS, ARPA radar, AIS, etc.) play an important part in the decision-making process of each watch officer – collision avoidance, traffic situation control, situational awareness, etc. In order to relieve the navigator of oversaturation with information of today's technology used on ships, in 2006 the IMO issued a "Strategy for the development and implementation of E-navigation" (MSC85, Annex 20). E-navigation is designed to improve the safety of maritime traffic by combining the information from existing and new navigation devices with data fusion concepts. A further release from burden may be that navigation is now scheduled to go paperless [e-nav 2014].

At first sight the scheme of e-navigation not only substantially improves but also removes the effects of GNSS fragility and vulnerabilities. However the careful operator should through data fusion not only understand the role and limitations of each navigation aid, be aware of the current status of each aid, but also to predict the occurrence of failure in the scheme of integrated positioning from the aid's behaviour [Bhatti, 2007]. All this consequently requires great concentration, especially in safety critical situations.

The seafarer feels very self-confident due to the service on-line access through satellite links, when it seems the service is present everywhere. If the operator issues problems during the use of some devices, even occasionally the decrease of reliability, the manufacturer immediately starts the campaign for the new, upgraded model. But the new model may be useless for the operator who observed the fault and acted too late [Lützhöft, 2002].

Some items were listed which release the operator from thinking about the complex technology and left to concentrate on the field of work. This diversion is good and bad. Good in a sense that the work is done with less stress, but bad for the operator may become even more careless in the time when it is possible to avoid the major failures. The fact is that human beings are subject to becoming rather too accustomed to machines, and tend to suffer an erosion of skills when reliant on new technologies. Bearing this in mind, this sometimes lethal absence of critical reflection necessary to retain skills, to even understand the need to retain these skills, maritime educators must attempt to instil in students an understanding of the dangers of passive reliance on technologies and the need to govern themselves according to every standard of safety they are taught – however the natures of GNSS over-reliance origins are not distinguished.

4 THE CONSEQUENCES OF GNSS OVER-RELIANCE

If the seafarer becomes accustomed to the output of an automatic device, he tends to relax, sometimes too much so, in regard to the environment and circumstances, and is slow to respond to errors, thus at times losing control over preventable incidents or accidents [Lützhöft, 2002], leading to marine accidents. One of the most notorious accidents due to blind faith in a GPS device was the grounding of the passenger ship Royal Majesty [NTSB, 1997]. The reason for this accident was that no one noticed that the GPS antenna lost contact with the receiver, and so the GPS device went to dead reckoning mode, which went unnoticed until it was too late. Another example was the grounding of the fishing boat Sanga Na Langa. Although the navigator knew the area well, he blindly trusted the GPS device, which that day, for reasons as yet unexplained, showed the wrong ship's position [MNZ, 2006]. The most recent example of a shipping accident due to over-reliance on a GPS device was the grounding of the cargo ship Douwent, on 26th February 2013, caused by the incorrect use of the device and its "Voyage planning" function; the GPS information did not match the passage plan so the OOW steered the ship towards waypoint according to the GPS he steered the ship in the direction of WPT 90. It was not a mistake of a GPS signal, but a human error while using a GPS and lack of checking the ship's position with alternative methods[MAIB, 2014]. Over-reliance on other ship's GPS receiver solution in a combination with bad bridge-management and worsened conditions may cause grounding of own ship as in the case of container ship Cap Blanche [TSBC, 2014].

There have been a number of similar cases of accidents in the maritime field caused by most of them is the false sense of security, the over-reliance on false the GNSS device or automation in general.

5 OUR SOLUTION

At our faculty we have designed an approach that we hope will be effective in instilling in our students the critical ability to avoid over-reliance on automated systems. We employ problem based learning, beginning without previous lessons on integration itself – in fact not even introducing the phrase 'integrated navigation system' – using a hands-on approach which should prevent students from relying on 'automated large systems' and equip them to find 'an opened channel' to their awareness. By the end of the process, the students will come to an understanding of integrated systems without the tendency to passively rely on technical devices.

Exercises The first meetings at the beginning of the semester on bachelor level are organized as a general audience warm up, introducing illustrative examples (as in section 4) of the potentially disastrous consequences of overreliance on automated navigational information. The teacher encourages students and guides them into the world of integrated navigation by asking them the simple question: *How do you know what time it is?* using science: understanding that matching the navigation data from different sources relies on having accurate information regarding time. *How is accurate time obtained? What is the access to the accurate time source at sea? How accurate is your watch? Which facts make you so sure you are really here, or on this course?* The answers, of course, supported scientifically. Students soon intuitively comprehend the importance of the simple question in the maritime context and then the need to follow the abstract (objective) model concept which leads them to understand the method of error calculations (see Figure 3) together with *feeling* the importance of making instant corrections. And once their doubt regarding standard responses reliant on automated devices has been undermined they are taught the necessity and means of confirming their solutions from independent sources.

List of hands-on exercises: Each group is given certain practical tasks selected from this list: *Test a group of clocks over ten days, Connect the gyrocompass* *with a computer and track the course, Use a pair of IMU (inertial measurement unit) and collect data on rowing boat and on motor boat, Measure the sea-depth and salinity at 30 pre-defined points, Learn the basics of how space weather influences sea navigation.*

All exercises are designed to prevent the students from being overwhelmed by scientific background e.g. error propagation modelling, but instructions emphasize to keep a sharp eye on: which quantity is logged or observed, when and how accurately, the basics of processing the data, and interpreting results to obtain accurate information after the fact.

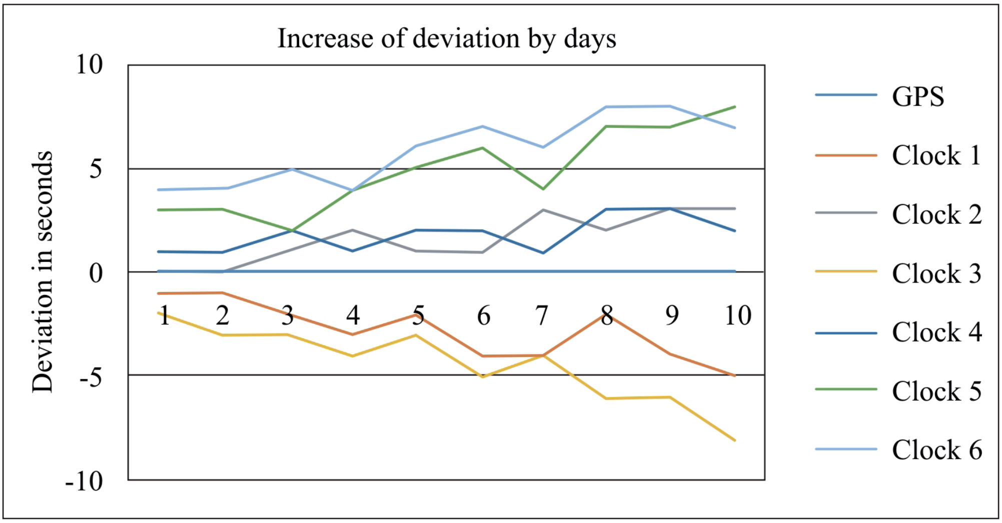

Figure 4 Students' results of the 10 days testing of six clocks

Team preparation work Through answering questions on experiences smaller group formation begins. Some students with sea experience ask at this point about ECDIS and they are requested to become the leaders of groups. Through the self-organized preparation sessions groups get inspired with aims and also get acquainted with instruments to acquire a sufficient level of confidence to start with their selected exercises. Students with sea experience and boat piloting licenses take the responsibility for the exercises executed in the near coastal sea area.

Practical work and results Each group accomplishes the prescribed tasks and prepare the results.

The *Time group* among answering the questions on timing from introductory session also realizes how non-uniformly the error of their clocks behave when comparing to the time acquired by the GPS receiver (results on Fig. 4).

The *Gyro group* mounts Gyrotrack on a motor boat and tracks the path together with a GPS receiver. Students solve the question how to combine the gyrocompass courses (NMEA output) together with the GPS tracked trajectory on the same map. Students acquire intuitive insight into error propagation models, and PNT data fusion methods that make logged data more reliable.

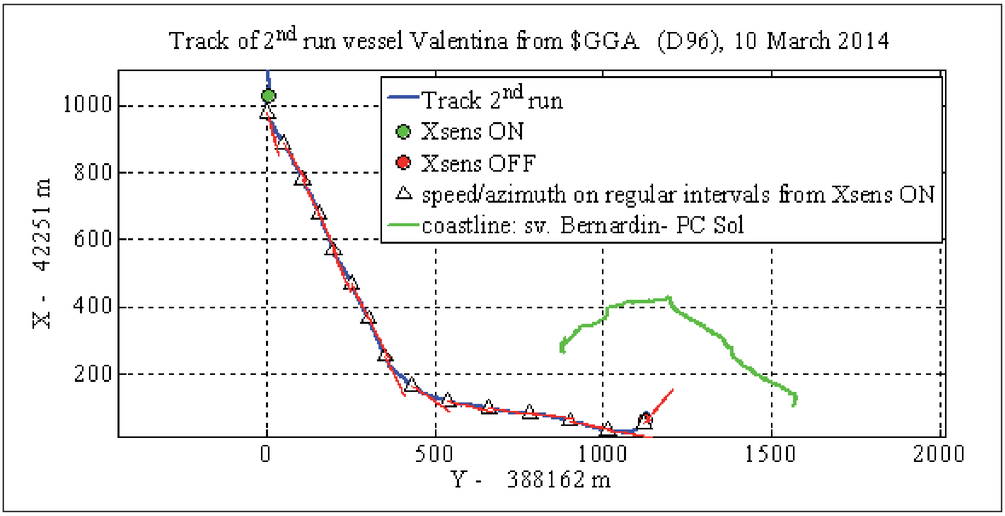

Figure 5 Improving the ability to match and evaluate the changes observed in Fig. 6 with the track form from the GNSS receiver.

Two *IMU groups* work on different types of vessels with a task to collect the data from the IMU units, attached on both sides and from the GPS receiver. Regularly sampled course calculated from GPS data is presented with red lines on Fig. 5. Initial task was to present how the data differences shows the differences between each vessel's navigation. One practical challenge due to healing from over-reliance was to explain how to transform IMU captured magnetic field densities vs. time diagrams (see Fig. 6) on to a nautical chart. Students combine the course from the GPS track with the calculated course from the IMU magnetometer. Error propagation models are with some more efforts again brought intuitively in the form of comparing vessel's courses data from different types of sensors.

Salinity Sea-Depth group dwelled on each of the pre-defined point and measure there both the seawater salinity at 0.5 m under sea-surface and the sea-depth. Results (for sea-depth at Fig. 7) are geo-referenced by the L1 GPS receiver set on 1s sampling the position fix. Students elevated their understanding of terms' repeatability and accuracy by comparing the measurements' results.

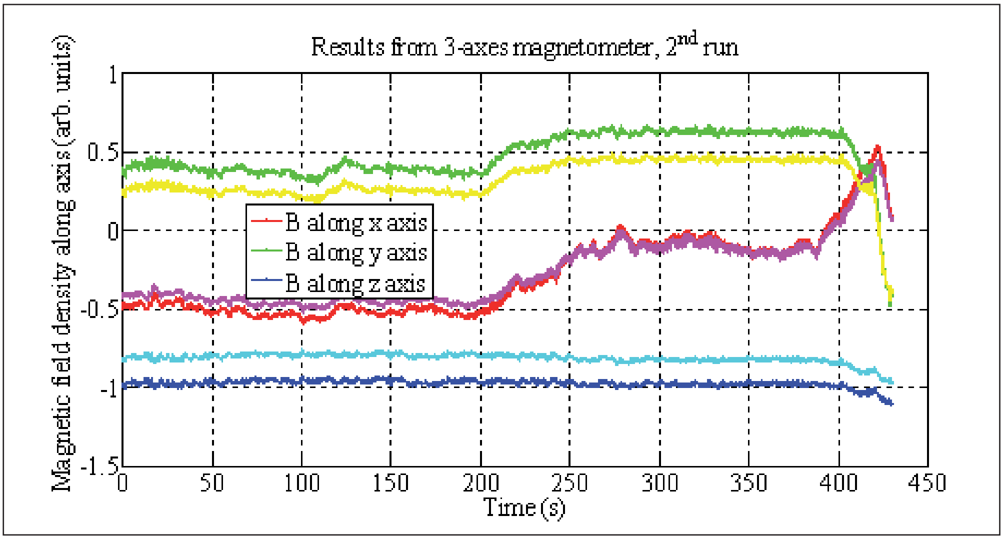

Figure 6 Test of the interpretation abilities: how students can describe the changes observed by the IMU's three-axes magnetometer

Process of visualization makes students understood the importance of making notes about the time of data sampling, and also the basics of transformation from the WGS into the local geodetic frame.

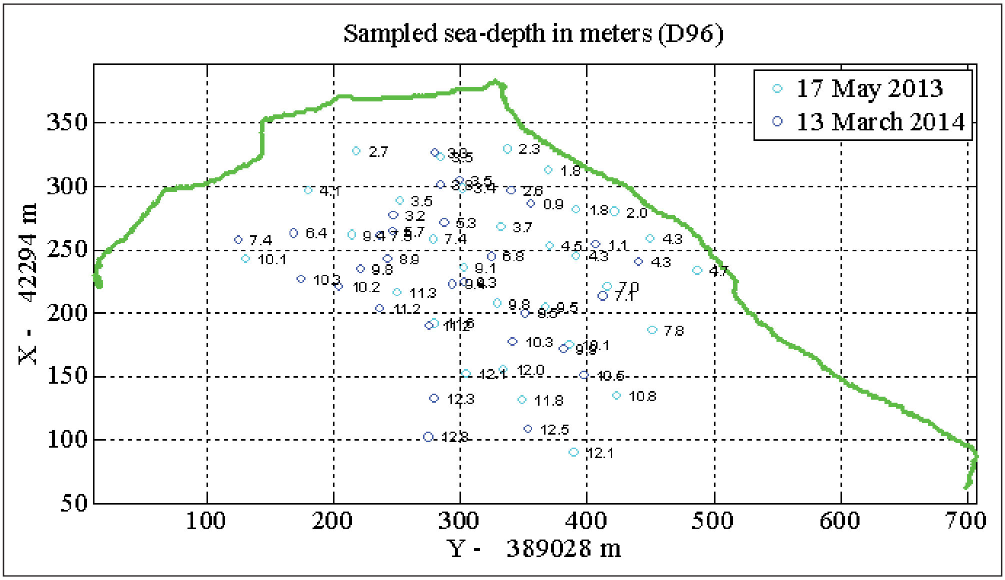

Figure 7 An overview of the sea-depth in meters near the faculty harbour in the local geodetic frame. Coastal line is coloured in green.

Space weather group collected the facts about the Sun-activity influences on navigation. Their findings well accorded by the invited lecture of Mr. Pavel Najman on June 6, 2014, who presented his research on disturbed ionosphere modelling.

Reflections of after-work Students are instructed to spend significant time on the post-fieldwork phase. Some of reflected conclusions are presented.

Students experienced how hard is to get on a pre-defined position and retain it for a minute or so without dynamic positioning aids. An important approach is to involve future navigators into IMU sensors' data visualization process. Students get hands-on experience to match the space where they are familiar with (e.g. GPS output) with the space for which they need some help of theory (e.g. magnetometer output). Through the data processing they intuitively become acquainted with the meaning of confidence, reliability. Thus some of students begin to understand how deeply and hazardously the over-reliance on a particular device may divert their situational awareness from reality in which something is going on but is not reflected in the data obtained from the device they use. And they get the feeling how this observed deviation can make their life unpredictable in the long-term. The aim is for the students of understand the need for data integration, which must come from the conclusion of the groups, clearly expressed in their reports which they are obliged to write in groups before making a five minute presentation of the essences at a plenary meeting.

Follow-up Some students after these presentations become interested in 'the science behind', but for the most part they then go on to delve into such subjects as postgraduates. During examinations at the bachelor level, most of them at least display sufficiently that they are cured of over-reliance on GNSS.

Lessons After the conclusion of exercises the lessons begin, continuing throughout the semester. Students are taught about basic technical facts of each navigation aid, including GNSS and also about the data transfer among instruments in the NMEA 2000 network. An important part of these lessons, albeit not very extensive, is the presentation of independent and uncorrelated data error modelling. During the exercises and again during lessons students are made aware of the origin of possible bias in the navigational aids and propagation of these errors in derived navigational solutions. Through illustration of the consequences of error students learn the need for regular calibration of as a potential lifeline for survival at sea.

6 CONCLUSIONS AND FUTURE WORK

Since deck officers will inevitably use GNSS to some degree, through the educational process a balance has to be achieved in their attitude between over-reliance on GNSS and its effective use. A better balance is obtained through understanding what instruments are capable of, and when it is better to rely on one's own senses. Within our scope the increased balance is achievable by the gradual increasing of the hands-on familiarization with the complexity of instrumental navigation also to encourage students to induce their experiences rather than switching from an over-reliance into blind instructions following. The sense for dealing with the unexpected must start through understanding the ever evolving causation of accidents and the simple realization that they are often caused by over-reliance automation. Students must be infused with the notion that the human is not replaceable.

During practical work the teacher should get an indication of how during the exercises the students' intuition and general navigation deck working competences develop. Ideally, the students develop spatial awareness that they underscore with science, knowledge and feeling crucial for the navigator. Final results are presented to an audience on the deck of the school boat.

Teachers and researchers of GNSS vulnerabilities are, it may be said, on the front lines of ensuring the safety of life and property at sea. One of our additional tasks is to influence those groups which decide on measures, standards and legislation to consciously follow new algorithms and technical innovations. We should not to forget RADAR, and celestial navigation. At least not before the GPS's resilience issues are resolved, not before the full operation of multi-constellation GNSS, and perhaps not before a backup GNSS systems network becomes more widespread.

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JAMMING-SPOOFING-MEACONING-RESILIENT GNSS PERFORMANCE AT THE OPEN SEA

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ABSTRACT. *Satellite navigation has become a public good, with the growing number of navigation and non-navigation applications being established on the technology. Potential threats on GNSS performance and operation have become the increasing concern of developers, operators and users of GNSS-founded systems and services, with the especial emphasis given to malicious artificial attacks, such as jamming, spoofing and meaconing (JSM). A targeted artificial attack on GNSS performance and operation can cause a considerable material damage and affects lifes. Here the potential consequences of the artificial attack on GNSS performance on the vessel navigation at the open sea are addressed, and a combined technological-procedural mitigation scheme for JMS- resilient GNSS Position, Navigation and Timing (PNT) performance at the open sea is proposed. Through the technology-supported modifications of navigation procedures a reasonable GNSS Quality of Positioning at the open sea can be achieved, overcoming the potential malicious attack on the vessel in the area with the reduced supporting Information and Communication Technology (ICT) infrastructure.*

KEY WORDS: *GNSS performance, jamming, spoofing, meaconing*

1 INTRODUCTION

The increasing volume of maritime transport emphasises the vulnerabilities of the GNSS operation at provision of positioning, navigation and timing (PNT) services at the open sea.

The crew, vessels and goods transported may be at the continuous peril as the result of potential provision engineered GNSS signals and navigation data. The potentials of provision of manipulated signals and data for the open-sea users ranges to the extents of jamming, spoofing and meaconing (JSM).

The lack of the supporting information and communications technologies (ICT) infrastructure at the open sea can be recognised a chronical issue persisting and even growing in the importance.

Here we propose a process that aims to assure the provision of the JSM-resilient GNSS PNT services at the open sea. The proposed process acts as a JSM counter-measure that can be implemented internationally and independently of the core GNSS operations. The anti-JSM effort of the proposed process can be considered a GNSS risk-reducing process.

2 PROBLEM DESCRIPTION AND PREVIOUS RESEARCH

Maliciously manipulated GNSS signals and data (Figure 1) normally sent through the air interface present the growing threats to numerous GNSS applications, but the particular concern is given to the safety-critical applications, such as those for navigation.

In general, the engineering of GNSS signals and data can take on of the three essential forms: jamming, spoofing, and meaconing.

In the case of jamming, the manipulation of the GNSS signal aims at overcoming the original GNSS signals at the position of the end user by malicious transmission in the same spectrum the signals of sufficiently large power, thus causing the geographically constrained outage of the GNSS PNT service.

Spoofing is a deliberate transmission of engineered (non-original) GNSS signal with the intent to cause false position estimation.

Meaconing is achieved by interception and re-broadcast of the engineered GNSS signals on the same frequency and with slightly higher power than the GNSS satellite in the malicious intent to influence position estimation process resulting in obtaining inaccurate (false) position estimate.

