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| IALA Guideline |

Gnnnn

Guideline on Digitalization of Waterways

Edition x.x

Date (of approval by Council)

urn:mrn:iala:pub:gnnnn

Revisions to this document are to be noted in the table prior to the issue of a revised document.

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|  |  |  |

1. Introduction and overview 8

1.1. Overview 8

1.2. Scope 9

2. Digitalisation Maturity And Conditions to be taken into account for the digitalisation of waterways 10

2.1. Digitalisation Maturity 10

2.1.1. Digital Maturity definitions as under development at IEC 10

2.1.2. Digital Maturity – learning from other modes of transport 10

2.1.3. Digital Maturity for waterways as adapted from the Capability Maturity Model (CMM) 11

2.1.4. Consequential required decision making process at IALA 18

2.2. Conditions to be taken into account for the digitalisation of waterways 18

2.2.1. Vessels vs waterborne vehicles 18

2.2.2. Advent of higher degrees of automation and of Autonomy 18

2.2.3. Mixed traffic in approaches, inland Seaways and Estuaries 20

2.2.4. Notion of the ‘autonomous ship system’ and its context – moving towards co-operative nature 21

2.2.5. Navigational aids versus Aids-to-Navigation and the generic shipboard navigation system architecture 22

3. Digital model, shadow and Twin 24

3.1. Generic Definitions 24

3.1.1. Overview 24

3.1.2. Digital Model – Definition in international standards 25

3.1.3. Digital Shadow – Definition in international standards 25

3.1.4. Digital Twin - Definition in international standards – the ITU example 25

3.2. The specific Relevance of the S-100 world 27

3.2.1. Specific relevant features of the S-100 World 29

3.3. Digitalisation Maturity of Waterway entities 29

3.3.1. IALA Digital Maturity Categories 29

3.3.2. Model under development at IEC applied 29

4. Digital Services for navigation in waterways 31

4.1. Introduction 31

4.2. digital services for Waterways as defined by IMO 31

4.3. Digital services for Waterways as defined by PIANC 31

4.4. Digital services stemming from S-100-World data products 31

4.5. Digitalisation Maturity concepts applied to Digital Services for navigation in waterways 32

4.5.1. IALA Digital Maturity Categories applied 32

4.5.2. Model under development at IEC applied 32

5. Architectures for Digitalisation of waterways 33

6. CONSEQUENTIAL REQUIREMENTS 34

6.1. Introduction 34

6.2. Connectivity Requirements in general 34

6.3. Specific Digital Twin (System) requirements 34

6.4. Generic functionality requirements 35

6.5. Keeping an overview on the consequential Requirements – Requirement traceability 35

7. Putting existing generic AtoN and VTS applications into the picture 37

7.1. Introduction 37

7.2. Digital shadows of remotely monitored floating visual Aids 37

7.3. [Smart | Digital] aton as outposts of the waterway authority towards shipping 39

7.4. AV-Adapted and AV-Supportive AtoNs 40

7.4.1. ‘AV-Supportive’ AtoNs -Why should an AV require Any aid from AtoNs? 41

7.4.2. Principle Capabilities of AV-Supportive AtoNs for AtoN-Assisted AVs 43

7.4.3. ‘AV-Adapted’ AtoNs to support shipboard automation 44

7.4.4. General Technical Considerations regarding AV-compatible AtoNs 45

7.4.5. Conclusions 48

7.5. Other application scenarios under discussion 48

7.6. Vessel Traffic management by using digital twins 48

8. OUTLOOK ON FUTURE, BUT IMMINENT PARADIGMATIC DEVELOPMENTS 49

8.1. Introduction to THE Concept of THE Metaverse and its derivatives 49

8.2. Introduction to the Concept of the Physical Internet 49

9. DEFINITIONS 51

10. abbreviations 52

11. references 52

12. Further reading 53

13. Index 54

List of Tables

Table 1 Airport runway service categories [2]. 8

Table 2 Fundamental relationship for AtoN supportive of AtoN-Assisted AVs 40

Table 3 Fundamental relationship for AtoN(s) adapted for vessels with different degree of automation 43

Table 4 Example calculations for time available for data communications at infrastructure site/AtoN. 44

List of Figures

Figure 1 Digitalisation Levels as derived from CMM [3]. 10

Figure 2 DLs applied to generic entities of the waterway & navigation domain 13

Figure 3 Overview of generic ‘mixed target fleet’ and different generic infrastructures and centres provided by shipping companies and shore authorities [12]. 18

Figure 4 Generic operational relationships and resulting generic communications relationships [12]. 20

Figure 5 Digital Model - Digital Shadow – Digital Twin [16] 22

Figure 6 Example of AtoN monitoring information. 36

Figure 7 Example of an on-demand AtoN used for increasing the intensity of AtoN lights based on traffic information from AIS (yellow trigger areas) and prevailing visibility (blue visibility meter). 36

Figure 8 Working principle of interactions between vessel and AV-compatible AtoN [12]. 43

Figure 9 Functional block diagram of a ‘Smart Hectometre Stone’ [12] 45

# Introduction and overview

## Overview

This guideline intends to define and explain what digitalisation of a waterway means.