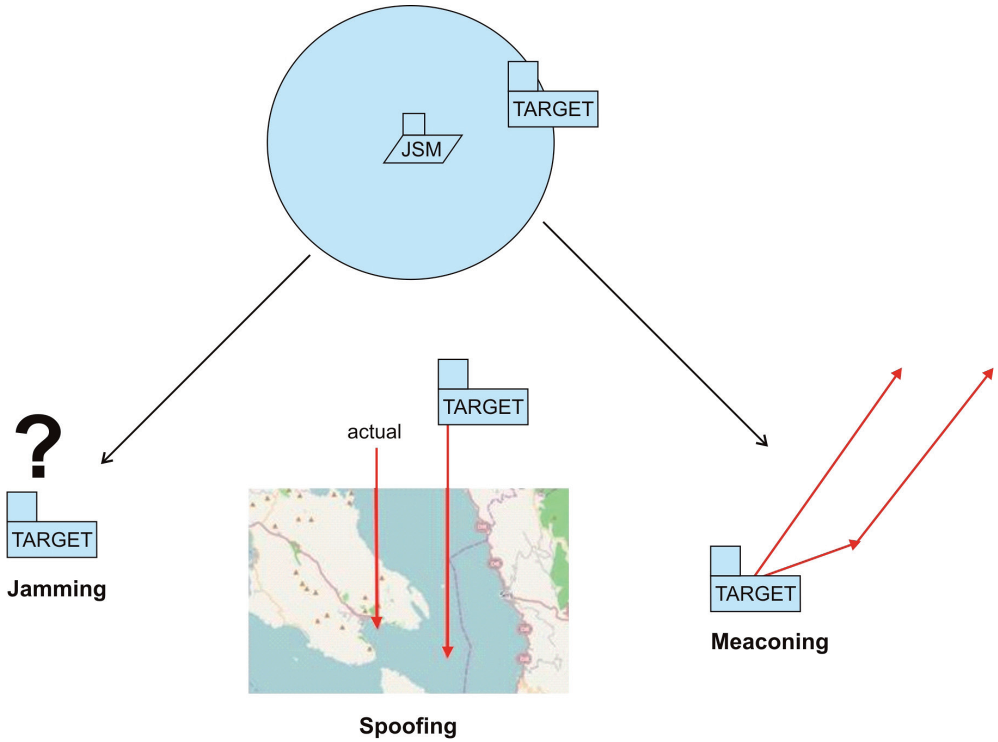

Figure 1 Challenges of the open-sea satellite-based navigation

The evil intent behind the Jamming-Spoofing-Meaconing (JSM) operation may cause significant damage when utilised at the sea. The range of potential targets of the JSM operation at the sea comprises:

- Vessel's load (the scenario in which the vessel is intentionally run ashore, and the remains of her load grabbed);
- Crew (the scenario of kidnapping crew for a ransom);
- Vessel herself (the take-over or hijacking scenario, intentional vessel destruction, hostile exploitation of the false vessel's location in protected sea areas).

Still, the operation at the open sea restricts the risks, with running a vessel ashore being less probable, but with crew kidnapping moderately-to-highly and vessel take-over highly probable scenario.

3 A SCHEME FOR JMS-RESILIENT GNSS PNT AT THE OPEN SEA

The risk assessment of the JSM attack deployment reveals its nature.

The *jamming attack* requires a simple and cheap equipment, making the attack a not highly sophisticated. This highlights the probability of the jamming attack deployment, since even a non-experienced operator can launch it cheaply, easily and successfully.

The *spoofing attack* is highly sophisticated by its nature, requires targeted professional education, skills, experience and a very sophisticated and relatively expensive equipment. By its nature, the spoofing attack is less probable than the jamming one, but should not be ruled out, since the attack can be successfully deployed in scenario that covers dedicated geographical area remotely. The prerequisites for such an attack include the high competence of the attacker, good organisation and lavish funding.

Although less sophisticated than spoofing and more sophisticated than jamming, the possibility of the meaconing attack should be considered moderately to highly probable. The prerequisites for such attack comprise moderate-to-high professional competence, good organisation and financial support considerably smaller than in the case of spoofing. Such an attack can be conducted with less-experience personnel using highly sophisticated equipment.

Considering the nature of the JSM attacks and their risk assessment, here we propose a procedure for development of the JSM resilience on the open sea. The procedure is built on the identification of the signatures of a JSM attack in operation that can be performed on the vessel using slightly enhanced GNSS receiver and the resilience development procedure.

The signatures of a JSM attack in operation may comprise one or more of the following:

- Received satellite signal strength changes to slightly to considerably higher levels than usual;
- Rapid change of the satellite signal strength can be observed at the moment of the start of a JSM operation;
- Increasing discrepancy with the readings of the other positioning sensors may be observed;
- Apparent discrepancy in relative signal power/strength of different GNSS signals (for instance: GPS L1 and GLONASS signals) may be observed;
- Discrepancy between satellite ephemeris and almanac data broadcast by different satellites of the same system may be observed;

- Sudden variations of the receiver's Automatic Gain Control (AGC) values;
- Variations in Doppler shift, carrier phase and the code starting times of mixed and accumulated data streams of the two dis-located receivers.

After identification of the signatures of the potential JSM attack in operation, the procedure for the resilience development against the JSM attack on the open sea can be defined, that has its foundation in the requirement for continuous GNSS performance monitoring both on the vessel's bridge, and regionally and globally.

The crew should be instructed to perform the continuous look-out procedure for signatures of the JSM attack operation through regular manual inspection of the received signal strength recordings, comparison with between GNSS receiver readings and the readings of the independent positioning sensors, and deployment of the specially designed GNSS receivers that will look for the signatures of the JSM operation automatically.

In (Filjar and Huljenic, 2012) a general process for the resilience development against GNSS vulnerabilities and risk has been proposed. The process can be mapped on the GNSS JSM risk assessment for sailing at the open seas, as presented in the remains of this chapter.

The proposed scheme for JSM-resilient GNSS positioning, navigation and timing (PNT) services at the open sea requires all three general resilience-development groups of tasks, defined in (Filjar and Huljenic, 2012):

- Preparatory segment,
- Monitoring segment, and
- Operational segment.

In preparatory segment, the risk of the reasonably possible threats should be assessed, as well as the its potential impacts on the navigation processes (what are the effects of a GNSS failure for navigation?). The measures to overcome those effects and risk should be devised.

Monitoring should focus on identification of the JSN attack signatures, and should comprise both manual and automatised activities, as well as the international collaborative approach in the JSM identification through continuous performance of the simultaneous multi-centred observations.

The operational segment of the proposed scheme should comprise:

- Alerts (both internal – within the vessel, and external – JSM operation report to international maritime safety authorities according to a dedicated protocol);
- GNSS infrastructure protection (should be lifted to the international level, since it cannot be conducted by the vessel's crew);

- Corrective actions (for instance, a temporal suspension of the GNSS utilisation and migration to alternative positioning techniques and resources, with the appropriate reporting to the international maritime safety authorities), and
- Co-ordinated restriction or temporal suspension of the other services relying on GNSS (such as AIS).

The proposed scheme is depicted on Figure 2.

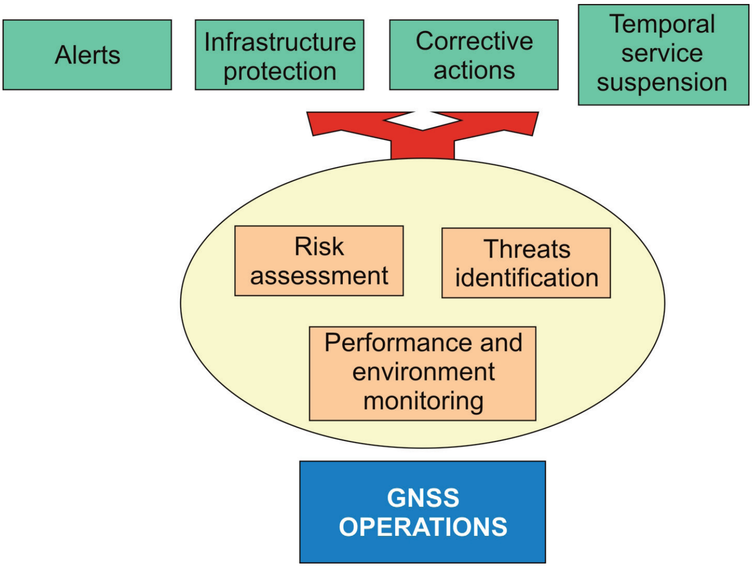

Figure 2 A scheme for JMS-resilient GNSS PNT services at the open sea

4 DISCUSSION

Exploiting GNSS vulnerabilities by creating risks related to GNSS utilisation is a part of the modern electronic warfare, extending to merchant navy as well as to naval forces. A risk of a JSM attack on the open sea is real and probable, but also identifiable. Modern state-of-the-art in electronic navigation focuses on system integration, hiding the system components. This may be seen as a potential risk, since a trained officer on duty cannot manually inspect the performance of a particular positioning sensor.

Understanding the principles of satellite navigation and GNSS vulnerabilities and risks becomes crucial for a modern mariner. A novel design of marine GNSS equipment is needed, that allows for easy manual and automatic inspection of

GNSS performance, with the aim of identification of the signatures of a JSM attack in operation.

With the established continued monitoring of the GNSS signal and PNT performance, the collation of the identified GNSS JSM operations data is highly recommended on the global scale, with the aim of creation of the risk database and the JSM risk knowledge development.

5 CONCLUSION AND FUTURE WORK

Modern utilisation of satellite navigation creates an environment for the malicious GNSS vulnerabilities exploitation caused by the following important characteristics of the GNSS usage:

- Over-reliance on GNSS,
- Existing approach in system integration for electronic navigation,
- Lack of crew's understanding of GNSS.

Here the problem is attempted to be resolved by introduction of a scheme for resilience development against GNSS JSM attacks on the open sea. The scheme calls for:

- Introduction of the new GNSS signal and performance look-out procedure;
- Additional GNSS professional education of the crew members;
- A novel maritime GNSS receiver design, that allows for both manual and automatic search for signatures of a JSM in operation, and
- International co-operation on combating JSM on the open sea.

Our group will continue the research on the subject, with the work to be concentrated on improvements in GNSS SDR equipment design, and the JSM-resilient GNSS operation process development.

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APPLICATION OF GNSS TECHNOLOGY FOR HIGH SPEED BOATS TRACKING AND COLLISION AVOIDANCE

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ABSTRACT. *Since each country with access to the seacoast is an interesting tourist destination, additional facilities are built in such countries to attract tourists. In addition to the usual rental offer of a variety of sea vessels, boats, yachts and sailboats, an increasingly popular trend of adrenaline sport is introduced in the form of high speed boats. They are also called Jetski and present a fast growing rental business in the area of adrenaline sports.*

In this paper possible solutions to detection and prevention of collisions will be analysed in order to raise the level of safety of sea traffic. The research is motivated by the fact that renting of fast boats is done mostly to amateur drivers. They are usually searching for vacation fun with little experience of manipulating high speed boats. Several implementation difficulties due to the high dynamics of these speed boats will be examined. The driving style of these boats which includes very quick change of speed and direction of movement is an additional challenge. Proposed embedded system is based on the Atmel AVR family of processors, and SIMCOM SIM908 GSM and GPS system. Proposed system was tested in real world scenarios during the touristic season on the Adriatic coast. Significant amount of GPS position data for collision detection analysis were collected including tourist behaviour data to test the earning reports generation module.

KEY WORDS: *collision detection, GNSS, speed boats, remote control*

1 INTRODUCTION

Rapid development of GPS and GSM-based embedded computers, their popularization and falling prices opened new areas of application in monitoring, supervision, and control of road and sea traffic. One of the applications is rental of speed boats popularly known as JetSki scooters (Figure 1). The owners of such rental companies have the need for supervision of the current speed boat's position and driver behaviour because drivers are mostly inexperienced amateurs. Additionally, owners have the requirement to obtain earning reports for each speed boat. Such monitoring requires a person that oversees the speed boats from a nearby coast. During the speed boat rental time it can be necessary to shut the boat down or to alert the driver of his wrong actions [1]. Rapid development of embedded computers that are aware of their position, speed, acceleration and movement direction made it possible to execute these tasks and further increase sea traffic safety by setting a geo-fence. This advanced surveillance application requires the boat's geo position inside of a geo-fence area. It enables an automated restriction of the driver's movement outside a certain area. Establishment of such a geo-fence results with prevention of boat alienation; prevents the drivers to enter an area reserved for swimmers; and prevents approaching the coast in a dangerous manner. As rental owners regularly have several fast boats it is very usual to find them at the same time in the same sea area. To increase sea safety as part of such a system speed boat trajectory analysis, collision detection and prevention is required [2].

Figure 1 Speed boats popularly known as JetSki

Proposed embedded system for monitoring and tracking of speed boats is based on the Atmel AVR family of processors [3], Analog Devices ADXL343 3-axis Digital Accelerometer [4], and SIMCOM SIM908 GSM and GPS system [5]. The same system is used for monitoring and tracking of road vehicles in [7] and is for this application upgraded with a waterproof housing, geo-fence functionality and real time software abilities.

The developed boot-loader software allows remote modification of the embedded computer main program using the Hyper Text Terminal Protocol and GPRS communication network [6, 7]. Main program is based and developed on the assumption that a permanent GPRS state-full TCP/IP connection to the server is available. The purpose of the server is to analyse the GPS and speed data received from the embedded system and to store it in a database for additional off-line analysis. Developed TCP/IP server is a socket daemon which enables multiple concurrent connections, collision detection between boats and message relaying for real time remote boat control. Remote speed boat control is enabled in the form of a mobile phone equipped with an appropriate application. The application connects using a permanent state-full TCP/IP connection to the socket server which relays commands to the boat if necessary. It has the ability to turn the speed boat's engine off and warn the driver of his dangerous actions or a possible collision situation.

In order to maintain demanded level of safety of sea traffic, and the fact that speed boats are rented mostly to amateur drivers without driving licenses, the law for companies engaged in the rental of speed boats (Jetski) requires remote control. In this way companies' experienced employees can oversee inexperienced drivers from a shore base and remotely stop them if necessary. At the present day there are many accessories on the market available for speed boat rental. They are mostly based on a simple remote control technology using analogue or digital radio waves with a limited range of a transmitting. But on the market available systems do not even remotely met the needs of companies in the speed boat rental business. There is a need for a device with more technological advancement that includes features like: automated control over boats speed outside a defined geological area and in the vicinity of the coast line, safety systems to prevent boat theft, collision detection and prevention capable of monitoring multiple speed boats rented in the same geological area, automated generation of financial reports of rented speed boats, etc.

2 JETSKI RENTAL BUSINESS REQUIREMENTS

To identify the needs of Jestski rental businesses, an analysis among the related companies has been done. Results of the analysis revile that there exist the need for supervision of the current speed boat's position and driver behaviour because, as mentioned, drivers are mostly inexperienced amateurs. The required advancement of systems available in this area is to enable remote control on larger distances. Remote devices with a transmitting distance limitation of a few hundred meters aren't suitable for this application. Possible alienation and grand theft presents a significant risk and concern for the boat owners. Additional automation in monitoring of inexperienced drivers is required as current technology has a significant disadvantage: monitoring a driver that is located over 500 meters away from the coast with binoculars requires very good skills and focus for the employees. As these rental companies have more than one speed boat on one location, the monitoring gets more and more challenging.

A few employees to supervise this very dynamic situation aren't enough anymore. The employees have to pay attention if someone is driving to close to the coast or to the beaches reserved for swimmers since both is prohibited by law. Additionally, employees have to monitor if someone is driving too far away into the open see since this could end in boat theft. And when there are two or more boats in the water at the same time, the possibility of collisions and driver injures increases significantly. Boat theft and alienation isn't possible only during the day while the boats are rented. It is also possible during the night when the boats are left unprotected in the sea or at the coast. This presents an additional expense for other employees like security guards so an overnight automated security system is required.

Automated supervising of the employees' financial (generated revenue) reports is a main interest for these rental companies so it is also required. Current technology limits the owners of the companies to rely on the honesty of their employees and earning reports written manually by employees on site. Proposed GNSS based device can fulfil almost every task found by this case study:

- Remote control of the boat's engine remotely by an experienced user on the coast;
- Automated control over the boat's speed outside the geo-fence and near the coast line;
- Automated or manual control to prevent boat theft;
- Automated collision detection and prevention for all currently rented speed boats;

- Automated generation of financial reports for employees supervision;
- Overnight automated security to prevent boat alienation.

This advanced surveillance application requires the current speed boat's geo position and enables automated restriction of driver's speed and movement outside a certain geological area usually called geo-fence. Establishment of a geo-fence result with prevention of boat alienation prevents the drivers to enter an area reserved for swimmers and approaching to the coast in a dangerous manner. As rental owners regularly have several speed boats it is very usual to find them at the same time in the same sea area. To increase sea safety speed boat trajectory analysis, collision detection and prevention is required also.

Additionally, by logging all geo-position data new analysis opportunities arise. For example, such data can be used later for generation of many reports or for any online real time calculation. Such real time calculations can be used to take the control over a speed boat in case of possible wrong driving actions. Furthermore, collision detection and prevention or prevention of driving to close to the shore can also be implemented. Report generation could be used for later creation of income reports like the one in Figure 2.

	Ime	start	stop	Vrijeme	Min	Br Osoba	Cijena
1	JET1	11.07.2012. 14:58:57	15:12:35	00:13:38	15	N/A	250.00
2	JET1	11.07.2012. 15:47:48	16:02:24	00:14:36	15	N/A	250.00
3	JET1	11.07.2012. 16:07:03	16:19:19	00:12:16	10	N/A	200.00
4	JET1	11.07.2012. 16:24:01	16:25:01	00:01:00	free	N/A	0.00
5	JET1	11.07.2012. 16:28:16	16:41:53	00:13:37	15	N/A	250.00
6	JET1	11.07.2012. 16:46:28	16:48:59	00:02:31	free	N/A	0.00
7	JET1	11.07.2012. 16:56:21	17:11:37	00:15:16	15	N/A	250.00
8	JET1	12.07.2012. 10:43:32	10:59:19	00:15:47	15	N/A	250.00
9	JET1	12.07.2012. 12:31:23	12:43:14	00:11:51	10	N/A	200.00
10	JET1	12.07.2012. 14:28:04	14:43:15	00:15:11	15	N/A	250.00
11	JET1	12.07.2012. 15:18:40	16:31:48	01:13:08	60	N/A	780.00
12	Ukupno:			03:08:51	170	0	2.680,00 kn

Figure 2 Automated generation of financial report

Source: Made by authors according to [8]

3 BOAT TRACKING SYSTEM ARCHITECTURE

Rapid development of embedded computers that are aware of their position, speed, acceleration and movement direction made it possible to execute required tasks and further increase sea traffic safety. Safety is increased by the automated supervision of driver's actions. The automated supervision can be implemented simple as just a geo-fence control or more complex like a collision detection system. Complete block diagram of the proposed system architecture is presented in Figure 3.

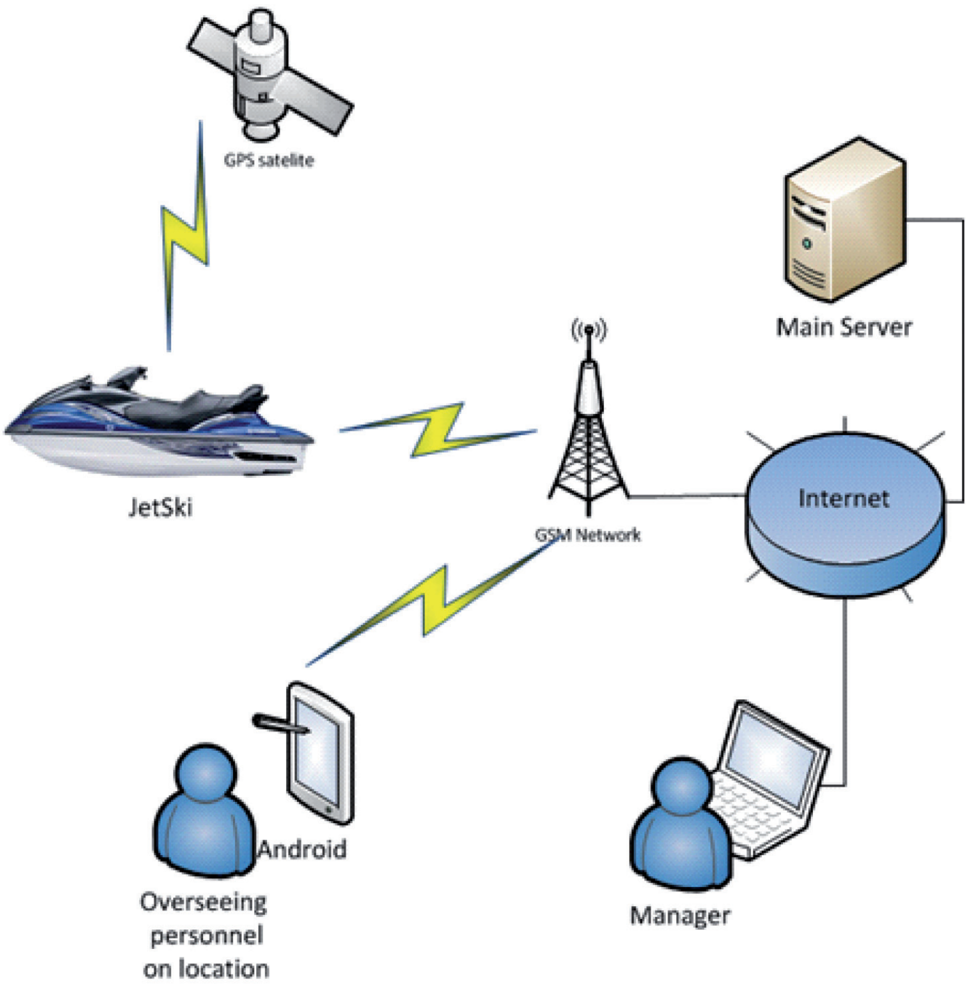


Figure 3 Block diagram of tracking system architecture

A GNSS capable device installed in the boat, with the knowledge of the boat's geological position and connected to the main server over a GPRS TCP/Ip statefull connection, can be used to report its position periodically to a central server and to perform server's or owner's commands. Saved geo-position data can be used for later creation of reports, studying of the boat's dynamics and analysis of the driver's behaviour. Additional remote device like a Smartphone with an appropriate application (Figure 4a) is required by the employee so he can read various reports and issue commands to the boats using the main server. The commands can be issued whenever the device in the speed boat is online. There are also some special requirements on the device enclosure and housing for device instalment inside of the speed boat and the interconnection to it. The device should be installed in a plug and play manner with a simple plug into the fabric formwork of the boat. Additionally, the device has to withstand high temperature, mechanical shocks, humidity and salty air as well as contact with sea water.

The system used for monitoring and tracking of road vehicles described in [7] is modified for this application and upgraded with a waterproof housing. Its remote software upgrade ability over GPRS network is required for rapid software changes and development of a main programme capable of fulfilling tasks found in the Jetski rental business requirements case study. This ability helped the authors to develop and test the proposed system on real world locations during the summer touristic season time while the speed boats were rented. Developed GNSS device is presented in Figure 4b and Figure 4c.

Geo-position calculation and analyses are done partly on the embedded system for geo-fence and sent to the server. Received GNSS data include course and speed data. They are stored in a database for deeper analyses on the server. The data can be also compared to the data received from other boats' embedded systems. Stored data in the database could be used for additional off-line analysis and report generating. But the real time analysis of the data is crucial for collision prevention and other automated tasks.

Developed TCP/IP server is a Linux's based socket daemon which enables multiple concurrent connections, simplified collision detection and message relaying for real time boat remote control. Remote speed boat control is enabled in the form of a Smartphone equipped with an application that connects over a permanent state-full TCP/IP connection to the socket server which relays commands to the boat if necessary. It has the ability to turn the speed boat's engine off, limit its speed and warn the driver of his dangerous actions or a possible collision situation. It can also put the embedded system in a security mode or a night mode to prevent theft of speed boats during off duty periods. Overnight security mode is used in two modes while the boat is in the sea, or

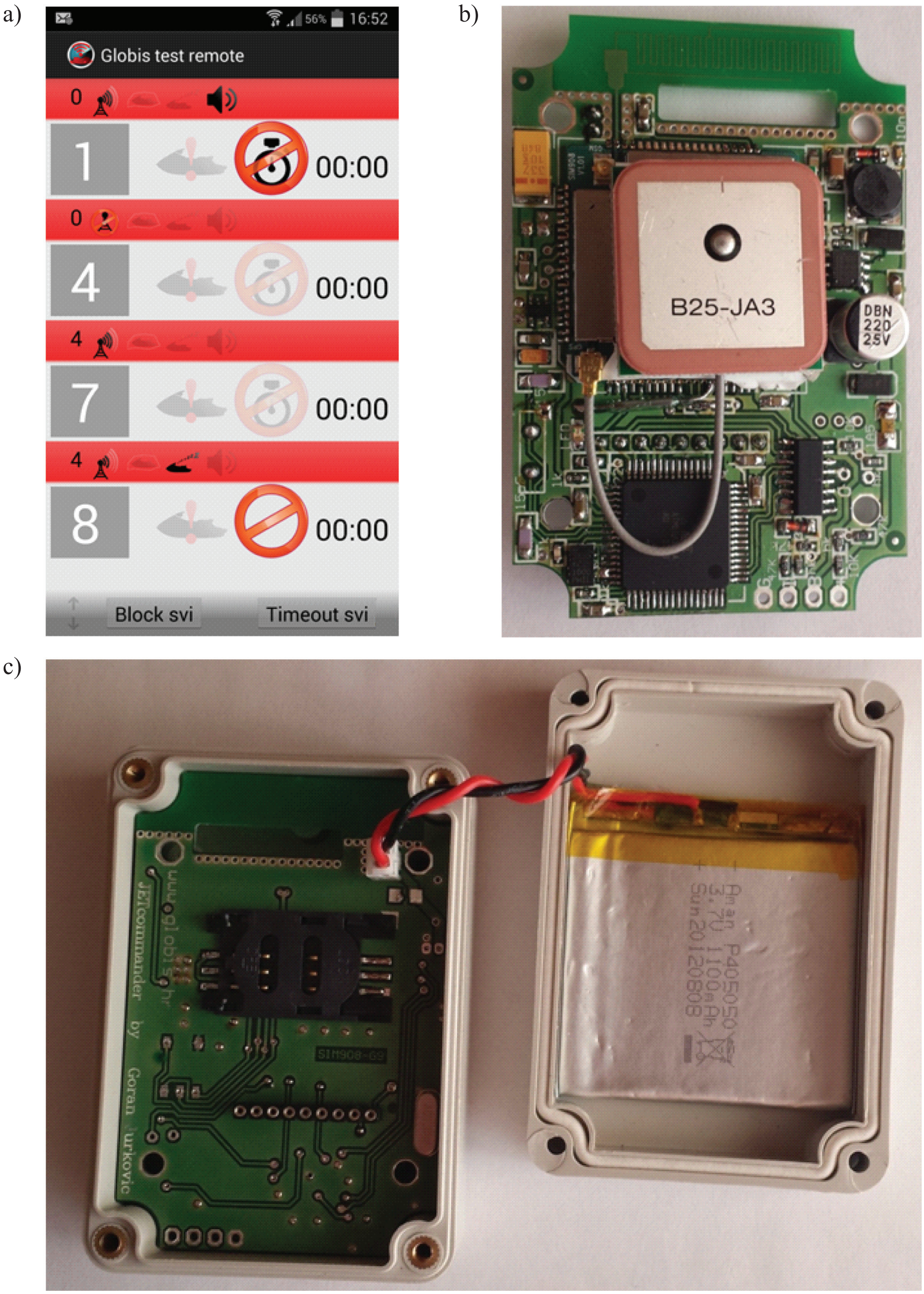


Figure 4 a) Android Application for employer's control over the speed boats; b) GNSS capable device assembled printed circuit board; c) GNSS capable device in waterproof enclosure.

storage on the coast. In the first mode the GPS location of the speed boat is used for detecting movement in situations while the speed boat is left in the sea overnight, but this method consumes more battery. The second mode is used when the speed boat is left on the cost. More advanced movement detection is done by using the built in 3-axis Digital Accelerometer that monitors any movement or shaking of the speed boat.

4 COLLISION DETECTION AND PREVENTION

To increase sea safety, speed boat collision detection and prevention was implemented also. Collision detection is performed using a virtual circle approach. In this case the virtual circle denotes an area around the speed boat that can be reached in a certain amount of time. The virtual circle around the speed boat has a variable radius calculated using the current boat speed (Figure 5). Safe distance between two objects must be more than twice the size of the object's possible travel distance obtained using its current speed.

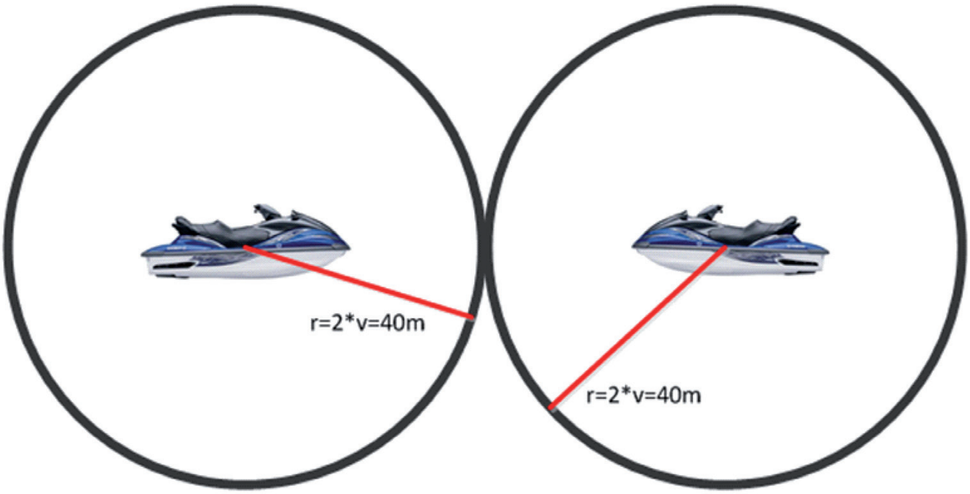


Figure 5 Simple collision detection method based on a virtual circle around the speed boat.

4.1 High speed boats and their dynamics

JetSki boats are popular because of its high speed and good driving dynamics. All other sea vessels have a slower driving dynamic like the ability of high acceleration and fast changing of trajectories. A standard JetSki can reach its maximum speed of over 20 meters per second (around 70 kilometres per hour) in a few seconds. The top speed of some models of speed boats can be up to 40 meters per second (around 140 kilometres per hour). Traveling course can be changed in less than a second, without losing any speed when changing its traveling course by a very big angle. These driving dynamics facts make the collision detection and prevention a challenging task. For example, recorded speed boat top speed and trajectory are presented in Figure 6.

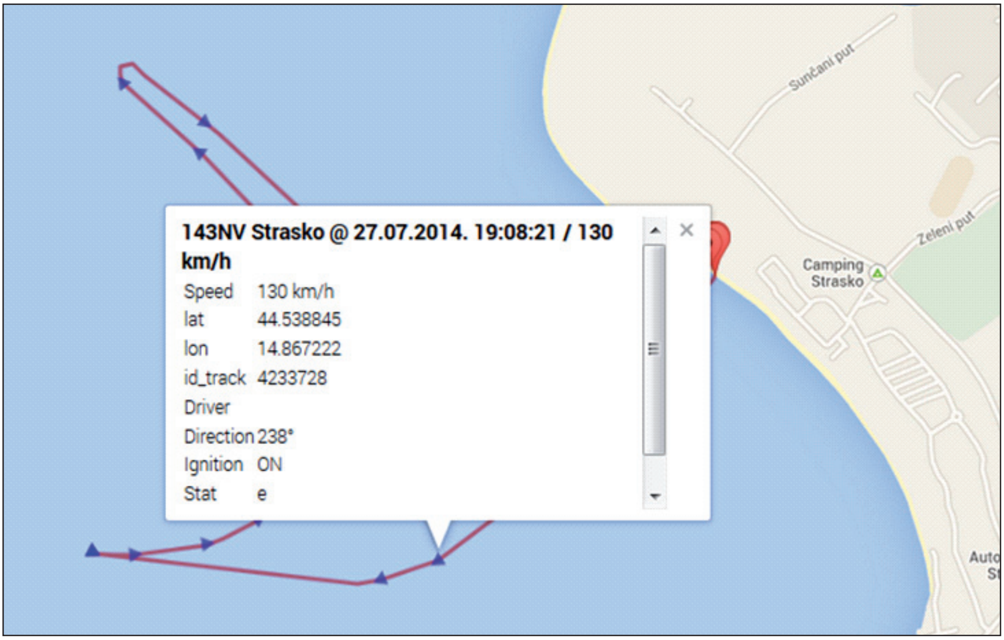


Figure 6 Top speed achieved and logged on a real location

Source: Made by authors based on [8]

4.2 Data Interchange

As this is a centralised system where all the collision calculations are done at the central socket server, safety radius of the collision free area has to be large enough because of the data interchange delay. The embedded system's algorithm is written to collect the GPS data, and sends it to the main Linux server over a GPRS connection and the Internet once every second. After socket server daemon receives current GPS data (location, speed and course), it compares this location with all the speed boats in the database that are near to the current boat's location within a thousand meters and makes the calculations. If a particular speed boat is entering the virtual circle of another boat, server responds to the embedded system inside the boat to reduce the boat speed.

The standard GPRS connection class 10 uses 60Kbps for download and 40Kbps for upload, but it switches automatically to 80/20 mode in a case of transmission of larger files. Local connection between the microcontroller and GPRS module is a constant 64KBps connection for upload and download. Data that are sent over GPRS are small data packages and the limits in the transmission speed aren't the issue. Increased number of mobile phones connected to GSM towers in one area congests the network and decreases GPRS throughput and data propagation. This could be a possible issue and further increase delays in received and sent data. Small delay is crucial for online collision calculations.

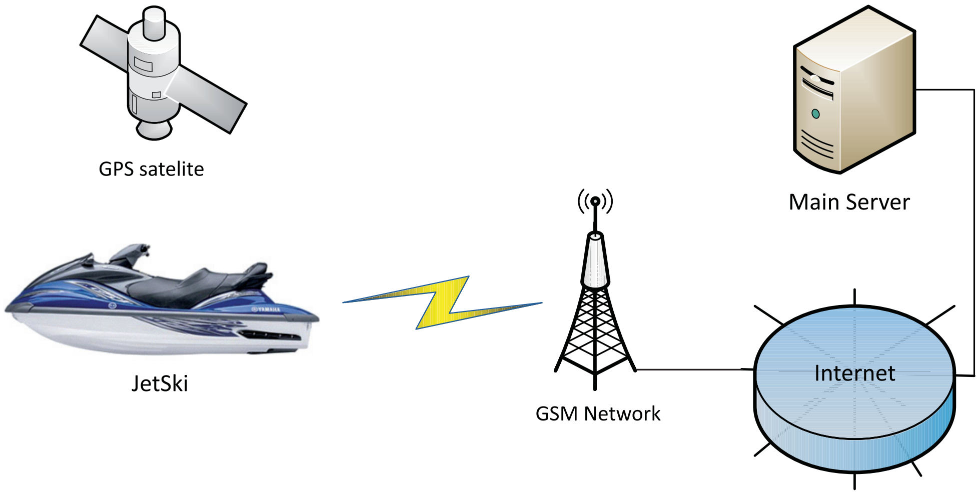
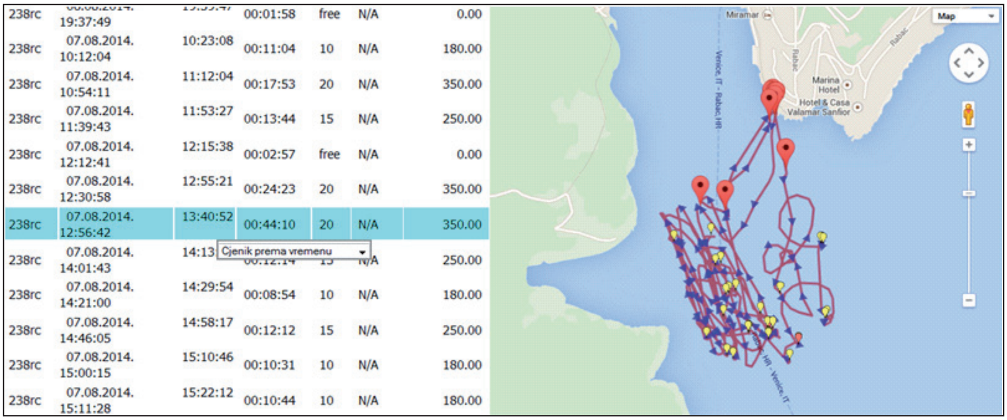


Figure 7 Block diagram of the proposed tracking system architecture

5 EXPERIMENTAL RESULTS

5.1 Vessel Tracking

By logging all geo-position data in server's database, reports could be generated afterwards for speed boat tracking and rental income analysis. Rate of data sending and recording was based on the speed boat's course change limited to a certain number of points in a minute. This approach generated enough data for basic tracking and generation of various reports. For collision detection, the data collection rate was higher (to one sample per second). Because of GPRS data traffic cost, collision detection was only enabled on a few boats for a small period of time in order to test the collision detection.



238rc	19:37:49		00:01:58	free	N/A	0.00
238rc	07.08.2014. 10:12:04	10:23:08	00:11:04	10	N/A	180.00
238rc	07.08.2014. 10:54:11	11:12:04	00:17:53	20	N/A	350.00
238rc	07.08.2014. 11:39:43	11:53:27	00:13:44	15	N/A	250.00
238rc	07.08.2014. 12:12:41	12:15:38	00:02:57	free	N/A	0.00
238rc	07.08.2014. 12:30:58	12:55:21	00:24:23	20	N/A	350.00
238rc	07.08.2014. 12:56:42	13:40:52	00:44:10	20	N/A	350.00
238rc	07.08.2014. 14:01:43	14:13 Cjenik prema vremenu				250.00
238rc	07.08.2014. 14:21:00	14:29:54	00:08:54	10	N/A	180.00
238rc	07.08.2014. 14:46:05	14:58:17	00:12:12	15	N/A	250.00
238rc	07.08.2014. 15:00:15	15:10:46	00:10:31	10	N/A	180.00
238rc	07.08.2014. 15:11:28	15:22:12	00:10:44	10	N/A	180.00

Figure 8 Generated income report with one driver's session trajectory generated from logged data on one real location.

Source: Made by authors based on [8]

5.2 Safety Area Estimation

In the touristic season, number of mobile phones on the beach increases significantly causing GPRS traffic and network congestion. Data propagation time through the GPRS and Internet connection increases from a few milliseconds to 2 seconds. So, unexpected delays in data acquiring and responding to it with an appropriate command are created. GPS data sample was acquired every second, but with a few seconds of communication network propagation. With such a delay collision prevention could not be established.

In real world field testing with two boats rushing to each other on almost top speed, the engine was stopped one second too late. The moment of engine shut down was the moment when the boats virtual circles began to overlap. Communication delay is a crucial factor here. So this centralised collision detection and prevention could be usable only with a two or three time larger radius of the virtual circle around the boat. In that case the boat is unusable, as the speed boat driving area is not big enough and it's impossible to drive two boats at that distance with one home location on the beach. Collision detection must be implemented as a decentralised system, with direct communication in-between boats over a radio signal network independent from the GSM network and a GPRS connection.

6 CONCLUSION AND FUTURE WORK

For a usable collision detection and prevention, speed boats must be equipped with some kind of boat to boat radio communication. It can be over a small distance and it can be with a smaller data transmission rate. The handshake and recognition procedure of the other parties in the communication must be fast. With such a type of communication every boat would reveal its current position, speed and course to other parties over a radio-communication network in a smaller circle like three hundred meters. Every boat's embedded system would receive and save data from nearby boats and calculate the collision possibility using all this data. In this way it would be a decentralized system for collision detection and prevention. Since, every boat would reveal its position to nearby boats; every boat would have data for its own local collision detection.

The calculations related to collision detection have to be done locally on an embedded system inside the boat. Only so the calculations can be done fast enough. Further advancement in collision detection and prevention would be in more advanced calculations that would take into consideration the current boat's course and speed. With a motion model it would be possible to predict the boat's future position, and to calculate the possibility of collision using the predicted data. More advanced collision detection and calculation can include the situation if the boat is moved from centre of the circle in the opposite way of the moving direction (Figure 9).

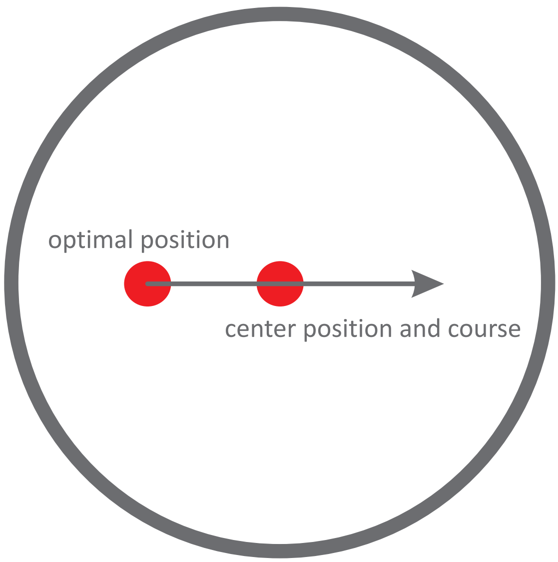


Figure 9 Moving vessel from centre position of virtual circle used for calculating collision.

Speed boats are very agile and dynamic. They change its course of movement with small speed drops and accelerate from low speed to top speed in just a few seconds. When the speed boat is changing its direction, the speed drop is proportional to the direction changed. For this reason is the boat moved from the centre of virtual circle to obtain more reliable collision detection. More complex collision detection calculations would enable boats to drive in parallel in the same direction, or to drive in opposite directions without an intervention of the collision prevention system to slow the boats down. So this type of collision detection is a good starting point for future work and analyses.

Acknowledgement

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DEVELOPMENT OF AIS AND ITS INFLUENCE ON MARINE TRAFFIC CONTROL

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ABSTRACT. *Automatic Identification System (AIS) has proven to be a quality source for non-SOLAS vessel traffic information. This paper presents possibilities of AIS technology development, and its influence on safety of navigation. The paper investigates development of AIS Class B and its influence on marine traffic supervising and control. It considers if and how is possible to manage marine traffic control with AIS for non-SOLAS vessels. The negative potential of AIS is analyzed by mass usage of AIS Class B. The paper concludes with recommendations, improvement suggestions and future work regarding marine traffic control development in the Adriatic Sea.*

KEY WORDS: *VTMIS, AIS, NON-SOLAS fleet, AIS improvements*

1 INTRODUCTION

Original intention of AIS system *(Automatic Identification System)* was ship-to-ship communication aiming at proper and timely identification of vessels, and subsequently, improving safety of navigation. However, regarding its characteristics, AIS became a useful tool for obtaining accurate information toward coastal stations (Vessel Traffic System (VTS) centers, Coast Guard, Port authorities, etc.).

AIS is an autonomous and continuous system for data exchange operating on Very High Frequency band (VHF) of the maritime mobile frequency spectrum. The system provides automatic data exchange between two or more AIS stations. AIS station is every station with the AIS device installed, fixed or mobile: vessels, aircrafts, coastal stations etc. The system is able to manage a multitude of reports with high-speed message updates, by using *Self Organizing Time Division Multiple Access* (SOTDMA) protocol (Filjar et al., 2005).

Ship borne AIS transceiver continuously transmits identification and other data to all vessels and port authorities in range on dedicated VHF radio channels. In order to obtain high readings accuracy and credibility, data are updated within short time intervals (varying from several minutes for static, unchanging data to few seconds when dynamic navigational data are exchanged).

According to International Convention for the Safety of Life at Sea (SOLAS), all commercial vessels of 300 GT or more must have AIS transceiver implemented on-board ship, conclusive with July 1st, 2008 (SOLAS 1974).

Taking the contribution of the AIS system to the safety at sea in consideration, the feasibility of installing AIS equipment on-board smaller vessels is unquestionable. Majority of experts confirm the fact that AIS, after radar, represents most important device regarding safety at sea (Sandford 2004) in terms of proper identification of collision risks.

Within the AIS device, received data are transformed in the standard NMEA format (Filjar et al., 2005), becoming readable on all compatible devices (e.g. radar, ECDIS[1], etc.) and computer navigational software (e.g. Jeppensen© Marine's Nobeltec system). The main characteristic is the real-time visual and data display of navigation-related information.

The AIS mandatory implementation timetable regarding type and size of vessels is shown in Table 1.