Also, this guideline intends to illustrate how digitalisation can benefit the safety and efficiency of navigation, the protection of the environment, the efficient maintenance of waterways and/or of the individual waterway infrastructure components, but also – as a final stage and in combination with highly automated or even autonomous vessels/waterborne vehicles – the implementation of the concept of the Physical Internet (PI) of synchromodal logistics.

Digitalisation of a waterway means increasing the *digitalisation maturity or digitalisation degree* of a waterway as a comprehensive infrastructure entity and/or of its specific individual infrastructure components. This increase of digitalisation maturity includes three themes as follows:

* Creating a *digital model* of the waterways, which may be further developed to a *digital shadow* and ultimately to a *digital twin*;
* Providing *digital services* to vessels regarding their navigation within the waterways and/or regarding vessel traffic;
* Governing the interactions of the above by a set of mutually supportive *architectures for digitalisation*.

There are at present not many internationally recognised digitalisation standards tailored to the specific needs of waterways. There are, however, international standards on relevant digitalisation topics addressing them either generically or with a different mode of transport (such as inland waterway transport, road transport, or rail transport) or a different non-transport ecosystem in mind (such as urban areas). In addition, there are such international standards in drafting stage. All of these are referenced and summarised here as appropriate to the digitalisation topic at hand in the waterways domain in order to make the reader aware of their potential and/or future applicability. Consequently, the present guideline version is ‘work in progress’ and as such resembles the process of digitalisation of waterways which may be considered to be still in its infancy. Future revisions of this guideline will show a more developed and therefore mature picture.

Section 2 of this guideline introduces the concept of digital maturity, methods to determine it, and how it may be applied to waterway, its associated infrastructure, data, and services. In addition, this chapter generically considers certain conditions to be taken into account for the digitalisation of waterways, such as the required generic waterway infrastructure support for (highly) automated but traditionally operated vessels/vehicles, the advent of remotely controlled vessels/vehicles of whatever degree of automation and of autonomous vessels/vehicles, the implications of vessels and waterborne vehicles operating in the waterway simultaneously, as well as resulting mixed traffic scenarios, all of which constitute challenges for the digitalisation of waterways.

Section 3 explains the concepts of digital model, digital shadow and digital twin and how these can be applied.

Section 4 discusses digital services, which can be provided to vessels/waterborne vehicles and suggests how waterways with different levels of services can be categorized.

Section 5 introduces architectures supporting the methodical digitalisation of a waterway. There are introduced several architectures each of which takes a certain angle of perspective, but all mutually support each other.

Section 6 turns toward the connectivity required for all aspects of digitalisation of a waterway, as well as towards other consequential requirements to achieve certain digitalisation maturity levels.

Section 7 shows how existing and well-understood AtoN applications fit into the larger picture of digitalisation of waterways and how they can be progressed by applying the concepts described in previous chapters.

Section 8 provides an outlook on future but imminent developments regarding concepts such as a ‘waterway derivative of the metaverse’ and the introduction of the Physical Internet (PI).

## Scope

Content to be added when the guideline is finalized.

# Digitalisation Maturity And Conditions to be taken into account for the digitalisation of waterways

This chapter introduces the concept of digitalisation maturity, methods to determine it, and how it may be applied to waterway, its associated infrastructure, data, and services.

In addition, it generically considers certain conditions to be taken into account for the digitalisation of waterways, namely:

* vessels vs. waterborne vehicles;
* the implications of vessels and waterborne vehicles operating in the waterway simultaneously, as well as resulting mixed traffic scenarios, all of which constitute challenges for the digitalisation of waterways;
* the required generic waterway infrastructure support for (highly) automated but traditionally operated vessels/vehicles, the advent of remotely controlled vessels/vehicles of whatever degree of automation and of autonomous vessels/vehicles.
* Seagoing vs. inland waterway vessels in port approaches, inland waterways and estuaries.

## Digitalisation Maturity

The digital maturity needs to be considered partly separately for the information on the waterway itself and for the digital navigational services that are provided for the users of the waterway. There is existing guidance on how to assess the maturity level of digital models in general which can be applied also to waterway infrastructures. However, the maturity of digital navigational services still lacks the widely agreed maturity levels and criteria and should not be confused with technology readiness levels (TRL).

### Digital Maturity definitions as under development at IEC

The joint ISO/IEC technical committee (JTC 1/SC 41/WG 6) is currently developing generic guidance for digital twin maturity assessments expected to be published by October 2025 [1]. The draft document suggests that maturity assessment may include multiple separate assessments dealing with different topic areas including for example the levels of convergence, capability or integration. The intention is to provide guidance for organisations to determine for example what features their digital twin should support to be able to cooperate with other digital twins. When finalized, the document can be accessed behind a paywall.

### Digital Maturity – learning from other modes of transport

The aviation domain has defined since long categories for types of airport runways based on level of approach and landing capabilities provided to the airplane. It appears that for digital maturity, this concept may be adapted by analogy to the waterway domain. The levels defined in the aviation domain are as given in the following table.