[1] Electronic Chart Display and Information System

Table 1 Implementation timetable of AIS navigational equipment on-board SOLAS vessels

Vessel Type	Implementation Date
Ships constructed on or after 1 July 2002 (new ships)	Date of construction
Ships engaged on international voyages constructed before 1 July 2002 (existing ships)	
Passenger ships	1 July 2003 (V/19.2.4.2.1)
Tankers	1st survey for safety equipment on or after 1 July 2003 (V/19.2.4.2.2)
Ships, other than passenger ships and tankers, of 50000 GT or more	1 July 2004 (V/19.2.4.2.3)
Ships, other than passenger ships and tankers, of 300 GT and upwards but less than 50000 GT	1st survey for safety equipment on or after 1 July 2004 or by 31 December 2004, whichever occurs earlier (V/19.2.4.2.4)
Ships, other than tankers or passenger ships, of 10000 and upwards but less than 50000 which call at port of an EU Member State	1 July 2005 (EU Directive 2002/59/EC)
Ships, other than tankers or passenger ships, of 3000 and upwards but less than 10000 which call at port of an EU Member State	1 July 2006 (EU Directive 2002/59/EC)
Ships, other than tankers or passenger ships, of 300 GT and upwards but less than 3000 GT which call at port of an EU Member State	1 July 2007 (EU Directive 2002/59/EC)

Source: (SOLAS 1974, EU 59 2002)

According to Table 1 and times related, it can be seen that, today, AIS is well-known established system. However, it is important to note its broad usage aspects, as to emphasize the fact that, considering its possibilities, it has underused potential.

According to SOLAS Convention, the category of vessels which are not required to possess the AIS device includes vessels in international and national navigation below 300 GT, yachts and other sport and leisure crafts, and other. Non-conventional vessels and fishing vessels (if larger than 15 meters), are obliged to possess AIS Class A device in the Republic of Croatia – to the date of May 31st, 2014. Implementation of AIS on Croatian fishing vessels is directed by the European Commission (EU 59 2002, EU 17 2009, EU 15 2011).

The proposed paper discusses spreading of AIS possibilities on vessels which are not included in the SOLAS Convention with regards to AIS implementation. The future of such vessels is explained in further text. Moreover, the insight of the impact on the safety of navigation and vessel monitoring systems is discussed.

2 AIS AND NON-SOLAS VESSELS

Application of the SOLAS Convention represents one of ship's classifications, defining vessels which must apply the convention provisions and vessels which are not required to do so.

In general, non-SOLAS vessels fall outside international regulations. Depending upon the needs, the state governments are deciding in which way and by which means they will perform the control and supervision of non-SOLAS vessels[2]. The need for non-conventional vessels' monitoring depends on features and characteristics of specific marine area, amount and nature of the marine traffic, as well as on the local flag administration.

Within the areas where the implementation of the AIS safety system is recommended, it is necessary to introduce measures based on regional collaboration, mutual understanding and neighboring maritime countries support. Although the regional cooperation is possible, it is assumed that it will work properly only with the initiative of the International Maritime Organization, which represents leading global institution regarding safety of sea navigation.

From the perspective of non-conventional vessels' risk, the following situations can be emphasized:

- terrorist attacks,
- marine environment pollution,
- biological pollution[3],
- trafficking,
- smuggling and other illegal activities.

Implementation of *Low Cost AIS*, or AIS Class B on-board non-SOLAS vessels represents an effective measure for non-conventional vessels' monitoring. As for the cost, it is considered that the price of devices will decrease with the increase of equipment implementation. Thus, mass production would reduce the expenses of the end-user.

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[2] For instance, in United States, for all ships of 100 GT or more, the International Ship and Port Facility Security Code (ISPS Code) is mandatory (ISPS 2003).

[3] e.g. uncontrolled spreading of algae – Caulerpa Taxifolia

In the Republic of Croatia, one of the main safety of navigation subjects is Vessel Traffic System (VTS). It is a technical, governmental institution responsible for monitoring and physical tracking of ships, and tracking of information transmitted from vessels (MPPI 2009). The functions of VTS institution reflects in safety of navigation improvement, safety of life at sea in SAR[4] operations, marine accident risk reduction, reduction of marine hazards, improvements of SAR systems, marine pollution mitigation, and coordination and conducting of marine environment cleaning actions in the case of marine pollution (MPPI 2009). Vessel Traffic Monitoring and Information System (VTMIS) service is a part of the VTS system intended for tracking, management and organization of the overall maritime traffic in inner sea waters, territorial sea and ecological and fishing protection zone of the Republic of Croatia (MPPI 2009). It consists of maritime coastal AIS system, coastal radar system, maritime radio-communication system, as well as of other corresponding means necessary for the insight of navigational conditions at sea. Furthermore, VTMIS service collects all relevant information in order to process, analyze, display and to distribute same real-time information to competent national and international offices and institutions (MPPI 2009).

Besides the supervision of conventional ships, VTS services are monitoring movements of all corresponding vessels in the Adriatic Sea by means of radar monitoring and AIS systems.

There is a question arising; on which vessels AIS system should be implemented in order to increase the monitoring efficiency in the Adriatic Sea, leading in that way to the improvement of the safety of navigation.

Status of yachts and boats in the Republic of Croatia is regulated by the Croatian Maritime code (NN 61 2011) and the Croatian Code on boats and yacht (NN 18 2009). The yacht is defined as a craft for sport and leisure; regardless it is used for personal or commercial purposes, with its length of 12 meters or more, intended for longer stay at sea, and authorized for the carriage up to 12 persons, beside crew. In 2013, 182921 yachts were registered in the Republic of Croatia, with 182 921 foreign yachts ports of call (DZS 2014). Apart from yachts, there are leisure, recreation and sport crafts. These crafts are intended for sea navigation and there are in category which is not a yacht neither an vessel, with is length of 2,5 meters or more and total propulsion power of 5 kW or more (MPPI 2009).

Because of this official classification, it is hard to define vessels which should implement and use the AIS Class B devices. If the AIS usage would be

[4] Search And Rescue

mandatory to yachts and boats users, all other boats less than 12 meters of length would be outside this regulation. Another question/issue which arises is the necessity of legal regulation introduction regarding mandatory usage, and what are the consequences which it entails? Legal regulation would bring obligation of usage, what would in return result in disagreement of users regarding the price and device operation. On the other side, once introduced, the obligation would result in better VTS coverage of various vessel and boat types, which are, so far, solely visible on radar displays. In the events of marine accidents, marine pollution and maritime safety endangering, safety services would be able to identify the vessel and, if necessary, to establish a proper communication.

By entering the name of the vessel in VTS search engine, it would be possible, to retrieve geographical coordinates of the vessel in question (e.g. in distress situations) in short time. This would further facilitate the rescue operations, since the VTS operators would have an insight of all other vessels and crafts present in the relevant area. Looking at mentioned facts, the usage of AIS devices on-board crafts would significantly improve the safety level of the in the area of the Adriatic Sea.

In events of marine pollution, sea and environment protection, these services would, immediately upon the pollution report, be able to identify the vessel responsible for the pollution damage. Today, marine pollution causers are found with the aid of satellite imaging (for example, EMSA's[5] CleanSeaNet service (EMSA 2014)), however investigations and processes would be significantly facilitated if vessels would have AIS devices built-in.

3 DIFFERENCES BETWEEN AIS CLASS A AND AIS CLASS B DEVICES

There are two types of ship-borne AIS devices: AIS Class A and AIS Class B. The AIS Class A is mandatory on-board ships of 300 GT or more which are engaged on international voyages, cargo ships of 500 GT or more which are engaged on national voyages, and passenger ships (carrying 12 passengers or more), irrespective of their size. The AIS Class B transceivers are smaller, simpler and lower cost than Class A transceivers. They contain VHF transmitter, two VHF Carrier Sense Time Division Multiple Access (CSTDMA) receivers, both alternating as the VHF (DSC) receiver and a GPS antenna.

[5] European Maritime Safety Agency

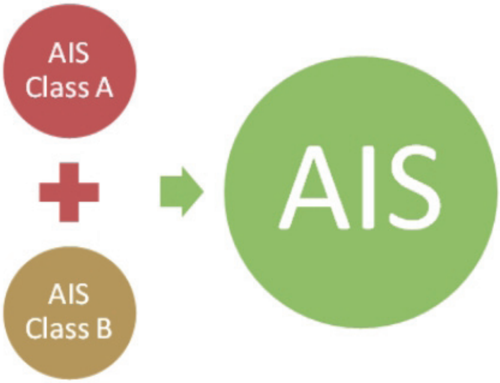

Figure 1 Distribution of Automatic Identification System

The following information is included in the AIS Class A messages of (IALA 2002, IMO A.917(22) 2001):

Static information: IMO and Maritime Mobile Service Identity (MMSI) number; Call sign and name; Type of vessel; Length and beam; Location of GNSS position fixing antenna

Dynamic information: Ship's position with accuracy indication (for better or worse than 10 m) and integrity status; Time in UTC (coordinated universal time); Course over ground (COG); Speed over ground (SOG); Heading; Navigational status (e.g., not under command, constrained by her draught, etc.); Rate of turn (where available); Angle of heel (optional); Pitch and roll (optional)

Voyage related information: Ship's draught; Type of cargo; Destination and estimated time of arrival (at master discretion); Route Plan-waypoints (optional); Number of persons on board (on request)

The last category of AIS messages represents **short safety – related messages**, which can be sent to all ships in the vicinity, or toward one station specifically, by using the MMSI[6] number as the receiver's address.

[6] Maritime Mobile Service Identity number.

Figure 2 Comparison of AIS Class A (a) and AIS Class B (b) information

Source: NAVCEN 2014

AIS Class B represents new devices' generation, more affordable for the users, however with certain limitations regarding operating range, transmitting power and other characteristics. This type of AIS transceiver does not emit IMO number and call sign, navigational/dynamic data and ship's draught. It does not support safety – related nor binary messages. The update intervals are significantly longer than in the AIS Class A device (Table 2), and the latter has the priority over the Class B. The Class B stations do not affect the channel capacity of AIS A traffic because AIS B is transmitted at lower power. Use of Class B will nevertheless increase the number of garbled message (Norris, 2006).

Both classes are using *Time Division Multiple Access* (TDMA) technique. The basis of TDMA is that the time is divided into discrete slots and only one station is transmitting during a time slot (Norris, 2006). When the slots are overloaded then ship AIS station use slots which are already in use by the most distant stations. Because of accurate time messages allocation GPS is very important factor in AIS system providing the standard time reference.

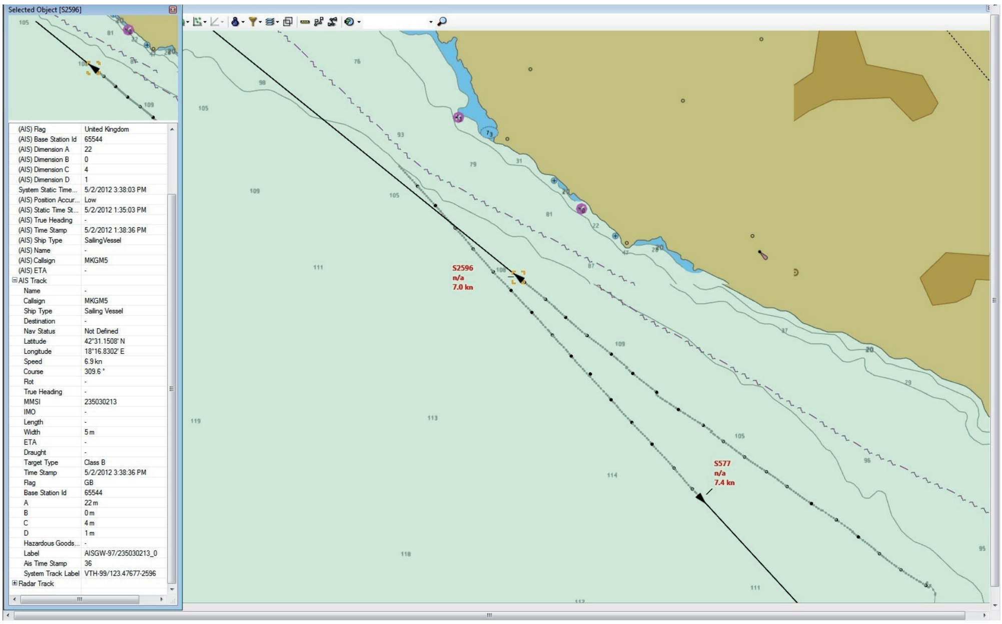

Figure 3 Presentation of AIS Class B on the VTS operator's control display (SAAB CoastWatch VTS Software)

Source: VTS Centre Split, Croatia, with permission

The AIS Class B device is able to receive short safety – related message; however it is not able to send one. Currently, there are two types of AIS Class B devices: i) those which are using *Self Organizing Time Division Multiple Access protocol* (SOTDMA – same as in AIS Class A) – B/SO devices, and ii) other, which are using *Carrier Sense Time Division Multiple Access protocol* (CSTDMA) – B/CS devices. In general, Class B/SO is more capable, while the Class B/CS is less expensive.

Figure 4 represents tracking of AIS Class B vessels using the Transas© AIS Network Viewer. This software is intended for reception, display, and recording and data analyses from different AIS sources. The figure shows AIS class B track in the period from June to September 2011 in the Middle Adriatic Sea – Split area.

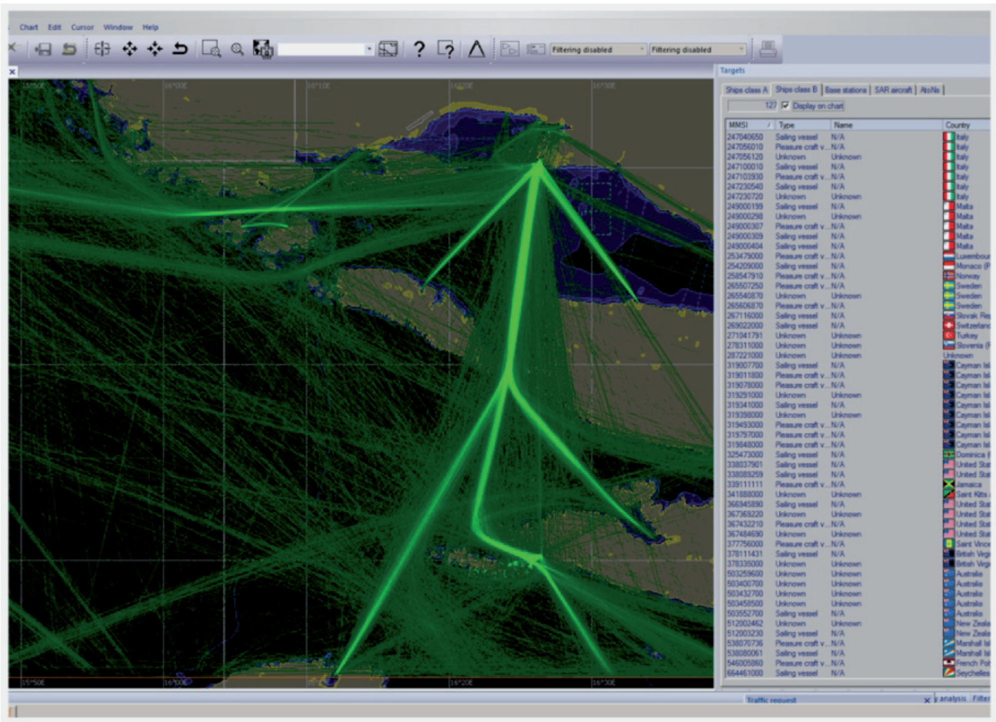

Figure 4 Tracking of AIS class B targets in the period from June to September 2011

Courtesy of Marko Perkovič using Transas© AIS Network Viewer, with permission

Table 2 Technical and functional differences between AIS Class A and AIS Class B (both SO and CS types)

Shipboard AIS	Class A	Class B/SO	Class B/CS
Transmit Power (Watts)	12.5 W/2W (low – power)	5 W/2 W (low – power)	2 W
Primary Access Scheme	**Self-organizing Time-Division Multiple Access (SOTDMA)**	**Self-organizing Time-Division Multiple Access (SOTDMA)**	**Carrier-sense TDMA (CSTDMA)** **Non – competing with SOTDMA units**
Positioning Reporting Rate	Either every 2, 3½, 6 or 10 s based on speed and course change. Every 3 min. when ≤ 3 kt.	Either every 5, 15 or 30 s based on speed (2-14,14-23, > 23 kt) Every 3 min, when ≤ 2 kt	Every 30 s Every 3 min. when < 2 kt
Static Data Reporting rate	Every 6 min	Every 6 min	Every 6 min
Frequency Range	25 kHz bandwidth between 156.025-162.025 MHz	25 kHz bandwidth between 156.025-162.025 MHz	25 kHz bandwidth between 156.025-162.025 MHz
Dedicated DSC Receiver for Channel Management	Yes	Yes	Time -shared
Position source / WGS – 84 to 1/10,0000 of minute of arc	Internal GNSS & External EPFS	Internal GNSS	Internal GNSS
Digital Interfaces	Input-Output & Multiple Presentation Outputs	Optional	Optional
Display	MKD	MKD	Optional
Safety Text Messaging	Receive & Transmit	Receive & Transmit	Transmit Optional, and only with non-alterable pre-configured messages
Application Specific Messaging	Receive &Transmit	Receive & Transmit (up to 3 slots)	Receive Optional, cannot Transmit
Transmit Data	All	No Rate of Turn, Navigation status, Destination, ETA, Draft, or IMO	No Rate of Turn, Navigation status, Destination, ETA, Draft, or IMO
IEC Certification Standard	IEC 61993-2	IEC 62287-2	IEC 62287-1

Source: NAVCEN 2014

4 ERRORS OF AIS CLASS A/B AND THE IMPACT ON THE SAFETY OF NAVIGATION

Recent studies revealed that the most common errors of AIS Class A are related to the MMSI number, vessel's type, name and the call sign, navigational status, length and beam, draught, destination and estimated time of arrival (ETA) (Mokhtari, 2007). AIS Class B, as described previously, is only able to receive majority of mentioned information. Therefore, lesser amount of errors is present in AIS Class B devices over the Class A.

AIS errors are divided in static and dynamic errors. Transmitted erroneous position of the vessel represents dynamic error. The cause of this error is related to the used GNSS system[7]. The ship borne AIS device is supplied with time signals from the internal GPS receiver. The time signal synchronizes the sequence of information/ data packages from all ships in the operating range. In case of the absence of time signal reception or GPS receiver defect, AIS would be non-functional. Failure of the GPS receiver appears because of various causes/reasons. One of them is constant offset of the vessel's position, present with the difference of provided positions between internal and external GPS receivers connected to the AIS device. The offset error also appears with incorrect setup of the horizontal reference system, other than WGS-84 (NI 2014). GPS errors represent great issue in VTS monitoring. The traffic image with incorrectly displayed vessels different than as showed with the radar image can produce confusing display. Another misleading error appears by entering the incorrect MMSI number, which can result in targets swapping (Norris, 2008).

AIS errors can be also classified as technical errors and errors caused by the human factor.

Figure 5 represents most common errors related to incorrect AIS messages. The results are based on three different studies – VTS-based AIS study, Data–mining AIS study and Proactive AIS study (Mokhtari, 2007). Incorrect navigational status, which represents most important information in avoiding collisions at sea, comprises of 30% of all vessels. Incorrect length comprises of 47 % of monitored ships, while the most common error (49 %) is related to incorrect destination and ETA.

[7] Individual, unintentional causes of satellite positioning error can be, in simple, classified as errors due to dilution of precision; satellite-related errors including satellite clock errors, satellite orbit errors, satellite transmitter errors; satellites' signal propagation errors in a dispersive and non-dispersive medium; receiver-related errors including noise and hardware biases; and multipath (Petrovski & Tsujii, 2012). On the other side, intentional interferences and jamming are representing growing threat to all kinds of GNSS users.

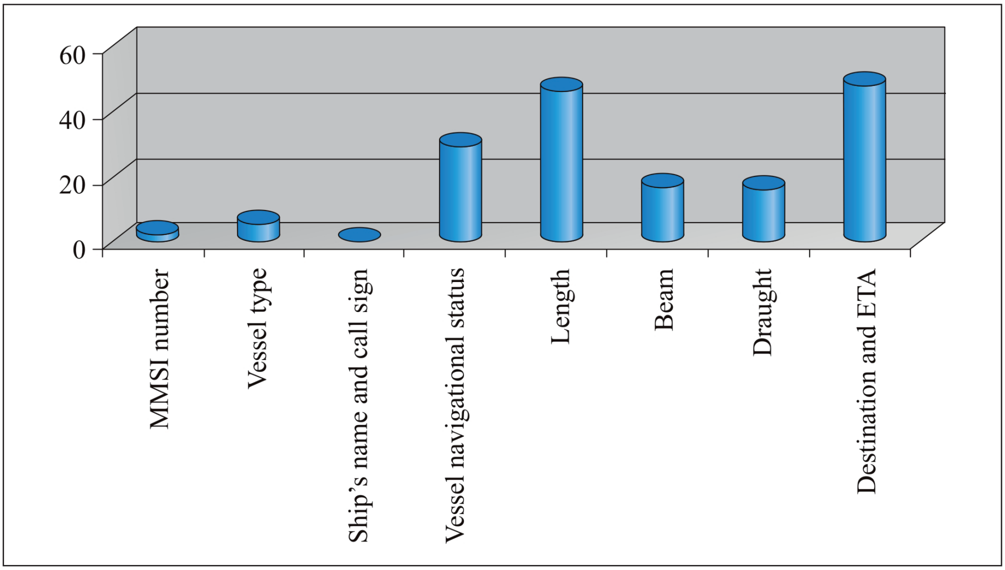

Figure 5 The most common AIS message errors, given in percentage

Source: Designed according to (Mokhtari, 2007)

The most common errors regarding AIS are those which are manually entered by the navigator. It is considered that the increase of AIS users could directly increase incorrect information – that the number of all types of AIS errors vs. number of both classes AIS terminals increases cumulatively. On the following Figures examples of erroneous information entered in AIS device are presented.

On Figure 6 it can be noticed that the name of the vessel is shortened. In AIS, vessel's name slot allows for 20 symbols. The type of the ship is defined as 'other', although it is a survey vessel. On Figure 7 it can be seen that the navigational status of the vessel is not defined, nor the ETA and vessel's draught. Those are the characteristics of Class B devices. Figure 9 reveals that the name of the vessel is not even entered.

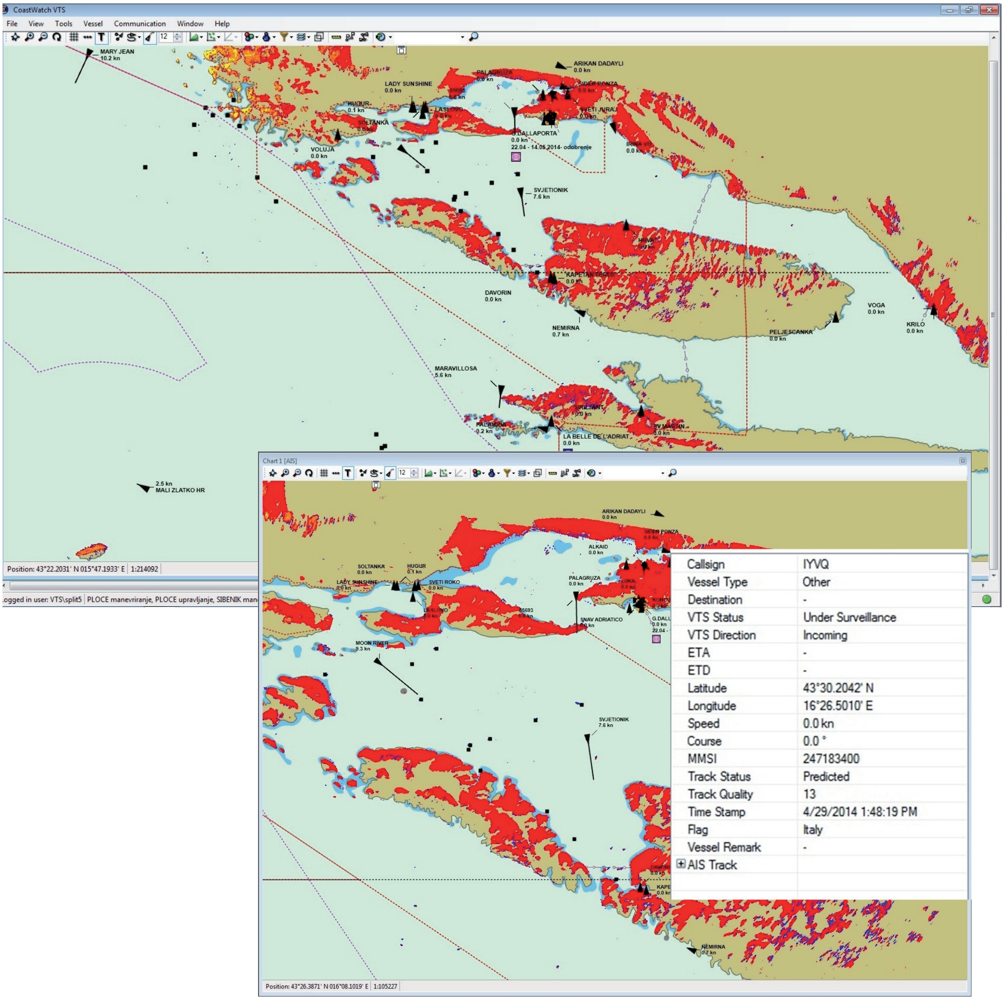

Figure 6 Vessel Traffic Service AIS and radar tracking displayed on Electronic Navigational Chart (ENC). Example of research/survey vessel in port of Split (SAAB CoastWatch VTS Software).

Source: VTS Centre Split, Croatia, with permission

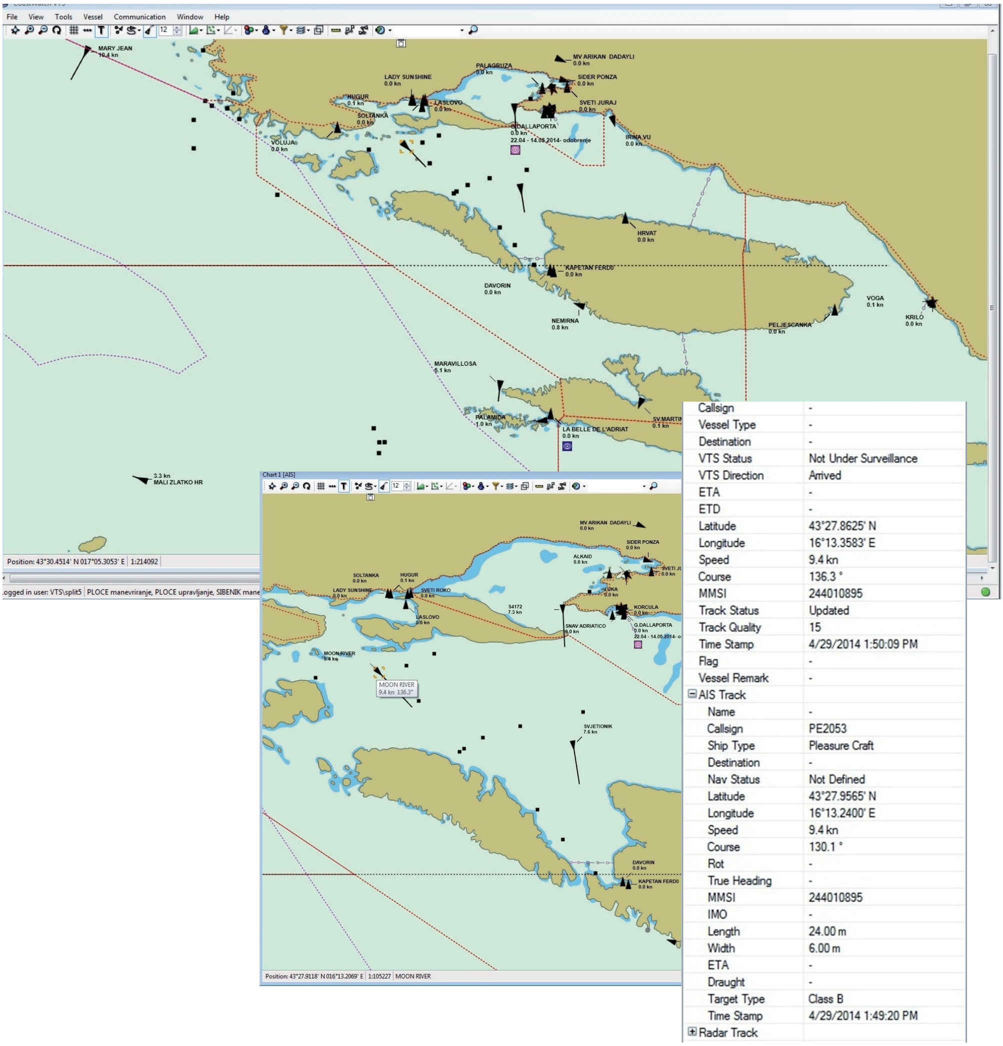

Figure 7 Example of AIS B vessel/target display on Electronic Navigational Chart (ENC) (SAAB CoastWatch VTS Software)

Source: VTS Centre Split, Croatia, with permission

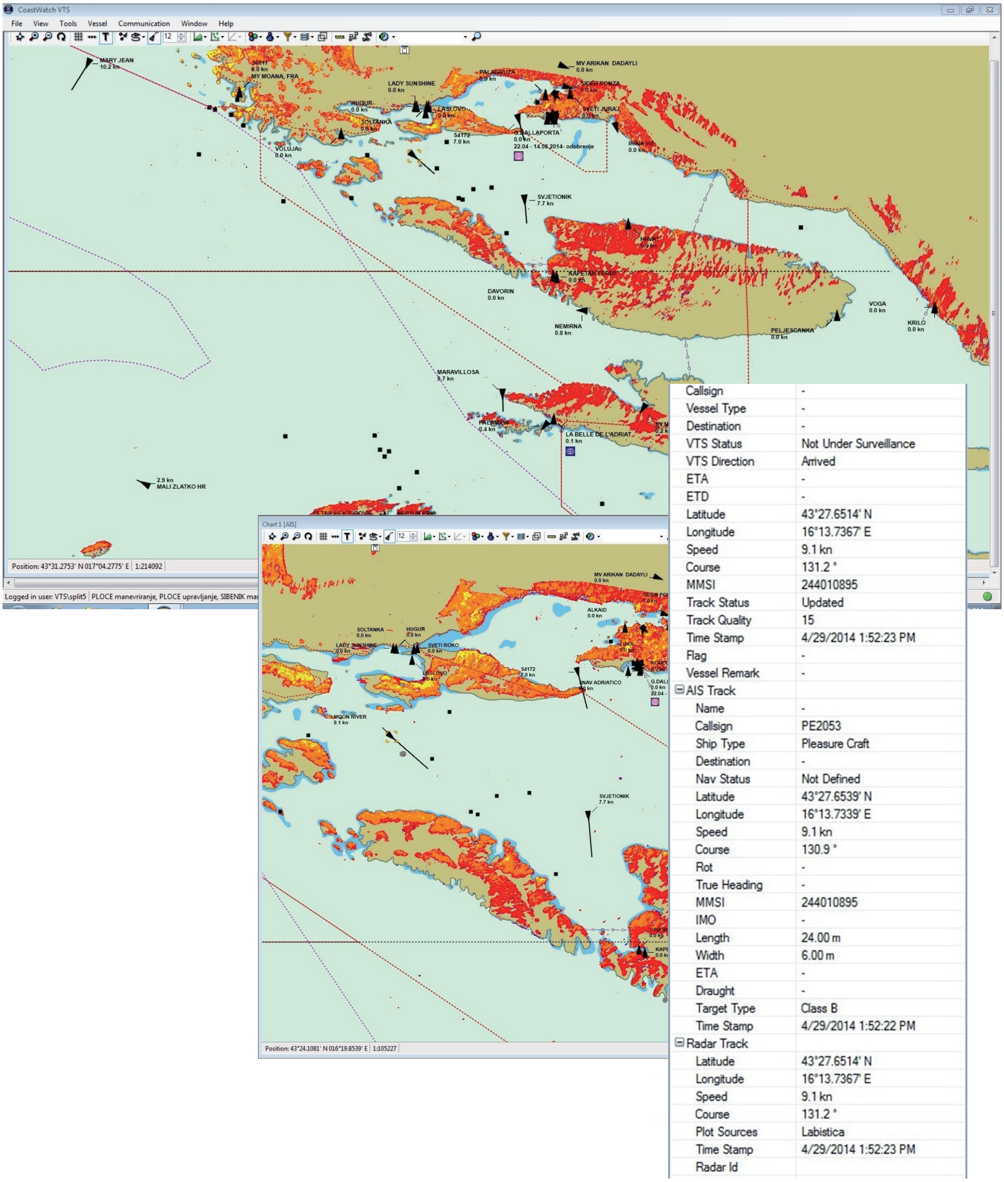

Figure 8 An example of both radar and AIS monitoring of AIS Class B target displayed on Electronic Navigational Chart (ENC) (SAAB CoastWatch VTS Software)

Source: VTS Centre Split, Croatia, with permission

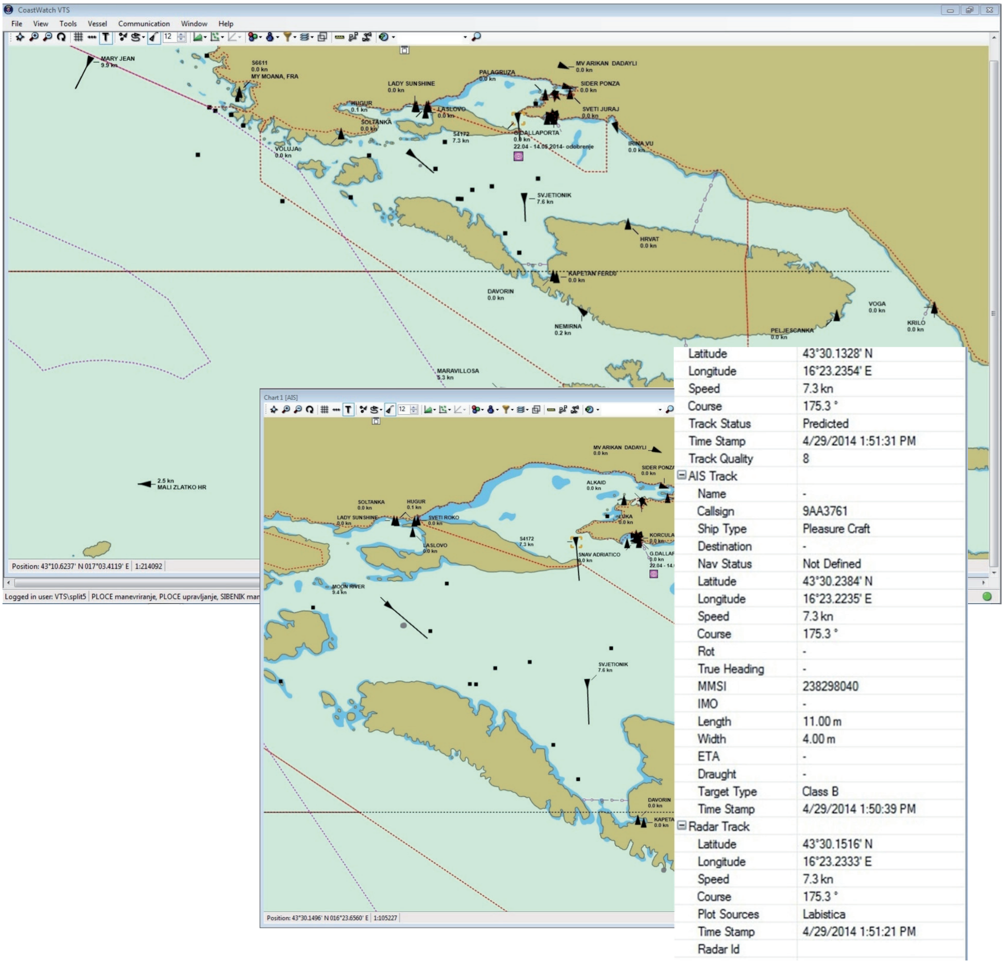

Figure 9 An example of AIS Class B target – leisure craft displayed on Electronic Navigational Chart (ENC) (SAAB CoastWatch VTS Software)

Source: VTS Centre Split, Croatia, with permission

Above examples (presented with Figs. 7-9) demonstrate common errors in AIS Class B devices, caused by the human factor solely. Presented screenshots are showing the vessel tracking by the VTS service. Although AIS system is not mandatory on non-conventional vessels, it is used due to its obvious assistance in terms of navigation safety. In almost all cases one or more AIS-related errors were present. For the VTS services, such errors are negligible in relation to the benefit of the AIS system but are different for ship usage. Ships without radar can easy misunderstood information from AIS device because they have no means for information error check. Navigation with wrong AIS information can be misleading and potentially dangerous. For the VTS services benefits are far more significant than irregularities and errors which occur.

5 DISCUSSION

It is not simple to set priorities in described issues. On the one hand, there appears better maritime traffic insight by the VTS centers, which consequently increases the level of safety of sea navigation. On the other hand, increase of errors due to incorrect information on AIS devices leads to reduced direct safety of seafarers, vessels' crew and vessels.

Studies have shown that AIS Class B users are exposed to would receive incorrect information; however that radar equipment is not mandatory for his type of ships (Norris 2006). Thus, with incorrect information could be much more dangerous than on AIS Class A vessels. The effect of adding AIS into nautical equipment and the conclusion was that AIS does have impact on ship maneuvering operations (Hsu et al., 2009).

Issues arising from the usage of the AIS Class B can be listed as follows:

- The system preserves its functionality only if all the vessels are fitted with appropriate equipment;
- The price of AIS devices is not insignificant;
- It is difficult to classify which types of vessels should be equipped with AIS devices;
- Tracking awareness and movement recording can cause false reactions of some users;
- By the increase of AIS usage, there appears the potential of traffic image congestion;
- The users should obtain an appropriate training.

If it would be legally regulated, AIS system would have its proper function. The purchase of the AIS equipment, due to its high cost relative to the value of small pleasure boats, cannot be imposed. However, with the installation obligation, the price of AIS transceivers would be reduced due to the mass production and sales.

As for sport and leisure boats, a problem appears regarding carriage obligation depending not only on the size of the ship, but also on the purpose and navigation area. The owners of boats in question are, furthermore, dissatisfied with the fact that the track of their movement remains permanent, both on monitoring displays as well as in data logs.

If non-conventional ships would use AIS transceivers, the display on appropriate equipment (especially on AIS displays) would be confusing, by means of highly dynamic and frequent boat movements. In addition with numerous crafts, it would lead to difficult tracking by vessel traffic monitoring services. The similar problem would be present on-board conventional, AIS Class A vessels, where the presence of numerous small boats would lead to display/s congestion.

The main non-conventional ships are yachts. Characteristics of such crafts are inconstancy of movement, longer periods of stay in marinas and ports, frequent overnight stays on anchorages, and, particularly important, diverse levels of crew's maritime knowledge. Typically, the navigation area of yachts is in the near of the location of the permanent berthing, although this navigation can be present on wider area. The yachts' navigation depends on its size. The navigation of smaller yachts resembles a boat navigation, which is strictly coastal navigation, stays in marinas and anchorages, with daily retentions near the beaches or other attractive sceneries (MPPI 2009).

Larger yachts are navigating similar to vessels – off shore navigation and port stays with known destinations and navigation routes.

Older generation AIS devices are able to display and present the position of the vessel, but not the identity of AIS Class B devices. On conventional, AIS Class A devices there exists an option of turning the AIS Class B objects display off, in order to avoid the congestion on the equipment screen. The information sent by and AIS Class B device will be present on conventional devices only in cases where there is enough space for related messages, although it has been shown that in some cases irregularities appeared (Norris, 2006).

The use of AIS is optimal when it is used in conjunction with radar equipment. However, AIS device must not be used of collision avoidance purposes solely. The tendencies are implying that all radar equipment should support AIS integration on-board vessels (IMO MSC.192(79) 2004).

Another issue is end-users' education and training which is essential. It is hard to define a way in which the crews should be trained for handling AIS devices. Nevertheless, lack of knowledge and misuse of such a complex device will lead to unwanted consequences. On conventional ships the education level is standardized and satisfying; however, regardless the well trained officers on watch (OOW), additional education and training on AIS equipment should be considered.

6 CONCLUSION

In recent years, there appears the global need for increase of the safety of navigation of ships which are not in the SOLAS safety system. Marine accidents (marine pollution, piracy, groundings, etc.) do not affect the conventional vessels only, and the monitoring and tracking non-conventional ships system should be established.

AIS system provides exchange of information ship to ship and ship to coast, providing easier identification, monitoring and inducement for vessel monitoring services (VTS).

The surveillance system should provide the access of the common situation image with crucial data and information available, especially in cases of situations where several safety of navigation subjects are present (search and rescue coordinating centers, vessel traffic services, harbor master offices, port authorities, etc.). Uniformity of displayed data would enable easier subject co-ordination and proper, timely, and supported decision making processes.

Considering the area of the Adriatic Sea, the use of AIS Class B would be beneficial. The implementation of this non-SOLAS system would improve safety of navigation, and should ease the investigation of marine accidents. The use should also increase situational awareness. The quality of navigator's data input is questionable, thus correct data interpretation would depend on navigator's ability for errors recognition, what can be achieved with proper education and training.

For the time being, and considering negative effects on conventional system, AIS Class B can be used for information purposes only and not for the base for decision making. Increase of AIS users could directly increase incorrect information – errors in a both AIS A and AIS B classes. However, with AIS system reaching fully operational level, along with other technical and training issues solved, it could significantly reduce human errors leading to marine accidents.

Acknowledgments

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QUANTIFICATION OF THE SINGLE LAYER MAPPING FUNCTION ERROR USING NEQUICK MODE

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ABSTRACT. *Ionosphere can be the largest source of error in Global Navigation Satellite System (GNSS) positioning and navigation. The error in satellite – receiver distance measurements is equivalent to so called Total Electron Content (TEC). This parameter is often converted between different satellite-receiver link geometries. The most common conversion uses single layer approximation of the ionosphere which can introduce an error to the estimation of the ionospheric delay. According to our study case which was modelled by the NeQuick model, the conversion error can reach value of 8 TECU in case elevation angles, underestimation of ionospheric height or high solar activity. In case two or all three are present, the error is even more severe. We also defined an asymmetry index which can be used to model the behavior of the mapping function error and potentially reduce its effect.*

KEY WORDS: *ionosphere, NeQuick 2, single layer model*

1 INTRODUCTION

Global Navigation Satellite System (GNSS) is commonly used for positioning and navigation. The GNSS based services are used in many areas such as maritime, aviation or public transportation. The position of a GNSS receiver is computed from measurements of times which GNSS signals need to travel between satellites and the receiver (Daly, 1993). In ideal circumstances the measured times would represent the true distance between the satellites and the receiver. However, there are several factors which can significantly change the signal propagation so that the measured time would not anymore represent the true distance and can lead to incorrect position solution.