1. Airport runway service categories [2].

|  |  |
| --- | --- |
| Level | Description |
| Non- precision Approach Runway | A runway served by visual aids and at least one non-visual aid, intended for landing operations following an instrument approach operation with a minimum descent height or decision height at or above 75 m (250 ft). |
| Precision Approach Runway, CAT I | A runway served by visual aids and at least one non-visual aid, intended for landing following an instrument approach operation with a decision height not lower than 60 m (200 ft) and with either a visibility not less than 800 m or a runway visual range not less than 550 m. |
| Precision Approach Runway, CAT II | A runway served by visual aids and at least one non-visual aid, intended for landing operations following an instrument approach operation with a decision height lower than 60 m (200 ft), but not lower than 30 m (100 ft) and a runway visual range not less than 300 m. |
| Precision Approach Runway, CAT III | A runway served by visual aids and at least one non-visual aid, intended for landing operations following instrument approach operation with a decision height lower than 30 m (100 ft) or no decision height and a runway visual range less than 300 m or no runway visual range limitations. |

The idea to learn from aviation for determining a digital maturity metric is as follows: By analogy, the role of a runway in aviation is assumed in the ‘wet’ domains (maritime and inland waterways) by the waterway. Again, by analogy, there can be digital services provided for shipping while passing through the waterway to a port, for example. (In the aviation domain in Table 1, these electronic services are the precision instrument approach and landing transmissions by the Instrument Landing Systems (ILS) provided at airports.) Different levels of service provision in the waterway domain reflect, again by analogy, the different requirements of shipping for support in different types of waterways. In aviation, these different needs are the visual ranges available vertically and ahead for landing decision making; in the waterway domain, this translates to different sets of digital services provided, which in turn may infer different degrees of digital maturity. Hence the notion of category designations for different digital maturity levels in the waterway domain. In the following section it will be demonstrated, how this idea of categories to designate a maturity level can be applied to the waterway domain, even using as a conceptional backdrop a well-established generic maturity model.

### Digital Maturity for waterways as adapted from the Capability Maturity Model (CMM)

In a project addressing digitalisation in the European waterway system called “Masterplan Digitalisation of Inland Waterways (DIWA)” different ***Digitalisation Levels (DL)*** were defined [3] , which together constitute the maturity model as given in the Figure 1. This maturity model was based on the much more elaborate ***Capability Maturity Model (CMM)*** [4] but simplified and adapted to the needs and specifics of waterways.[[1]](#footnote-1)



1. Digitalisation Levels as derived from CMM [3].

The explanations and examples in the subsections 2.1.3.1 and 2.1.3.2 complement the Figure 1.

#### General explanations

The whole Maturity Model is set against the backdrop of a the present most often purely analogue environment, where – for example – communication by word of mouth via analogue (radio) communications means and data storage on paper prevail. This analogue backdrop is not shown in the Maturity Model figure itself.

DLs can be assigned to any relevant entity under consideration, such as an organisation and/or a development. The kind of entities will be introduced further below. Here the DLs as such will be introduced.

The assignment of a DL intends to indicate the maturity of an entity regarding digitalisation, to be specific regarding certain characteristics relevant for digitalisation. *An entity can only achieve a higher DL when all prerequisites or requirements from a lower DL have been accomplished or fulfilled respectively.*

That does not imply that the entity under consideration in its entirety is fulfilling the features of that DL. That may be difficult when considering larger organisations as the entity under consideration, for example. All parts of the entity relevant for digitalisation and therefore for the assignment of the DL need to conform to the features of that DL, however. Those relevant parts should be indicated.

#### Additional explanation and examples for DLs

To illustrate the meanings of the above DLs, the following examples are given per each DL.

* Reactive

A waterway administration that has a website but only with static reference information, no interaction possibilities. Customer contact is primarily conducted via phone (voice) and traditional (paper) mail. Every waterway service offering has its own (customer) database. Management considers IT/digitalisation a purely supportive tool instead of a business enabler. Generally speaking, it is strongly advised to leave this DL and progress to higher DLs.

* Organised:

*‘Traditional digital features’* are interpreted here as those exhibited by well-established digital systems in the waterway domain such as AIS and S-57 based ECDIS.

*‘Building digital capabilities’* is construed as the (systematic) building of digital capabilities is introduced to/by stakeholders in/of the waterway domain starting with this level.

* Digitised

*‘Digital information exchange’* means, that data and/or information exchange is using pre-defined structures, such as machine-readable templates, as a pre-requisite and as opposed to e.g. bitmap-based documents. This in turn results in exchange of structured data/information as a rule, thus again prompting appropriate encoding, protocols, and interfaces supporting this exchange.

***Examples:***S-57-format of ECDIS (at present) and S-100-format (in the future); Notices to Mariners.

*‘Limited real-time situational picture’* means that the positions and intents of all vessels in a given area are available but limited in terms of geography and/or technology.

***Example:***Radar coverage only on certain parts of the waterway, AIS coverage only on certain parts of the waterway, Radar-AIS-fusion only available for some areas covered by both radar and AIS simultaneously.

*‘Advanced digital features in silos’* means that digital data/information is available and combined in an automated fashion to provide new services.

***Example:*** berth occupation calculation based on AIS and berth polygon data.

* Connected

*‘Advanced digital features aligned with partners’* means, that available digital data/information is combined automatically to provide new services across organisational boundaries.

***Example:***Waterway route calculation taking en-route limitations (as contained in Notices to Mariners) into account across areas of multiple organisations.

*‘By default’* means that all communication data exchange (ship-ship, ship-shore) is done digitally machine to machine in a (semi) structured format. Spoken word via VHF or other means and/or unstructured data exchange (email, texting) are considered exceptional.

*‘Full real-time situational picture’* means that positions and intents of all vessels in the entire area of competency of multiple organisations are available.

***Example:***Full AIS coverage, full Radar-AIS-fusion available in radar covered areas, every vessel intent is known or predicted.

* Intelligent

*‘Digital transformation’* means that an entity has adopted digital technology throughout all its parts relevant for the IDL assessment. ‘Common goals for its implementation are to improve efficiency, value or innovation’ [5].

*‘Artificial Intelligence (AI) assisted process optimisation’ means…[content to be added}*

***Example:***Authority patrol vessels are positioned at locations where the likelihood of their required use is the greatest (following from risk level prediction based on statistical and real-time data). Bridge operators are assisted by image recognition algorithms to detect potentially dangerous situations.

*‘Predictive digital capabilities’ means…[content to be added]*

***Example:***Future traffic situation, berth occupation, lock cycle and bridge openings are automatically predicted within a small probability bandwidth on a large scale.

*‘Automated response to standard situations’ means…[content to be added]*

***Example:***Vessels entering designated (even temporary) danger or no-go zones are automatically detected and contacted with increasing forcefulness to contain and mitigate potential unwanted events.

#### Applying the Maturity Model to waterways & navigation

The most desirable DL might be ‘Intelligent’, rendering ***‘Intelligent waterway & navigation’*** the highest achievable target. According to the definition and explanations above, this would mean,

* that the digital transformation of the waterway domain would have been completed (for all of its parts relevant for digitalisation);
* that AI assists in the optimisation of processes related to waterway provision, operation and maintenance as well as in the optimisation of vessels’ navigation processes proper;
* that prediction algorithms are in place to support waterway and vessels’ navigation processes; and
* that there are implemented standard responses in waterway provision, operation and maintenance processes as well as vessels’ navigation processes.

This goal might not be achievable within a short time frame and/or with the technologies available within that time, however. Hence, it is necessary, to also use the other different DLs, thus rendering the following intermediate states of the digital transformation of the waterway and navigation domain:

* ***‘Reactive waterway & navigation’;***
* ***‘Organised waterway & navigation’;***
* ***‘Digitised waterway & navigation’; and***
* ***‘Connected waterway & navigation’.***

As a consequence and in order to securely meet a waterway administrations’ objective to assess the effects on digital transitions during their respective planning and/or implementation period, *all proposals for digitalisation of entities discussed by DIWA need be assessed regarding their minimum and potential maximum achievable DL.* This would also support roadmapping and migration path design by building on the results of these assessments.

For simplicity of reference, the following abbreviations to the different DLs have been assigned:

* **III - Intelligent**
* **II - Connected**
* **I - Digitised**
* **0+ - Organised**
* **0- - Reactive**

The DLs ‘Reactive’ (**0-**) and ‘Organised’ (**0+**) can be frequently found presently, i.e. at ‘situation zero’, when a limited number of digitalisation processes have partly become effective and thus frequently constitute the starting point for any (future) increase of digitalisation maturity proper. The latter DLs are therefore abbreviated with Roman numerals ‘above zero’.

This categorization takes up the aviation categorization as introduced in the section 2.1.2 by analogy and as adapted to digitalisation maturity.

#### All entities of the waterway & navigation domain affected

The term ‘waterway & navigation domain’ - as well as any possible alternative terms for that matter – is an umbrella term, namely a composite term, to be precise. It designates a meaning- and purposeful composition of several entities that interact in order to achieve their intended purpose and meaning. Applying the above DL concept to the ‘waterway & navigation domain’ actually applies it to all the entities it is composed of: vessels, waterway field infrastructure, organisations providing services, and data objects for exchange, to name the most important ones. This means, ***that each and every entity can and will have an DL*** – in general as a generic object and when considering individual instances of these entities (Figure 2).



1. DLs applied to generic entities of the waterway & navigation domain[[2]](#footnote-2)

Therefore, it would be possible or even required to use the notions for example

* of a ‘connected vessel’, designating vessels, the DL of their relevant digital equipment would have reached ‘Connected’,
* of an ‘intelligent waterway field infrastructure’, the DL of their digital representation and installations would have reached ‘Intelligent’,
* of ‘digitised organisation’, the digital processes of which would have reached the DL ‘Digitised’,[[3]](#footnote-3) and
* of an ‘intelligent data object’ supporting those digital data exchange processes and interactions of the above entities on the DL ‘Intelligent’. In the example depicted, the feature ‘Required Data Quality’ in Figure 2 is labelled with the DL, because this feature often is critical to the achievable DL.