One of the most severe errors is caused when the GNSS signal passes through the ionosphere (Norsuzila et al., 2007). There are several techniques used to compensate the ionospheric effect. Multi-frequency receivers can eliminate about 95 % of the error due to the dispersive nature of the ionosphere (Satya Srinivas et al., 2012). Receivers which can receive signals only on one frequency can use service augmentation system such as EGNOS or WASS. These systems use a network of multi-frequency stations which compute the ionospheric error and sent its value to the receiver. Another possibility is to use an ionospheric model to compute the ionospheric error. Currently the most common ionospheric model in GNSS receivers is Klobuchar ionospheric model used both by GPS and Beidou.

Klobuchar model as well as augmentation systems use so called ‘single layer approximation’ of the ionosphere to convert ionospheric error between different elevation angles (EUROCONTROL GNSS Tools Team, 2003), (Wenjun et al., 2014). As this approximation considers the ionosphere as a single thin shell it ignores its vertical structure. Such simplification introduces an error and can have significant impact on correct estimation of ionospheric condition (Nava et al., 2007). In this paper we present results of quantification of the conversion error modeled with ionospheric model NeQuick 2 and propose a simple approach to reduce it.

2 IONOSPHERE

The ionosphere is a part of the atmosphere which contains charged particles in such quantity that it can significantly change speed and trajectory of propagating electro-magnetic wave (Barclay, 2003). These effects are equivalent to the main ionospheric parameter – *electron density*. The electron density for given location and time depends on concentration of ionizable gas, current solar radiation and neutral winds. The typical vertical structure of the ionosphere is shown in Figure 1.

In general, electron density is highly variable both temporally and spatially and its prediction is a challenging task (Zolesi and Cander, 2014).

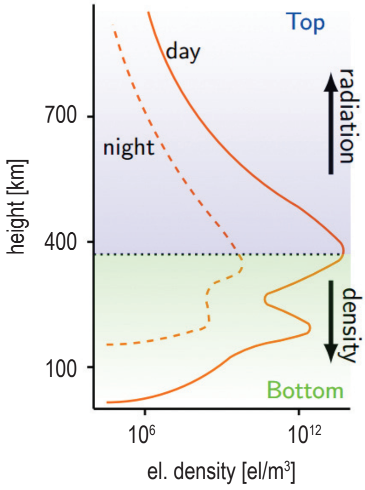

Figure 1 A typical electron density vertical profile of the ionosphere. The electron density profile during day and night is represented by full and dashed line, respectively. The dotted line shows the average height of the electron density maximum; made by the authors according to Ya'acob et al., 2008.

3 TOTAL ELECTRON CONTENT

Ionospheric error of a satellite – receiver link depends on the total amount of the electrons along the propagation path *S* of the signal. The error in meters *ΔR* can be expressed as:

$$\Delta R = \frac{40.3}{f^2} \int_S N_e \mathrm{d}S \tag{1}$$

where N_e is electron density in a particular part of the path d*S*. *TEC* can be obtained by integration of the N_e along the signal path *S*:

$$TEC = \int_S N_e \mathrm{d}S \tag{2}$$

We commonly distinguish two types of TEC: *vertical* and *slant total electron content*. Vertical total electron content (*vTEC*) at a certain geographical point stands for total electron content in the direction of the zenith angle. TEC between a satellite and a receiver is usually referred to as the slant TEC (*sTEC*). That signifies that the TEC is at a different angle from the zenith angle. The TEC is usually given in TEC Units (TECU) where TECU = 10^{16} electrons/m^2.

4 SINGLE LAYER APPROXIMATION

In case we use an augmentation system to obtain value of ionospheric error, the system sends us value of vertical TEC. To make the value useful, we have to convert it to the appropriate elevation angle of our satellite – receiver link. To convert the *vTEC* to *sTEC* or vice-versa, we use so called 'mapping function' f_{mp}:

$$sTEC = f_{mp}\{vTEC\} \tag{3}$$

The most often used mapping function is based on single layer approximation of the ionosphere. This approach approximates the ionosphere as a single thin shell with zero thickness at a certain hight (typically called ionospheric height; usually between 250 – 400 km). Both the vector of *vTEC* and *sTEC* pierce the shell at one point called Ionospheric Piercing Point (IPP) (Figure 2). Approximating the Earth as a sphere the *single layer mapping function* can be written as:

$$f_{mp} = \sqrt{1 - \left(\frac{Re}{Re + hm} \sin\chi\right)^2} \tag{4}$$

where:

Re is the Earth radius,

hm is the ionospheric height and

χ is the angle between vectors of slant and vertical TEC.

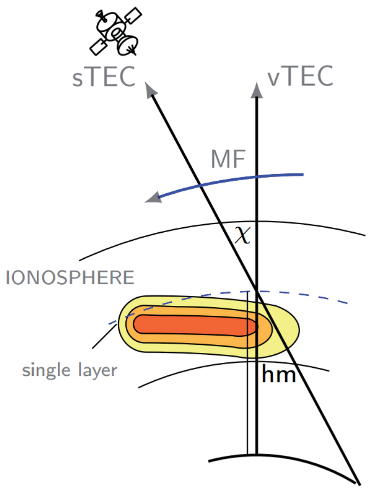

Figure 2 Thin shell approximation of the ionosphere

5 METHODOLOGY & DATA

To compute the mapping function error one has to have measurements of one IPP for both slant and vertical direction. This is in reality very difficult to achieve (Nava et al., 2007). For our purposes we decided to model the error using an ionospheric model NeQuick 2.

5.1 NeQuick 2

The NeQuick is based on the model introduced by Di Giovanni and Radicella. The NeQuick constructs electron density distribution of the ionosphere by sum of Epstein layers. It enables to calculate electron density in any given point in the ionosphere, and therefore also total electron content and electron density profile along the ray-path between any two given points Radicella and Nava (2010). The version 2 of the NeQuick used for the analysis was obtain from the International Centre for Theoretical Physics in Trieste. The model is driven by solar radio flux F107 which is an index often used to quantify condition of solar activity. It is usually given in solar flux units (sfu) while 100 sfu is considered to be medium activity.

5.2 Modelling

We chose to analyze the mapping function error with dependency on geographical location, azimuth, elevation angle, ionospheric height and solar radio flux. The geometry and computations of the analysis were made in Matlab. Our case study for one IPP includes satellite-receiver link for each degree of azimuth around the IPP (Figure 3) with the same elevation angle.

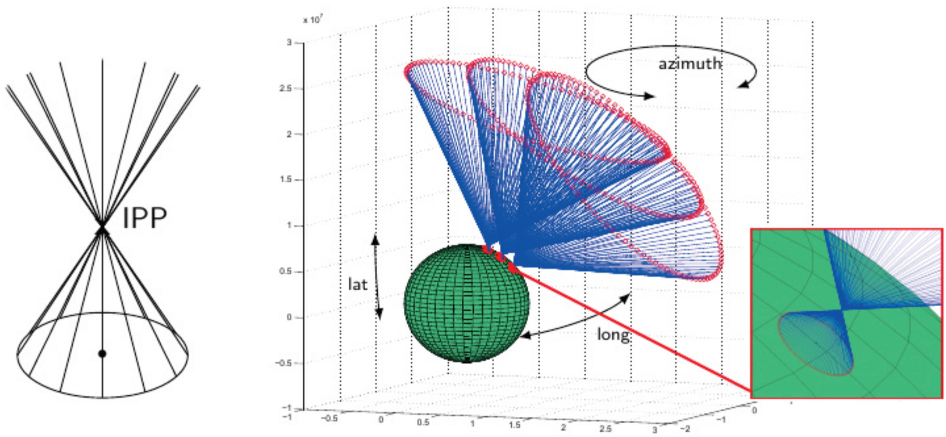

Figure 3 Scheme of the mapping function error calculation

For each link we computed the *sTEC* and apply the mapping function to obtain mapped $vTEC_m$. We defined the error of the mapping function as the difference between the $vTEC_m$ and the *vTEC* computed from the IPP directly:

$$error = sTEC \cdot MF - vTEC = vTEC_m - vTEC \tag{5}$$

For each IPP case we identified the ideal ionospheric height by finding the height which has the minimum error for the test case. This height is then set as the height with 0~km of difference.

6 RESULT

For given elevation angle, ionospheric height and space weather condition the highest absolute error is near the equator. The North Pole region shows the highest relative values (Figure 4). This can be caused by the fact that the TEC at pole regions is usually low and even small absolute deviation can cause high relative difference.

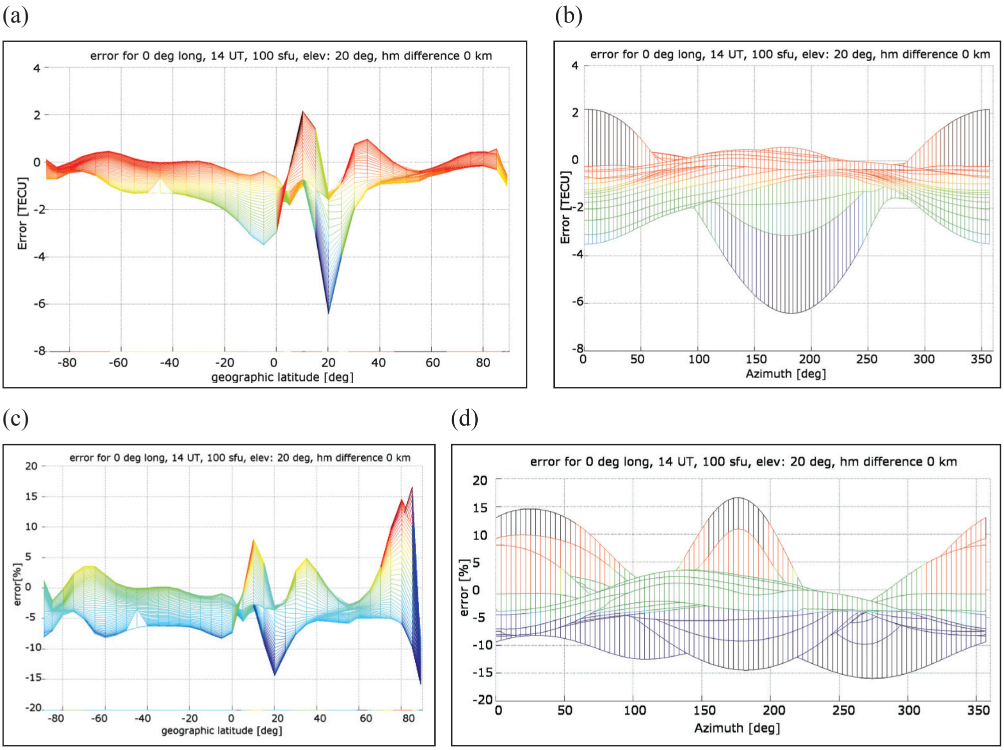

Figure 4 Mapping function error depending on geographical latitude (a) and azimuth (b) in absolute values and in percentage (c, d)

The values of maximum absolute error can be found in Tables 1, 2 and 3.

Table 1 Maximum errors for elevation 20 deg and ionospheric height difference 0 km

F10.7 [sfu]	75	100	125	150	175
Max error [TECU]	5.2	6.4	7.3	8.3	9.4
Max error [%]	39.1	22.9	23.1	24.1	29.4

Table 2 Maximum errors for F10.7 100 sfu and ionospheric height difference 0 km

El. angle [deg]	5	10	15	20	25	30	35
Max error [TECU]	8.06	7.7	7.07	6.4	5.65	4.9	3.24
Max error [%]	23.1	22.5	22.7	22.9	22.84	22.46	19.23

Table 3 Maximum errors for F10.7 100 sfu and elevation 20 deg

H diff [km]	5	10	15	20	25	30	35
Max error [TECU]	8.06	7.7	7.07	6.4	5.65	4.9	3.24
Max error [%]	23.1	22.5	22.7	22.9	22.84	22.46	19.23

More detailed analysis of the error at the equatorial region shows that the error is much higher in the South-North direction where the TEC gradient is higher than at the West-East direction where the TEC gradient is lower (Figure 5).

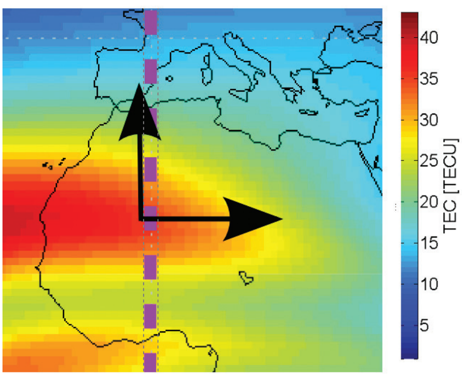

Figure 5 Detail of the TEC gradient around equator

7 ASYMMETRY INDEX

The results let us to the idea to represent the error in a way which would be independent on geographical location. We defined an *asymmetry index* (IND_{as}) as the ratio between the ionosphere of the bottom and upper part of the signal path (Figure 6). We empirically identify vTEC for 200 and 600 km of the path as the best option:

$$IND_{as} = R_{Bot} \cdot R_{Up} \tag{6}$$

where

$$R_{Bot} = \frac{TEC_{Bot}}{vTEC} \tag{7}$$

$$R_{Up} = \frac{TEC_{Up}}{vTEC} \tag{8}$$

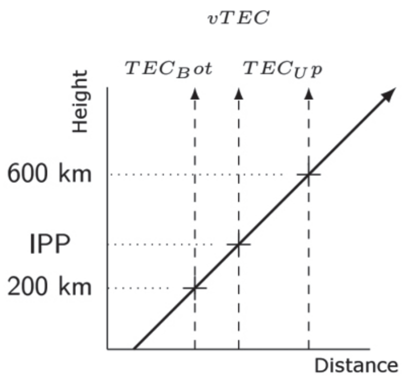

Figure 6 Vertical TECs to calculate IND_{as}

Such approach is not perfect as it uses information of *vTEC* from bottom and upper part while in practice only half of the ionosphere is important. However, we tried to make the index as simple as possible to be easily applicable.

If we display the error to the asymmetry index we can show how the error varies. To model the error dependency we made regression analysis and chose parabola (Figure 7) as the modeling curve. We plot the error dependence on elevation angle difference from ideal ionospheric height and solar radio flux (Figure 8).

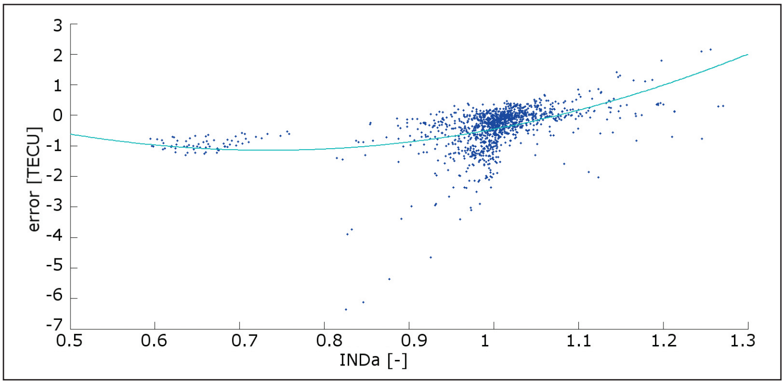

Figure 7 Statistical regression of TEC error to asymmetry index

a)
b)
c)

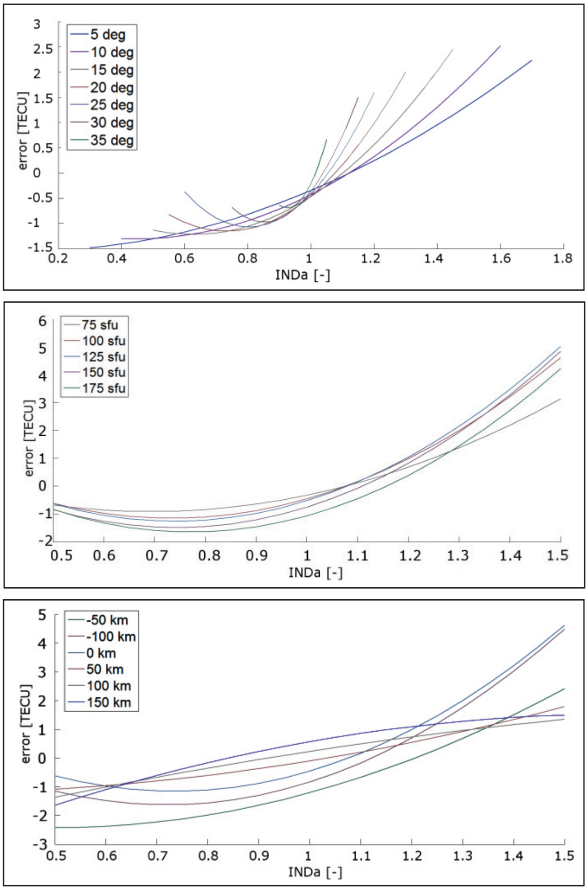

Figure 8 Variation of mapping function error depending on asymmetry index for changing solar radio flux (a), elevation angle (b) and ionospheric height (c)

8 SUMMARY AND DISCUSSION

The error caused by the single layer mapping function can have significant impact on estimation of the ionospheric error especially for low elevation angles, periods with high solar activity and for underestimated of ionospheric height parameter. We proposed an approach to model the mapping function error using asymmetry index. This index would use only two total electron values one for bottom and one for upper part of the signal path. Such approach could be used in augmentation system or in ionospheric models do correct the error caused by the single layer mapping function. However, there are still some outliers which are not covered by this approach and which should be investigated.

Acknowledgment

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ACCURACY OF EMBEDDED GPS RECEIVERS FOR RECREATIONAL USE

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ABSTRACT. *Advances in the GPS receiver and various other technologies have made navigation affordable and suitable for a variety of applications. Unlike in the past when civilian GPS appliances were designed primarily to solve engineering tasks providing fast and accurate measurements, GNSS of today serves hundreds of low-cost consumer applications, ranging from geotagging, sportsmanship, social networking, outdoor navigation and others. Although many personal navigation applications focus primarily on service availability rather than measurement accuracy/integrity, finding the right balance between the two and bundling it in a user-appealing value-for-money context has been a critical success factor. The paper presents results from field tests undertaken to assess positional accuracy of recreational GPS-enabled devices including smartphones. The results showed minor differences in the positional accuracies achieved by the smartphones tested. The corresponding accuracies of the evaluated Garmin recreational receiver demonstrated much higher accuracies. The devices were hence compared with respect to their unit prices, portability and versatility, and recommendations were given as to their possible uses.*

KEY WORDS: *low-cost GNSS, smartphone navigation, GPS for recreational use*

1 INTRODUCTION

Civilian GNSS have proven to be inexpensive and abundant supply of location information creating a whole new world of tools, aids and applications. In addition to helping users knowing where they are and what there is of interest around them, GNSS have also helped users to reference simultaneously their location to other people sharing same interests, geography or social group. This, coupled with the user-friendliness of the hardware platforms used, made GNSS-based positioning and navigation widespread in a number of civil sectors.

Although many personal navigation applications focus primarily on service availability rather than measurement accuracy (Huber, 2011), finding the right balance between the two and bundling it in a user-appealing value-for-money context has been a critical success factor. Indeed, a typical user is not likely to question the measurement results, however, the integrity of the end service and the corresponding pricing remain important regardless of whether the application is of a profit-making or recreational type. With respect to the former, according to (Oxera, 2013), the use of GNSS-based navigation saves more than one billion hours of travel time and 3.5 billion litres of fuel globally. It is reasonable to assume that the criteria which the utilised navigational solutions were selected against were primarily associated with the overall price rather than positioning accuracy or any other technological feature. Nevertheless, as the magnitude of the savings made is linked directly to the accuracy of the measurements taken, achieving higher accuracy for the same price is critical.

In balancing the above price-accuracy trade-off, various supporting technologies have been used to complement GNSS. Assisted GPS (AGPS), high sensitivity GPS chipsets (HSGPS) and location-based sensor fusion have been most common shifting requirements for computational power away from the device/CPU itself and improving signal acquisition. These technologies have been employed in a number of portable devices such as smartphones, tablets, wrist watches and others. As smartphones are considered to be personal devices almost always carried by their users (Zandbergen and Barbeau, 2011), they have proven to be a convenient platform for low-cost location-aware applications.

According to Asymco (2014) and GSMA Intelligence (2014), nearly seven billion mobile subscriptions are estimated to be in use in the World today. In developed countries there are approximately 120 cellular and 87 broadband subscriptions per 100 inhabitants, whereas the US and the European smartphone markets demonstrate nearly 75% market saturation and are soon expected to reach the inflection point thus coming close to saturation (Asymco, 2014; ITU World Telecommunication, 2014). Lesser developed countries on the other hand, such as those in the Asian Pacific and Middle East and Africa regions, are forecasted to generate significant growth in the coming years both in the number of subscribers and the generated revenues. It is hence estimated that in 2014 the number of mobile-cellular subscriptions in Africa, Asia & Pacific and the Arab States will almost reach five billion (ITU World Telecommunication, 2014). Moreover, as can be seen on Figure 1, the number of mobile broadband subscriptions in the developing countries has tripled in the last four years and doubled worldwide. Given that subscribing to mobile broadband suggests advanced usage of both the mobile device and the corresponding services available, potential market for location based applications is undoubtedly vast.