#### Implications of the Maturity Model for the waterway & navigation domain

Certain important implications associated with increased digitalisation of the waterways & navigation domain are brought to the fore by employing the Maturity Model, as follows. They are not ‘invented’ by this or any other maturity model.

##### Disambiguation of regulations, operational procedures, terminology, and data models

As opposed to the analogue domain, ***data exchange by digital technologies generally disallows ambiguities in data object definitions and in data models governing these data objects.*** Since data objects and data models are just representations of the real world they intend to represent, up to the ultimate degree of creating a digital twin of an entity, the necessary disambiguation needs to start with the terminology related to the data objects and interaction concepts that govern the data object definitions and data models. This in turn prompts the need to remove ambiguity from operational procedures governing the interaction concepts as well as from regulations governing the operational procedures in turn.[[4]](#footnote-4),[[5]](#footnote-5)

This needs to be done to that extent induced by the desired DL: For arriving at ‘digital information exchange as a default’, which is a key feature of ‘even only’ the DL ‘Connected’ (**II**), basically all relevant regulations, operational procedures, terminology and data models need to be free of ambiguities, as far as possible.

Obviously, this is a major task, in particular when starting from IDLs **0-** or **0+**.

##### Increased variety and/or proliferation of co-operative technologies with DL increase

Another consequence of the increase of DL is the increased variety and/or proliferation of co-operative digital technologies employed, necessitated by the very definition of the DL.

A technology is called co-operative when requiring a terminal (such as an transceiver) on each side of the (communication) link to accomplish its (communication) task: Both terminals need to work together, i.e. co-operate, in accordance with a pre-defined set of rules (such as data object encoding, link protocols governing the digital data exchange processes, and – in the case of radio communication - radio frequency usage stipulations).[[6]](#footnote-6)  The opposite is a non-cooperative technology that does not rely on the co-operation of any other entity to perform its task (for example radar).

The desired benefits of DL increase are improved functionalities available for the waterway, navigation processes and/or human users therein. However, DL increase also brings with it the increased variety and/or proliferation of co-operative technologies. These benefits of the DL increase are thus correlated by necessity with the disadvantage of ***increased interdependency***. To mitigate this disadvantage, certain non-cooperative technologies are still needed on a regular basis and/or for fall-back arrangements even with the advent of the highest possible DL throughout.

Therefore, even when arriving at higher or even the highest possible DL, it will be necessary to also provide certain non-cooperative technologies ‘with a digital edge’ and to provide certain ***fall-back arrangements.***

#### Implications of the DL-Match-Principle during implementation and deployment

The combination of the above implications of the increase of the DL in the waterway & navigation domain results in the necessity for the DLs of above entities, which have one or several operational relationships between them, to match. I.e. ***it is necessary that the entities involved in the same operational relationship demonstrate the same DL.*** This principle is called ***DL-Match-Principle*** here.

An ***DL mismatch*** is a situation where different entities engaged in the same operational relationship(s) would not only be unable to use the benefits offered by the entity with the higher DL - which could be considered a less important disadvantage -, but may result in a more severe situation where the necessary operational relationship may not even be established, whatever this may mean in practical detail.

To adhere to the DL-Match-Principle and thus to avoid DL mismatches is relevant in particular during implementation and deployment. The following examples illustrate the above:

* A ‘connected vessel’ would expect a ‘connected waterway field infrastructure’ and relevant operational centres with DL ‘Connected’ – due to the ‘digital information exchange by default’ feature of DL ‘Connected’ (**II**).
* A ‘connected vessel’ (DL=**II**) – due to the feature ‘digital information exchange by default’ – expects a certain digital information exchange when entering a waterway field infrastructure by crossing its boundary, but an DL mismatch occurs if this field infrastructure does not support this DL-**II** digital information exchange being ‘only’ a ‘digitised waterway field infrastructure’ (DL=**I**) which has – by very definition of the DL – ‘advanced digital features in silos’, only.

It is important to note, that in the digital domain, there ***does not exist a ‘graceful degradation’ by default*** – as opposed to the analogue domain, which may lead to dropping from DL to (very) low DL if no graceful degradation is in place: The ***assumption*** that the occurrence of an DL mismatch will still ‘always’ allow for ‘some sort of’ operational relationship being available ‘somehow’ ***is flawed from the outset in the digital domain***. Any ‘graceful degradation’ needs to be designed into the desired DL of the waterway & navigation domain embracing all relevant entities and operational relationships.

On the other hand, the DL-Match-Principle states the ideal of the Maturity Model: As with any ideal, there may be circumstances, which disallow for reaching the ideal state. Hence the resulting question for further study would be:

* What ‘DL match margin’ would be permissible between which (specific) entities engaged in which (specific) operational relationship(s)?
* What would be permissible degradations DL in regular case operations, and
* What would be permissible or anticipated DL fall-back arrangements for exceptional conditions?

Finally, it needs to be re-iterated that any DL mismatch ***will demonstrate its impact only during implementation and deployment,*** not necessarily when discussing regulatory, operational, and technical in general during planning phase unless specifically taken into consideration. It is therefore advised to carefully study the implications of the DL-Match-Principle early on and act upon findings accordingly.

#### Tentative conclusion for IALA

At present, it appears that the CMM derived digitalisation maturity model as applied to the waterway & navigation domain is the most matured option available. Therefore, it should be used as long as no better digitalisation maturity model, which is adapted to the ‘wet’ domain(s), is available. But even if there will be a better one available, this one will have served good for study and planning purposed.

This CMM derived digitalisation maturity model henceforth is called **IALA Digitalisation Maturity Model (IALA-DMM)** and the associated digitalisation maturity categories **IALA Digitalisation Levels (IALA-DL).**

### Consequential required decision making process at IALA

[content to be added]

## Conditions to be taken into account for the digitalisation of waterways

This chapter generically considers certain conditions to be taken into account for the digitalisation of waterways, such as the required generic waterway infrastructure support for (highly) automated but traditionally operated vessels/vehicles, the advent of remotely controlled vessels/vehicles of whatever degree of automation and of autonomous vessels/vehicles, the implications of vessels and waterborne vehicles operating in the waterway simultaneously, as well as resulting mixed traffic scenarios, all of which constitute challenges for the digitalisation of waterways.

### Vessels vs waterborne vehicles

There must be distinguished between vessels (defined by their purpose of carrying cargo and/or persons) and vehicles (all other purposes). While IMO deals with vessels only, the waterway may be used and will be used by both; also waterway authorities more and more employ vehicles in that sense for their purposes of maintaining the waterways, even already today. This constitutes a ‘mixed traffic’ between vessels and waterborne vehicles that needs to be taken into account conceptionally. With increase of digitalisation maturity, there will be potentially an increase of (digital) interactions.

Both autonomous vessels and vehicles as well as remotely controlled vessels and vehicles have arrived in the waterways, and both need to be taken into account concurrently when considering the digitalisation of waterways. Hence, the following generic terms are used here to designate the fundamental operational concepts under consideration in the context of digitalisation of waterways:

* **AV** – Autonomous vessel or autonomous vehicle; deliberately ambiguous in general usage to take up the discussion on the difference between vessel and vehicle (see above).
* **ROV** – Remotely operated vessel or vehicle; same logic.

### Advent of higher degrees of automation and of Autonomy

With the advent of highly automated and even autonomous *vessels* and their consideration at IMO using the technical term of Maritime Autonomous Surface Ships (MASS), IALA has engaged in the consideration of the potential impact on Marine AtoNs early on. Some of the findings of an IALA workshop on ‘Marine Aids to Navigation in the autonomous world’ in 2021 [6] are highly relevant for the digitalisation of waterways as follows (emphasis added):

* ‘Marine Aids to Navigation will continue to be essential infrastructure for all degrees of maritime autonomy on vessels and will continue to be required to support safe, efficient and pollution free transits. This includes identifying options for position, navigation and timing (PNT). This may lead to the development of adaptive AtoN to support different degrees of autonomous vessels’ ([6], finding No. 5).
* ‘MASS will require a robust and resilient communication ‘system of systems’ to support complex and vital communication needs, allowing communication between ships,remote control centres, VTS, AtoNsand other elements that may be required in a MASS operating environment’([6], finding No. 6).
* ‘All developments in the provision of AtoN to support MASS must consider their role in a mixed maritime environmentwhich includes both conventional vessels and MASS, and be fully compatible with both’ ([6], finding No. 8).

These findings either expressively state or imply the following claims, which in turn prompt critical questions:

* It is claimed, that AtoN infrastructure will be **required** in the future for AVs (besides being still required for traditionally operated vessels). *Is this really a substantiated statement or just an optimistic self-assurance?*
* It is stated, that the co-operative nature of any AVs’ operations prompts stringent requirements, including robustness and resilience, for their communication with all entities involved. The **communications between AVs and AtoNs** are of particular interest here. *Would those communications be visual or (digital) radio communications or both maybe even?*
* It is stated, that AtoNs may also be an option to **fulfil AVs’ PNT requirements**, the prerequisite of which is that these AtoNs would be meaningful for AVs at all. Hence, *what would be the requirements for an AtoN providing PNT to an AV, which – by very definition – would be operating entirely electronically?*
* It is stated, that ‘developments in the provision of AtoN’ must address a **mixed target fleet** of both traditionally operated, automated vessels (to whatever intermediate degree of automation), and AVs.
* The ‘provision of AtoN’ could be fulfilled by a single AtoN service comprising only a new variety of AtoN, that is ‘automation-supportive’, ‘AV-compatible’, and ‘traditional’, all at the same time. *How would such an AtoN appear? What would be its visual and electronic interfaces towards an automated vessel and even to an AV? What degrees of shipboard automation would the same AtoN be capable to support?*
* Or, could the mixed target fleet requirement only be fulfilled by an AtoN service portfolio of different, partly new AtoN services? *How would an AtoN service portfolio look like that comprises different varieties of AtoN services that operate concurrently with each individual AtoN service only addressing a certain portion of the mixed target fleet, only?*
* The design goal of an **‘Adaptive AtoN’** has been postulated. In engineering, ‘adaptive’ is understood as being capable of adapting functionality *at run-time.* Here, ‘adaptive’ would imply an ‘Adaptive AtoN’ to support at run-time the different degrees of automation in vessels addressed, up to the AV proper. *What would be the consequential run-time sensitive design requirements for that ‘Adaptive AtoN’?*