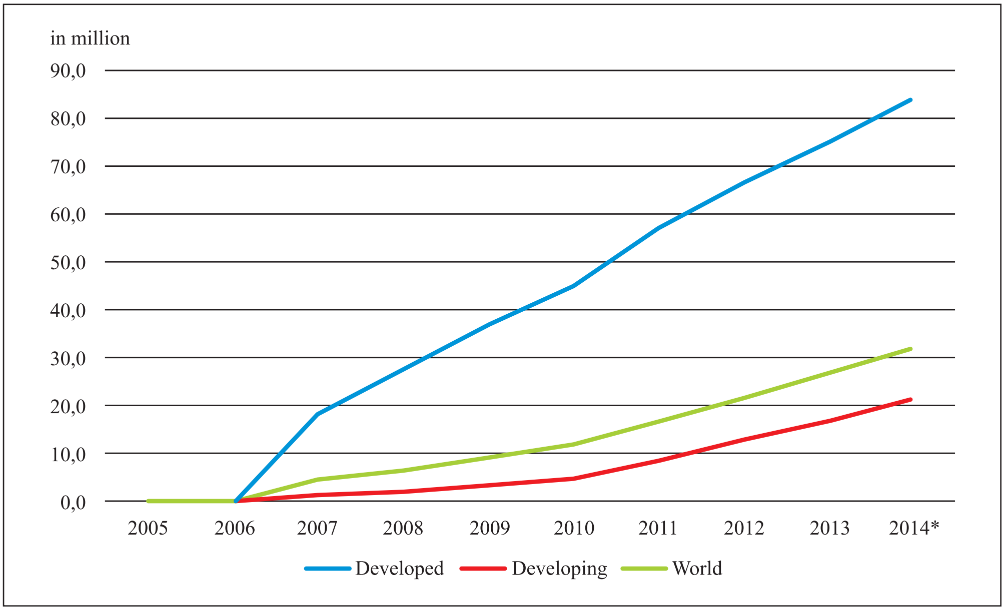


Figure 1 Number of active mobile broadband subscriptions (ITU World Telecommunication, 2014)

2 PERFORMANCE MEASURES

The above described growth of the mobile device & applications development industry has largely been driven by increased demand from developed regions for high-end smartphone models featuring always-on ubiquitous location, along with a strong push from emerging economies for lower-cost products. As a result, innumerable new applications, built up on different smartphone platforms, have turned out. As with many other hi-tech products, their most critical success factor have been the price-performance balance.

Targeting mass market price-sensitive users, performance measures used to assess modern GNSS devices for recreational use somewhat vary from the typical navigation performance indicators, shifting the focus away from technical issues. Unlike assessing technical features such as positional accuracy or signal availability (Specht and Szot, 2012; Serr, Windholz and Weber, 2006; Rodríguez-Pérez et al., 2006), the non-technical performance indicators are not as exact and may hence be misleading. Thus for instance, iOS-based applications are categorised as "top-paid", "top-free" and "top-grossing".

The first two are measured by the number of downloads made whereas the applications in the last category are credited for the generated revenue. As the number of downloads and the corresponding ranking should reflect application's quality and the level of service provided to its users, the ranking may be deemed an important performance indicator. It should be however noted that none of the categories specify the time span during which the downloads or the revenue generated took place, nevertheless, the ranking is seldom questioned by the users. Figure 2 provides a typical ranking of iOS navigation applications (iTunes AppStore, 2014).

Figure 2 iOS navigation applications ranking (iTunes AppStore, 2014)

In addition to the ranking criterion, the corresponding price is often seen as the second most important factor influencing user's decision to use a certain recreational device/application. If the two dominant smartphone application marketplaces in the World today are compared against each other, it can be seen that navigation applications sold on the Android market are more expensive than the corresponding iOS applications (Table 1) which may be attributed to the Android's larger market share (Table 2). Nevertheless, as ¾ of the applications are priced within the $10 budget, it is reasonable to conclude that fewer people are willing to purchase expensive applications proving the end user price a significant influencing factor.

Table 1 Top 100 paid navigation application market value (iTunes App Store, 2014; Google Play Store, 2014)

	iPhone	Android
Total top 100 apps value:	$1.283,00	$1.432,98
Average application price:	$12,83	$14,33
Max application price:	$84,99	$78,74
75 percentile:	$9,74	$12,18

Table 2 Global smartphone operating systems share (IDC, 2013)

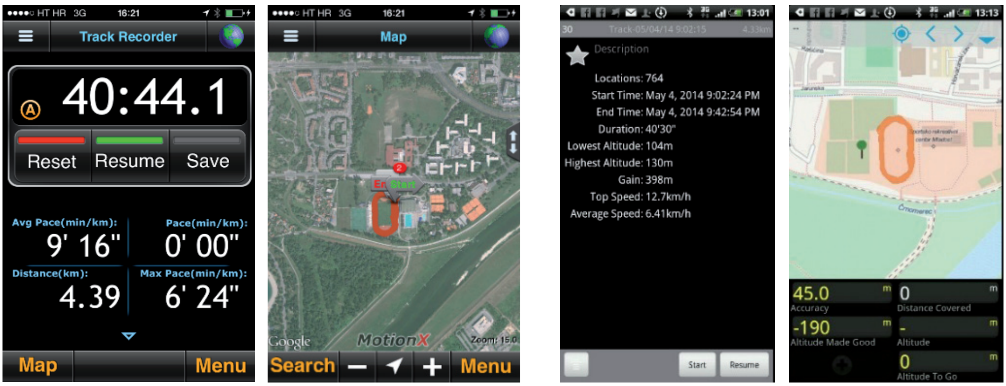
OS	2012 sales (millions)	2012 market share	2013 sales (millions)	2013 market share
Android	500,1	69%	793,6	78,6%
iOS	135,9	18,7	153,4	15,2%
Microsoft	17,5	2,4	33,4	3,3%
BlackBerry	32,5	4,5	19,2	1,9%
Others	39,3	5,4	10	1,0%

Even though the performance of any recreational navigation device is seldom evaluated by the user against technical parameters such as positioning accuracy or signal availability, both parameters influence the device's overall ranking and may hence be considered critical success factors. The corresponding demands for the achievable accuracy and availability vary with the purpose and typically range from a few metres to few hundred meters depending on the positioning mode used (Sabak, 2013; Zandbergen, 2009; Zandbergen and Barbeau, 2011). Higher accuracies are achieved by employing supporting technologies such as A-GPS, WAAS, Bluetooth and others.

3 FIELDTESTS UNDERTAKEN AND THE RESEARCH METHODOLOGY

Field tests were undertaken to assess positional accuracy of three recreational devices, a GPS-enabled wristwatch and two smartphones. The first smartphone (hereafter referred to as *Smartphone1*) featured an A5 dual core processor, 512MB RAM, A-GPS SBAS-WAAS, digital compass, accelerometer and a three-axis gyro. The measurements were taken using the Fullpower Technologies USA MotionX-GPS mobile application running on the iOS 7 platform. The application utilises the patented MotionX® Technology platform for activity tracking marketed as the leading development platform for wearable and Internet-of-Things sensor-based solutions.

The second smartphone (hereafter referred to as *Smartphone2*) was an Android 2.3.4-based device featuring 1.2GHz dual core processor, 1 GB RAM, accelerometer, gyro and a compass. The measurements were recorded using the Schollmeyer Software Engineering Germany GPS Essentials mobile application marketed as the "Swiss army knife" of GPS navigation on Android smartphones and rated 4.3/5 on the Google Play Store. Figure 3 provides typical screenshot examples of the MotionX-GPS and GPS Essentials mobile applications.

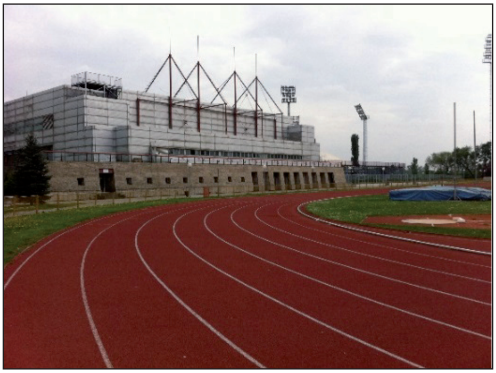


a) MotionX-GPS b) GPS Essentials

Figure 3 Typical screenshots of the mobile applications used

As said earlier, the third receiver evaluated was an HSGPS wristwatch featuring 20MB built-in memory and a temperature sensor, altimeter, compass and a barometer as supporting sensors. The device is hereafter referred to as the Wearable GPS. Being a passive device it does not support A-GPS. To download and manipulate with the measurements taken, the Garmin BaseCamp 4.2.5 software was used running on Microsoft Windows platform.

To minimise differences between individual trials as well as to emulate a typical recreational use, the tests were carried out on an athletic stadium by walking an arbitrary chosen lane (lane 4) and simultaneously collecting data with all three devices. The area at and around the stadium was reasonably open with only one adjacent building (Figure 4a) and a stand with a canopy (Figure 4b). As there were no tall buildings nor trees surrounding the test site, only marginal signal blockage, attenuation or multipath was expected (Figure 4c).



a)

b)

c)

Figure 4 The athletic stadium

The positioning accuracy was assessed by analysing the number of readings falling in the geometry of the walked lane using the Quantum GIS desktop (QGIS) software. Even though such an approach is susceptible to erroneous readings falling in the given lane and hence designated as correct despite the absolute distance from the reference point being greater than the lane width (Figure 5), it was chosen as it best portrays the recreational use of GNSS.

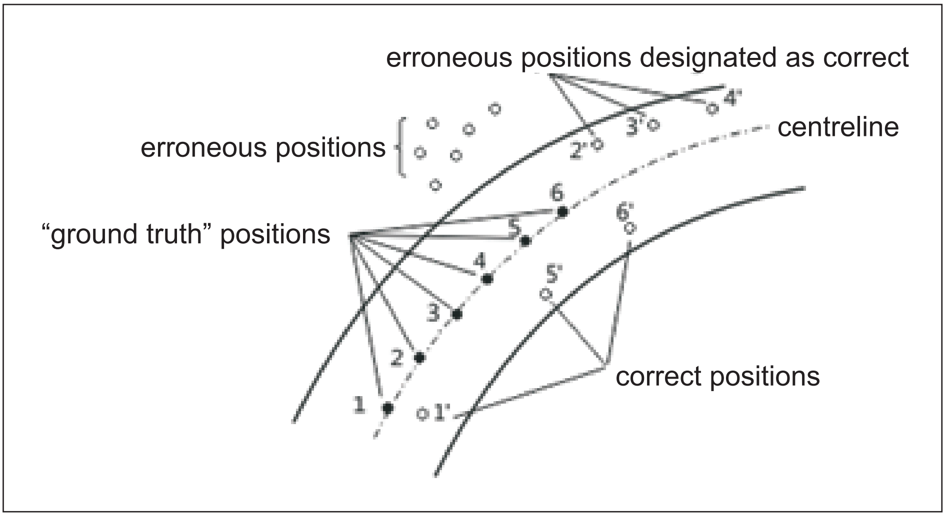


Figure 5 Accuracy measurement methodology

The geometry of the walked lane as well as the remaining lanes on the running track were generated by first measuring the "ground truth" represented by the centreline of the walked lane (lane 4). Polygonal shape geometries 122 cm in width (the width of the physical lane) were then created (Figure 6) by measuring the 61 cm distance both sides from the centreline. After creating the walked lane geometry, geometries of the remaining lanes on the running track were generated with the Trace tool of the QGIS software using the 122 cm offset. The coordinates of the "grand truth" were acquired by combining measurements

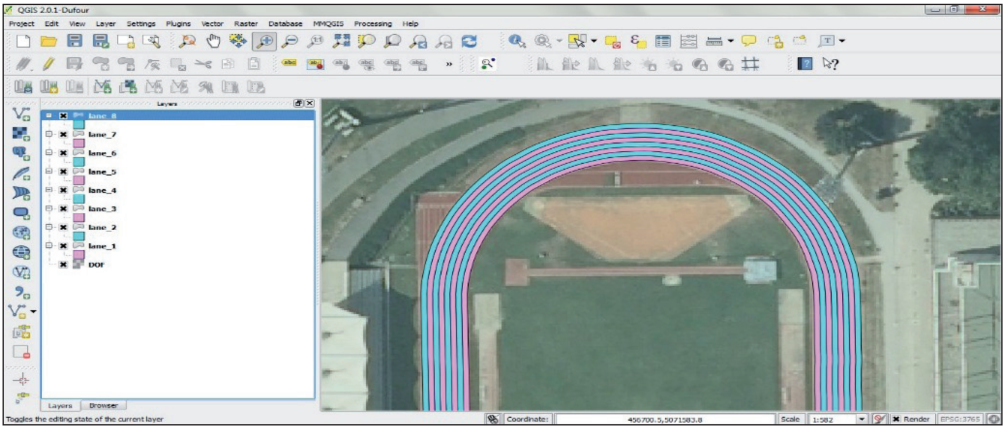


Figure 6 Geometries of the track lanes

from a Trimble Geo7x geodetic receiver with aerial imagery. The former provided static measurements at the key locations defining the running track geometry (top of the arches and beginnings/ends of the straight segments). Given that the running track represents a symmetrical geometric shape, connecting the measured points with the corresponding straight and circular segments and closing them in an appropriate shape provided the "ground truth" geometry needed. Such an approach was seen as least susceptible to measurement errors.

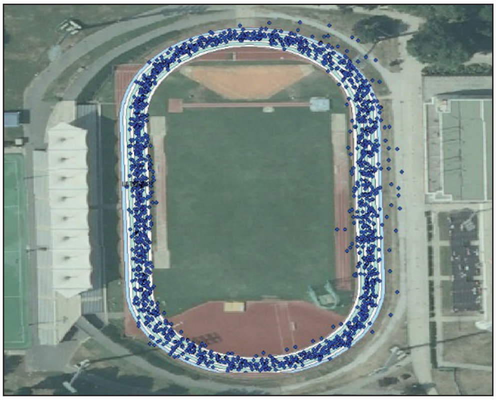
The tests took place in winter/spring season 2013/2014. All three devices were setup with the one second logging interval. Sixty runs were made in total with nearly 15.000 points recorded. The runner/surveyor remained in lane 4 during all 60 laps. Both smartphones had the AGPS functionality enabled during the trials. To assess the positioning conditions regarding receiver-satellite geometry, the PDOP factor was calculated using online mission planning tools available. With average PDOP below 4 during the entire trial period, it may be concluded that the positioning conditions were satisfactory.

The measurements were taken such that the smartphones were hand-held facing upwards while the wearable GPS was strapped to the surveyor's wrist. Given that the latter receiver was hence facing downwards, its measurements were expected to demonstrate somewhat degraded accuracy.

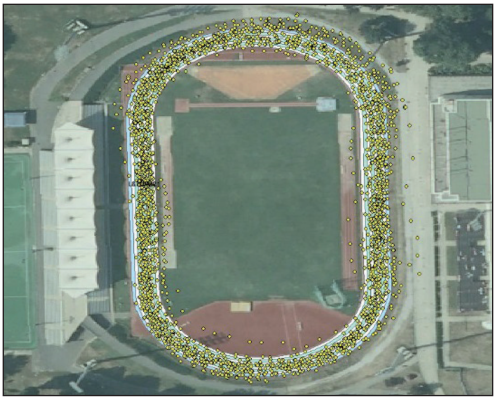
4 RESULTS

As said earlier, the positioning accuracy was assessed by analysing the number of readings falling in the geometry of a given running lane using the QGIS software. Figures 7a, 7b and 7c depict the dispersion of the readings taken by the Smartphone1, Smartphone2 and the wearable GPS respectively.

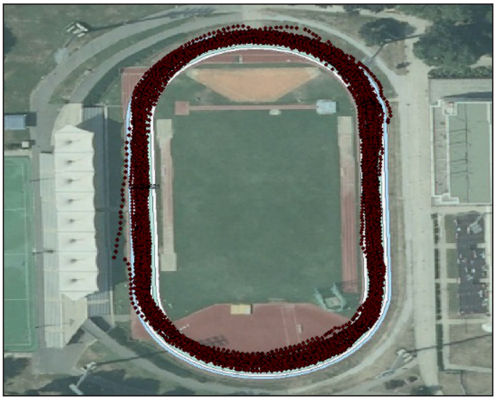
As can be seen from Figure 7 the tests showed minor differences in the achieved positional accuracies. However, even though all three receivers were setup with the same one second logging interval, the smartphone receivers demonstrated much lesser signal/positioning availability given by the frequency and the duration of signal loss.



a)



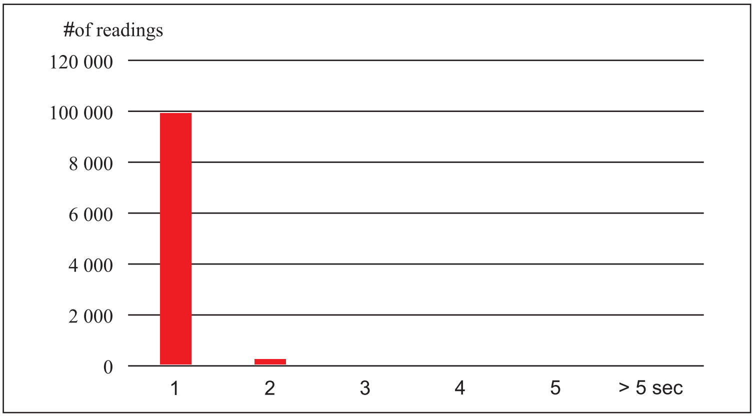
b)



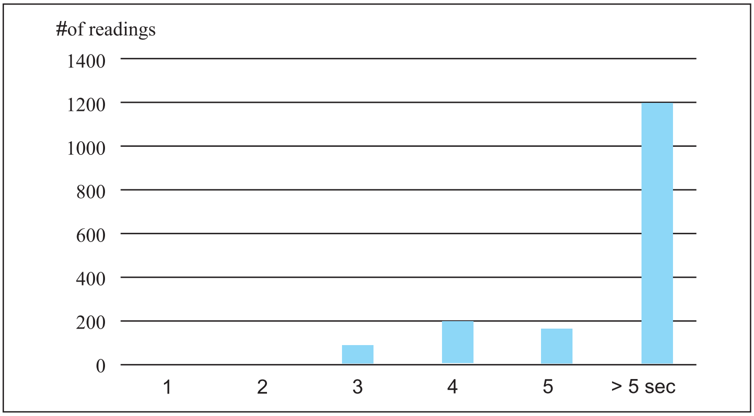
c)

Figure 7 Readings from the receivers tested

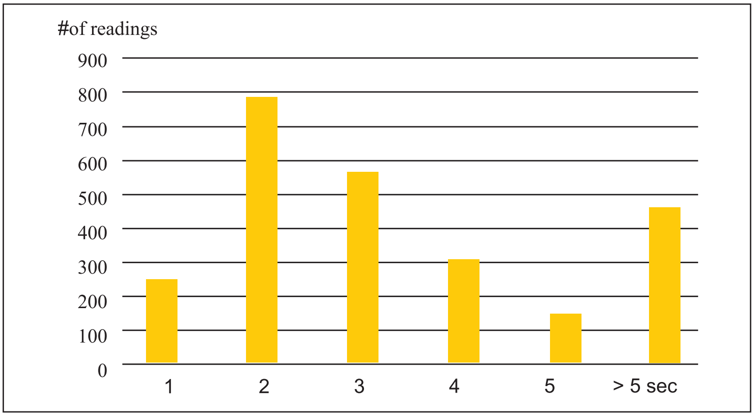
Figure 8 provides info on the signal loss distribution for the three receivers. As can be seen from the figure, the Smartphone1 receiver was virtually unable to provide any readings with 1s logging interval which may be attributed to the built-in accuracy filtering engaged during the trials. Furthermore, in comparison with the wristwatch receiver, both smartphones demonstrated poor positioning availability. Even though the Smartphone2 receiver provided higher availability range than the Smartphone1, the majority of the readings were recorded in intervals greater than the required one second. In addition, the GPS Essentials mobile application showed certain inconsistencies in the time stamps recorded. As these were treated a consequence of a software bug, they were disregarded from further analysis and hence will not be discussed in the paper. It may therefore be concluded that both smartphone receivers and/or the corresponding mobile applications would not be suitable for purposes requiring continuous reliable positioning.



a) Wearable GPS receiver



b) Smartphone1



c) Smartphone2

Figure 8 Positioning availability

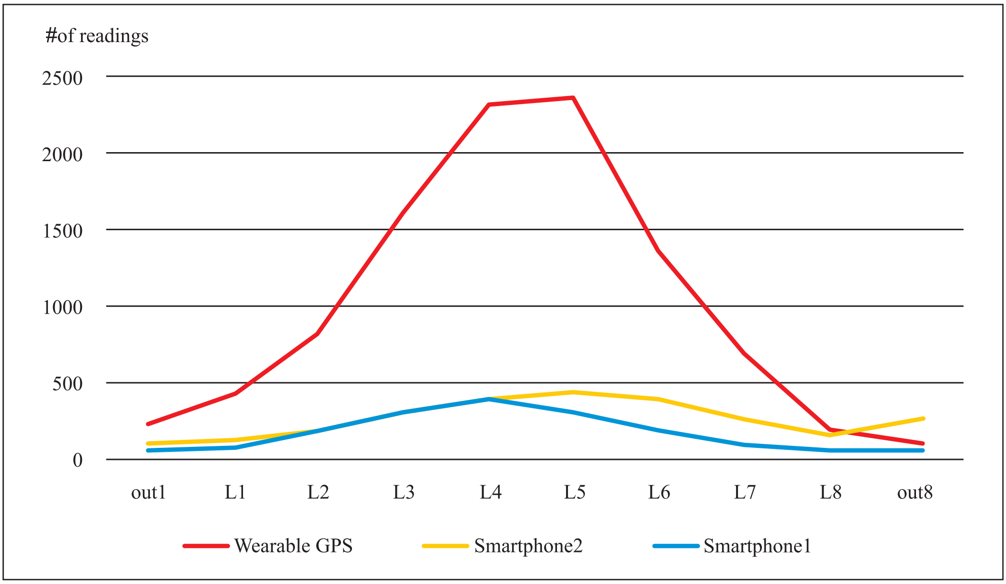


Figure 9 Positioning accuracy

Table 3 Recorded positions by running lanes (in %)

	out1	**L1**	**L2**	**L3**	**L4**	**L5**	**L6**	**L7**	**L8**	**out8**
Wearable GPS	2,27	4,17	8,38	16,54	23,10	23,61	13,01	6,52	1,62	0,78
Smartphone1	3,63	3,93	11,32	17,99	23,70	18,11	10,36	5,48	2,92	2,56
Smartphone2	3,30	4,01	6,99	11,84	16,01	17,08	14,94	9,38	5,72	10,73

Figure 9 and Table 3 provide data on the achieved positioning accuracy for the three receivers tested. As can be seen from the data, less than one fourth of the measurements from all three receivers fell in the correct lane (L4). Interestingly, even though it yielded worst availability results, the Smartphone1 receiver demonstrated the highest number of correct readings. If the 95th percentile is used as the accuracy measure, it can be seen from Table 3 that only the wristwatch receiver had 95 per cent of the errors within the geometry of the running track.