There have been developed different terminology domains and – in the recognition of the need to capture the implications of the a ‘mixed fleet’ – a variety of ‘degree of automation’ or ‘degree of autonomy’ scales. For example, the International Organization for Standardization (ISO) has published intermediate terminology definitions recently [7]; different organizations relevant for shipping have defined different scales for either ‘degree of automation’ (Central Commission for the Navigation of the Rhine (CCNR) [8]) or ‘degree of autonomy’ (International Maritime Organization (IMO) [9]; Lloyd’s Register [10]; Sheridan [11]). In a philosophical sense, strictly speaking, there is no such thing as a ‘degree of autonomy’, since the entity under consideration – here: a vessel – either is autonomous of whatever relevant constraints, or not; there is however possible and meaningful any degree of automation operative within that entity, culminating eventually in its ‘autonomy’.[[7]](#footnote-7) Here, ‘degree of automation’ with ‘autonomy’ as its final stage is preferred.

### Mixed traffic in approaches, inland Seaways and Estuaries

Many sea-going vessels operate frequently in inland waterways in several parts of the world, for example when approaching ports via estuaries or during canal passages, and – conversely – inland waterway vessels operate in coastal waters, too. Further, the IALA defined system of AtoNs and the substantial relevant IALA recommendations and guidelines for its membership have been applied to both domains. Similarly, as an example of an IALA peer organisation, the World Association of Waterborne Transport Infrastructure (PIANC) has this comprehensive perspective, too. A universally applicable terminology will facilitate an emerging internationally harmonised understanding of the advent of AVs and ROVs in both the maritime and the inland waterway domains, i.e. in both ‘wet’ domains. The Figure 3 below may be drawn to illustrate the ‘mixed target fleet’ in fundamental generic categories on the left hand side. On the right hand side, the relevant generic shore entities are shown such as waterway field infrastructure, including AtoNs, and all kinds of shore-based centres.



1. Overview of generic ‘mixed target fleet’ and different generic infrastructures and centres provided by shipping companies and shore authorities [12].

* **Generic vessels by design rules domain** mainlyare sea-going ships, estuary ships, leisure crafts, and inland waterway vessels. ‘Design rule domain’ means to say, that there are specific legal/regulatory bodies defining what a vessel of this rule domain should consist of and carry subject to a carriage requirement. Here, the present and/or future legal/regulatory situation regarding digital electronic equipment is of particular relevance, and that may differ in different rule domains, too.
* Generic vessels by mode of operation:
* A *Traditionally operated vessel* is a vessel the navigating functions of which are performed by a crewmember on-board by using appropriate **Human-Machine-Interfaces (HMI)** designed for that task. The degree of automation supportive of that task is encapsulated within the ‘traditional operation’ and is therefore irrelevant here as long as the on-board human master is in charge of the vessel’s navigation.
* A *Remotely Operated Vessel (ROV)*is a vessel the navigating functions of which are performed remotely as the regular case from a **Remote Control Centre (RCC)** by a human at that centre. Whether a ROV is actually crewed or uncrewed[[8]](#footnote-8) is irrelevant in regards to its navigating functions as long as they are performed remotely as the intended regular case.
* An *Autonomous Vessel (AV)* is a vessel the decision-making and execution of navigation proper (‘sailing’) of which are performed autonomously in the strict sense of the word and as the regular case by an appropriate machinery of the vessel itself without on-board or remote human interaction.[[9]](#footnote-9) Whether the AV actually is crewed or uncrewed is irrelevant in regards to its navigating functions as long as the shipboard machinery performs them as the intended regular case.[[10]](#footnote-10)

ISO draws attention to the temporal or to the process character of AVs’ autonomy: Autonomy is confined to a period and/or to a defined operational scope, that is called **Operational Envelope** ([7], 3.1.3, note 2, in conjunction with Annex B). It likely will be required that AVs are subject to a constant **Autonomous Vessel Monitoring & Contingency Response functionality** performed at an **Autonomous Vessel Control Centre**while navigating autonomously. As part of the contingency response, an AV may fall back to become an ROV (or even a vessel traditionally operated by a crew on-board).