5 CONCLUSIONS

As said earlier, performance measures used to assess modern recreational GNSS devices shift the focus away from technical features such as positional accuracy or signal availability and put emphasis on the price. With billions of mobile subscriptions in use today and increasing demand for portable hardware platforms capable of supporting a variety of applications, smartphones are seen by many a key platform for low-cost consumer positioning. Even though GNSS' used for recreational purposes are seldom expected to provide any mission critical outputs, reliable continuous positioning – represented typically by the positioning accuracy and signal availability – is still a measure the positioning devices need to be validated against. This is particularly important in safety critical or life threating applications such as for instance distress calls, remote hiking etc.

To assess positioning performance of typical consumer mobile devices of today, field trials were undertaken using two smartphones and a wearable GPS. The results showed that both smartphone receivers and the corresponding mobile applications used would not be suitable for purposes requiring continuous reliable positioning. As the cost of the device was identified a key influencing factor, the devices were compared with respect to their unit prices as well as their portability and versatility using the weighted score card method.

Table 4 GNSS devices scored

	Wearable GPS	**Smartphone1**	**Smartpone2**	***Weight***
Accuracy	5	3	2	*4*
Position Availability	5	2	3	*5*
Functionality	1	5	4	*2*
Integration potential	1	5	5	*3*
Price	5	1	3	*5*
Total Score*:	**75**	**52**	**61**	

5 = best, 1 = worst

Both weights and individual scores for a given criterion were set arbitrarily by the authors thus emulating a typical end-user feedback. The overall score for a given device was calculated as:

$$S = \Sigma \, c_i \cdot w_i \qquad (1)$$

where

S = overall score

c_i = individual score for a given criterion

w_i = weight factor of a given criterion.

Despite being partial, the results may indicate that the dedicated GPS wearable device is likely to best meet the requirements of recreational GPS use even though it has been much limited in non-location based features. More conclusive results would require a much larger sample of the customer feedback data which may indeed be a recommendation for future work.

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MODIFICATION OF RINEX OBSERVATION FILES WITH CALIBRATED TOTAL ELECTRON CONTENT

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ABSTRACT. *Total Electron Content (TEC), proportional to the ionospheric error in Global Navigation Satellite Systems (GNSS), can be calculated using dual-frequency measurements. To improve the calculation accuracy TEC should be calibrated, i.e. the inter-frequency biases introduced in the satellites and the receiver should be removed. Data from GNSS reference stations is publicly available in Receiver Independent Exchange Format (RINEX). Several software tools can be used to process such files. Modifying pseudoranges and carrier-phase data by removing the calibrated TEC, a version of the original RINEX file that does not contain ionospheric error was made. Modification procedure's validity was proven by performance evaluation in position domain. Such a modified RINEX file could be used as a reference in comparison of different ionospheric error correction methods in position domain, where the methods would also be represented forming RINEX files modified following the same procedure.*

KEY WORDS: *GNSS, ionosphere, RINEX, Total Electron Content*

1 INTRODUCTION

In Global Navigation Satellite System (GNSS) the receiver position is calculated using trilateration, a process where distances from known points in space, in this case satellites, are measured to determine the receiver location. Receiver has the information of satellites' positions as they are transmitted through the navigation messages and the distance is calculated from the signal propagation time. To enable that, clocks on the receiver and satellites have to be synchronized. GNSS signals cross the ionosphere and, as it contains free electrons and ions, the signal gets refracted. Propagation speed of the electromagnetic signal thus slows down and the reception time gets delayed. Longer propagation time is translated into longer calculated distance between a satellite and a receiver which finally, if uncorrected, results in major error in GNSS positioning (Misra, 2012). The time-delay is frequency dependent and it can be calculated measuring the propagation time on two sufficiently distant frequencies. However, large majority of commercial GNSS receivers uses single frequency position calculation. Unlike dual frequency receivers, such receivers cannot determine the actual ionospheric time-delay. They have to rely on correcting the ionospheric error with ionospheric models, such as Klobuchar model in Global Positioning System (GPS) and NeQuick G in Galileo.

The ionosphere is a part of atmosphere that consists of very dynamic layers and its condition varies diurnally, seasonally, in the solar 11-year cycle and depending on the geomagnetic coordinates. Besides those regular changes, it also varies under the influence of solar activity and the Earth's magnetic field. Ionospheric error is proportional to the Total Electron Content (TEC), the number of free electrons on a path through the ionosphere with cross-section of 1 m^2. It is quantified with a TEC unit (TECU), which equals 10^{16} electrons/m^2 (Zolesi, 2014). Vertical TEC (VTEC) is defined as the TEC in the zenith direction from the receiver and slant TEC (STEC) represents the TEC on the signal path between a GNSS satellite and a receiver. Ionospheric delay becomes larger as the satellite elevation lowers because the signal passes through the thicker segment of the ionosphere.

2 TOTAL ELECTRON CONTENT CALIBRATION

Dual-frequency GNSS receivers measure carrier-phase observables (quantified in cycles) and code-delay observables, i.e. pseudoranges (quantified in meters) for each of the frequencies transmitted from a satellite. Pseudoranges provide lower accuracy but have the advantage in the lack of ambiguity whereas phase measurements have high precision, but the ambiguity of the integer number of cycles has to be resolved. Combining measurements on two frequencies, TEC can be calculated and the influence of the ionosphere removed, which improves the accuracy in determining the distance from a visible satellite to the receiver. However, the process of levelling carrier-phase to code-delay observables is affected by inter-frequency biases (IFB) which are produced by the receiver and by the satellites (Sardon, 1994). IFB, known also as Differential Code Biases (DCB) exist between signals on different frequencies (P1-P2 bias) and also between signals on the same frequency which are coded differently (P1-C1 bias). IFB are caused by the transmitter and receiver hardware, where signal path and processing time are different for different coding schemes and antenna phase centres differ for different frequencies. The process of estimation and removal of IFB is often called TEC calibration. IFB are usually removed using DCB P1P2 and P1C2 files (Schaer, 2008). However, those files contain averaged monthly values of DCB, which is insufficient as DCB diurnal variation can be very significant, up to 8.8 TECU (Ciraolo, 2007).

Ciraolo calibration procedure can only be used in post-processing as it requires the observation and navigation Receiver Independent Exchange Format (RINEX) files from the day before and the day after the observed day to be present. Such data is necessary to reconstruct the whole satellite arches since their appearance over the horizon, until the time they disappear again. The data from full satellite arches are used in the process of carrier-phase to pseudorange levelling in order to get results as accurate as possible and to reduce the appearance of the short arches (Ciraolo, 2007). TEC obtained by the calibration process is more accurate because the occurrence of negative TEC, impossible in nature, is minimized in comparison with non-calibrated TEC.

3 RINEX DATA FORMAT

Several networks of GNSS multi-frequency stations provide open access to RINEX data archives. The most common types of RINEX files are the observation and navigation files in versions 2.10 and 2.11. The RINEX files have the ASCII structure, which is convenient for easy reading by the observers (Gurtner, 2007). RINEX files usually contain 24-hour data and the naming structure is strictly defined for easier software manipulation. The RINEX file names consist of the station marker code, day of the year, year and the letter describing the RINEX file type. Each RINEX file begins with a header that contains information about the station that collects the data and global information applicable to the entire file. There are separate navigation files for

GPS and GLONASS data, each of them containing data from the navigation messages broadcasted by the satellites of the corresponding system. Navigation RINEX file consists of satellite ephemerides data, satellite clock corrections and, in case of GPS, Klobuchar ionospheric model parameters. RINEX observation files contain signal parameter measurements for all visible satellites of all the supported constellations, made by a certain receiver. Therefore, every receiver creates a unique observation RINEX file, with a header containing station specification, observation types and time of the first observation, followed by the observation data. Observation data for each epoch consists of the list of visible satellites and pseudorange, carrier-phase, Doppler and Signal-to-Noise Ratio (SNR) observables on all supported frequencies for each visible satellite.

4 RINEX MODIFICATION PROCEDURE

RINEX observation files used in this research were derived from Septentrio binary data acquired by a receiver situated in Zagreb, Croatia with observables collected every 60 s. This proof-of-concept procedure did not include GLONASS measurements because the data analysis tool gLAB is only capable of the GPS data analysis (gLAB, 2013). The used RINEX files contained pseudorange, carrier-phase, Doppler delay and SNR measurements in three (L1, L2 and L5) frequency bands.

Pseudoranges C1 and P2 and carrier-phase measurements L1 and L2 were available for all satellites in GPS constellation. Considering that pseudoranges and carrier-phases on two frequencies are sufficient for TEC calibration, measurements that were available only for certain satellites, such as P1, C2 and C5 pseudoranges and L5 carrier-phase, as well as Doppler and SNR measurements, could be omitted in the further analysis. TEQC tool was used to discard such data from the RINEX files (TEQC, 2014). However, SNR data was preserved through the signal strength indicator ranging from 1 to 9, displayed after every pseudorange and carrier-phase measurement. The resulting RINEX file was more compact and the data for each visible satellite were equable and displayed in one line, making it suitable for further changes (Figure 1, top). The TEC calibration was executed on both, the reduced and non-reduced RINEX files to examine the influence of data discarding in TEC domain. Dual-frequency positioning using both files was also compared using gLAB to examine the possible differences. Results confirmed that the discarded data were not necessary for calibration or determining the position of a static receiver, as the calculated TEC and position were equal in both cases, which justified the usage of reduced RINEX files in further steps of the research.

The STEC produced by the calibration was used to remove the ionospheric error present in pseudorange and carrier-phase data of the processed RINEX file with reduced data set. For each epoch and for each satellite where calibration produced the value of STEC, the following equations, derived using first order ionospheric index of refraction (Garner, 2008) were calculated:

$$C_1^{IoF} = C_1^{RINEX} - \frac{40.3 \cdot TEC}{f_1^2}, \tag{1}$$

$$L_1^{IoF} = L_1^{RINEX} + \frac{40.3 \cdot TEC}{f_1 \cdot c}, \tag{2}$$

$$P_2^{IoF} = P_2^{RINEX} - \frac{40.3 \cdot TEC}{f_2^2}, \tag{3}$$

$$L_2^{IoF} = L_2^{RINEX} + \frac{40.3 \cdot TEC}{f_2 \cdot c}, \tag{4}$$

where f_1 and f_2 are the GPS frequencies of 1575.42 MHz and 1227.6 MHz, *TEC* is STEC in TECU, C_1^{RINEX}, P_2^{RINEX} are the original pseudoranges (in meters) and L_1^{RINEX}, L_2^{RINEX} are the original carrier-phase measurements (in phase cycles) from a RINEX file for those two frequencies. C_1^{IoF}, L_1^{IoF}, P_2^{IoF} and L_2^{IoF} are pseudoranges and carrier-phase measurements that no longer contain influence of the ionosphere (iono-free). To preform single-frequency positioning performance evaluation, the data calculated using equation (1) would be sufficient, but for completeness of the procedure, equations (2), (3) and (4) were also calculated. 1 TECU contributes to the pseudorange length with 16.24 cm on f_1 and 26.74 cm on f_2, whereas the carrier phase for 1 TECU advances 0.856 cycles on f_1 and 1.095 cycles on f_2. The modified pseudorange and carrier-phase data can be seen at the bottom part of the Figure 1.

The first line in each part of Figure 1 shows the date, time, number of visible satellites and their pseudo-random noise (PRN) codes. Following lines in the top part of the figure contain L_1^{RINEX}, L_2^{RINEX}, C_1^{RINEX} and P_2^{RINEX} for satellites listed in the first line, with each value followed by an SNR indicator. The bottom part is form similarly, only containing L_1^{IoF}, L_2^{IoF}, C_1^{IoF} and P_2^{IoF}. The resulting modified RINEX file has the same header as the original and the same number of lines containing measurements.

```
14  8 10  5 21  0.0000000  0 10G11G18G12G30G28G26G05G15G24G17
134123259.753 4                 25522807.778 4
126350779.635 6  98455146.549 3  24043754.798 6  24043755.150 3
132208548.544 6 103019656.572 3  25158453.168 6  25158454.594 3
127239434.873 6  99147629.969 4  24212863.446 6  24212869.013 4
116243132.958 7  90579058.758 5  22120333.828 7  22120335.146 5
107014646.549 8  83388044.972 6  20364207.178 8  20364207.088 6
132014620.621 7 102868531.495 4  25121552.537 7  25121554.428 4
109136714.394 7  85041599.307 5  20768027.419 7  20768027.160 5
119941020.975 7  93460554.555 4  22824018.903 7  22824021.782 4
119623362.260 7  93213018.420 5  22763565.619 7  22763568.165 5
```

```
14  8 10  5 21  0.0000000  0 10G11G18G12G30G28G26G05G15G24G17
000000000.000 0 000000000.000 0  00000000.000 0  00000000.000 0
126350800.770 6  98455173.672 3  24043750.776 6  24043748.526 3
132208576.889 6 103019692.948 3  25158447.774 6  25158445.711 3
127239474.063 6  99147680.263 4  24212855.988 6  24212856.731 4
116243151.243 7  90579082.224 5  22120330.348 7  22120329.415 5
107014662.181 8  83388065.033 6  20364204.203 8  20364202.189 6
132014653.966 7 102868574.288 4  25121546.192 7  25121543.978 4
109136728.251 7  85041617.090 5  20768024.782 7  20768022.817 5
119941039.858 7  93460578.788 4  22824015.310 7  22824015.864 4
119623388.429 7  93213052.004 5  22763560.639 7  22763559.964 5
```

Figure 1 Example of one epoch of the original (top) and modified (bottom) data in an observation RINEX file

For each time stamp all the visible satellites are listed. For those satellites whose data in the calibration process produced a valid value of STEC, new iono-free pseudoranges and carrier phases are written. If the calibration process was unsuccessful for some satellite, either because of lack of data in the original file or because of short satellite arches, zeros are written in place of measurements.

Single frequency positioning performance of original and modified RINEX files were compared using gLAB. Original RINEX file was used in two cases, without any ionospheric correction in positioning process and with usage of Klobuchar model with broadcasted parameters. The modified RINEX file containing iono-free measurements was used without additional ionospheric correction in the positioning process. The 10° elevation cut-off was applied to discard satellites with lower elevation because of the low signal strength, higher possibility of multipath occurrence and a very long path through the ionosphere and especially troposphere. Figure 2 shows calculated north, east and up positioning error in relation to the nominal a priori position of the receiver, with results for each positioning method represented in different colour.

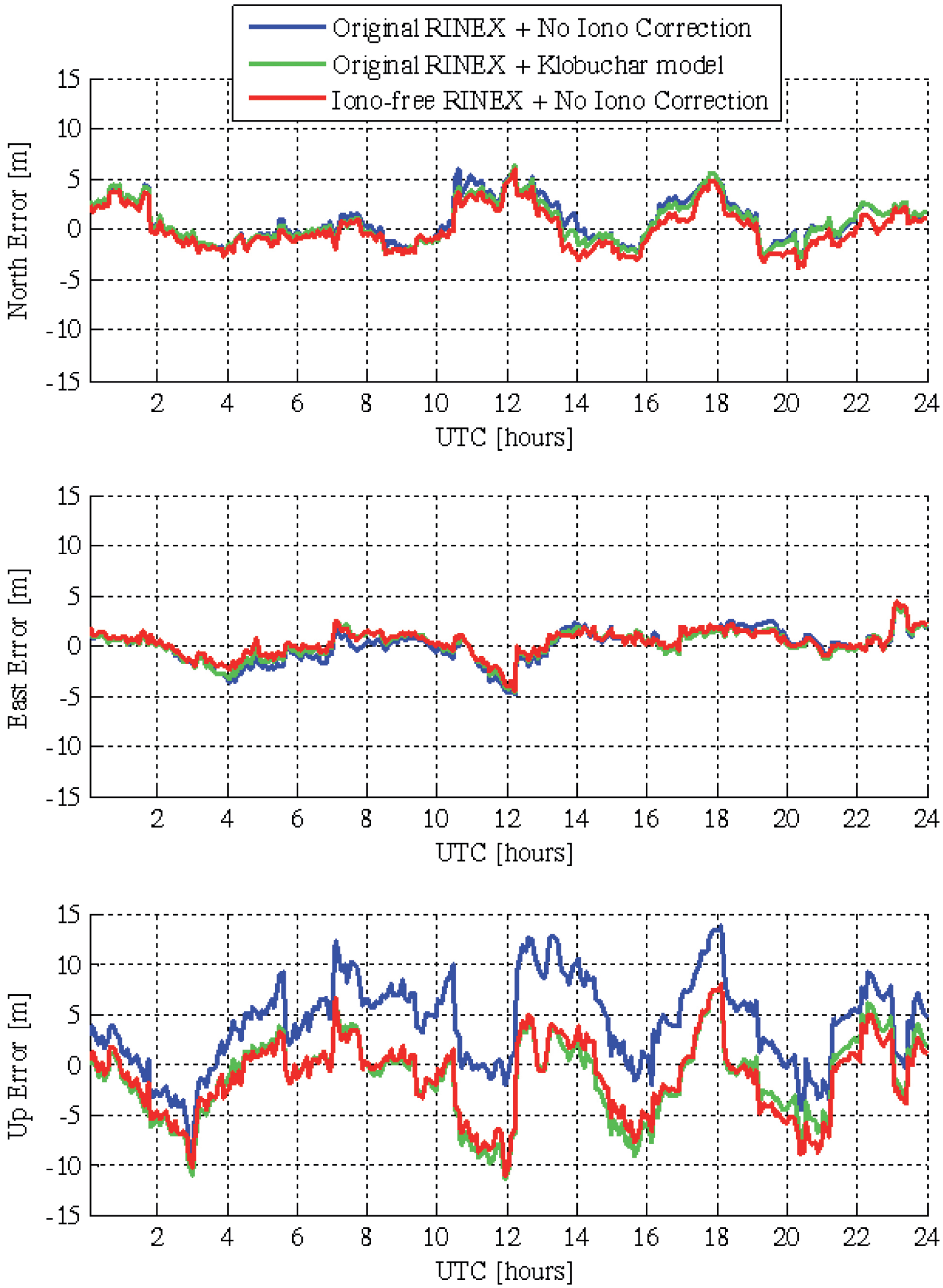

Figure 2 Positioning error in north, east and up direction for different positioning methods on ZGRB station, 10 August 2014

Comparing the errors, it is visible that the error in the receiver height calculation is higher than the horizontal positioning errors for all the observed positioning scenarios. The difference between calculated values for those scenarios is also the highest in the upward pointing direction. That was expected because of the generally unfavourable geometry of receiver and satellite's positions in GNSS, where all the signals come to the receiver from above, with no possibility of correction from the opposite side, unlike the cases of north-south and east-west positioning. An example of daily average positioning errors and standard deviations is presented in Table 1.

Table 1 Daily average absolute positioning errors and standard deviations on ZGRB station, 10 August 2014

		Original RINEX + No Iono Correction	**Original RINEX + Klobuchar model**	**Iono-free RINEX + No Iono Correction**
Error [m]	North	1.83181	1.73645	1.69085
	East	1.21752	1.10495	1.02430
	Up	4.92185	3.30246	3.15529
σ [m]	North	2.12341	2.06273	2.03199
	East	1.56424	1.39675	1.27418
	Up	4.41350	4.02950	3.83466

This data confirms that the positioning using the original RINEX file without any ionospheric corrections applied produces the worse solution in all directions, that the application of Klobuchar model improves the accuracy and that the modified iono-free RINEX file has the best positioning performance in all directions.

5 CONCLUSION

In this paper the process of removal of ionospheric error from an observation RINEX file using the TEC obtained by Ciraolo calibration method was described. RINEX file containing GPS data consisted of measurements made every 60 s. The data set was then reduced in order to keep only the data necessary for calibration and positioning, which simplified the structure of the file. Such a transformation could be done for RINEX files from any GNSS station of interest.

The calibration, calculating satellite and receiver IFB and resolving code-phase ambiguity, was used to obtain referent TEC from the available RINEX files. In order to remove ionospheric error from pseudorange and carrier-phase data, it was necessary to translate the calibrated TEC into the amount of code-delay and phase-advance caused by the ionosphere and apply the opposite amount to the measurements. Pseudoranges and carrier-phases were recalculated and stored in a modified RINEX file that no longer contained influence of the ionosphere. Positioning performance of the original and modified RINEX files was compared. The purpose of positioning error comparison was the validation of proposed procedure of RINEX file reduction and modification. Higher positioning accuracy achieved with modified RINEX files confirmed this method for removal of ionospheric influence from RINEX data as valid.

Furthermore, in place of calibrated TEC data, the TEC obtained from any source (such as ionospheric model or GNSS augmentation system) could be used, applying the proposed RINEX data modification procedure. That would result in RINEX files which would contain residual ionospheric error and could be used to evaluate the ionospheric correction performance in position domain. In such positioning performance test, iono-free RINEX file described in this paper would be used as a reference. Ionospheric models are usually compared in TEC domain, but understanding their accuracy in position domain could be easier modifying the RINEX files and evaluating the positioning performance using some of the available software tools that support RINEX format.

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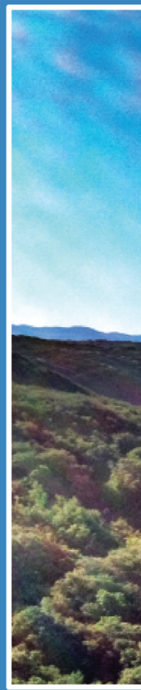

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