* Generic shipping company centres:
* *A Remote Control Centre (RCC)*is a shore-based centre that performs the remote operation of an ROV and is operated by or on behalf of the shipping company that also operates the ROV. RCC appears to be an established term and is used here for that reason, although remote control, strictly speaking, may be limited in scope compared to remote operation.
* An *Autonomous Vessel Control Centre**(AVCC)* is a shore-based centre that monitors and controls an AV and is operated by or on behalf of the shipping company that also operates the AV. Since an AV, by its very definition, does not need a operation by crew or human remote control in regular cases, there will likely be a requirement that the AV is constantly monitored and contingency response is active in non-regular modes of operation or even malfunction of the AV. Hence, Autonomous Vessel Monitoring & Contingency Responseis the main functionality to be performed by the AVCC. Since an AV may fall back to an ROV as part of the contingency response, the AVCC may also fall back to an RCC. [[11]](#footnote-11)

While all of this mixed traffic has been present in the ‘analogue world’ for long, the projection of these different (generic) entities into the digital domain (by means of e.g. data modelling) requires (fresh) specific attention to them.

### Notion of the ‘autonomous ship system’ and its context – moving towards co-operative nature

ISO has defined the term **‘autonomous ship system’** to indicate that each AV needs to operate in an ecosystem comprising the ‘support services’ and the ‘remote control services’ ([7], Annex A) besides the AV itself. In addition, ISO embeds the autonomous ship system within a **‘wider context’**. On the shore side, this wider context includes ‘river services (locks, bridges), fairway services (tugs, anchorages), port services (mooring, cargo handling, supplies, inspections, reporting, checks), and pilot’, and – relevant for the topic at hand here – ‘**fairway information** (MSI and **AtoN**) and traffic services (VTS, MRS, RIS)’ ([7], Figure A.2, transcribed; emphasis added). The various **operational relationships** between the various components of the autonomous ship system itself and between the autonomous ship system and its wider context imply an increased required connectivity compared to the present situation. These **functional and physical links** need to be established by **a variety of communication technologies**.[[12]](#footnote-12) The Figure 4 overleaf generically transforms the ISO statements into the overarching architecture for e-navigation. The position of the AtoN Service of a waterway authority would be part of the ‘Common technical shore-based system for fairway & navigation applications’ on the right hand shore-side of Figure 4 [13], [14].

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1. Generic operational relationships and resulting generic communications relationships [12].

### Navigational aids versus Aids-to-Navigation and the generic shipboard navigation system architecture

Traditionally, the shipboard functionality supporting the helm regarding navigation proper was labelled ‘navigational aids’, while the aid provided from shore infrastructure in that regard was labelled ‘Aid-to-Navigation’. *Trade-offs regarding the relative weight of navigational aids and Aids-to-Navigation for the navigation have always been an issue,* but with the advent of AVs intensity of debate will increase, as will be discussed further down below.

PNT data is particularly important for navigation, and therefore IMO has identified and described the **(shipboard) navigational aids relevant for PNT** in considerable generic detail with IMO’s *‘Guidelines for Shipborne Position, Navigation and Timing (PNT) data processing’ (MSC.1/Circ.1575) [15]*. These Guidelines discuss the integration of PNT related data derived from shipboard sensors to arrive at a consistent PNT data solution for navigational purposes; they also introduce a **generic shipboard navigation system architecture**, which is structured hierarchically in three functional layers in the vertical dimension. These are from bottom to top:

* *Sensor / Source Layer:* Here reside all shipboard sensors, the pre-processing entities for their data as well as the radio communication front ends to the physical radio links. This layer provides the technical interfacing to the physical and operational environment of the ship.
* *Data Processing Layer:* This core layer is specialised in processing, storing, and retrieving data relevant for the navigation of the ship, including the selection, filtering, and routing of the available physical radio communication links as well as the handling of all relevant alerts from navigational systems but also from other bridge equipment as received from Bridge Alert Management.
* *Operational Layer:* This layer provides the HMI to the bridge team to support their navigational task for traditionally operated vessels. When applied to an AV, the Operational Layer would contain the autonomous shipboard decision making functionality, the **‘Autonomous Onboard Controller’** ([7], 3.2.4), and a dedicated HMI would no longer be required during regular operation.

It is important to note, that the above IMO Guidelines would be applicable to traditionally operated and AVs alike: The functionality of all layers would still be required, likely with higher demands on the PNT data quality even, in order to satisfy the demands of the Autonomous Onboard Controller.

With these generic considerations and definitions, the stage is set to embark on further aspects of the digitalisation of waterways.

# Digital model, shadow and Twin

## Generic Definitions

### Overview

A digital model is a digital representation of a physical object. Depending on the level of synchronisation between digital and physical objects, the digital representation can be also called digital shadow or digital twin (Figure 5).



1. Digital Model - Digital Shadow – Digital Twin [16]

The most basic digital model of a waterway includes information about the characteristics and maintenance events of a waterway as a comprehensive infrastructure entity and information related to specific waterway infrastructure components relevant for navigation and (synchromodal) logistics in digital, reusable and preferably standardized format. It thus provides a comprehensive virtual representation of a physical waterway, including virtual representations of the specific physical waterway infrastructure components. Specific relevant individual waterway infrastructure components are for example locks or berths with (automated) cargo handling along waterways and in ports and – of particular interest to IALA – the marine aids to navigation, namely comprising – amongst others – AtoNs proper, vessel traffic services (VTS), radio communication and radio navigation means provided from ashore.

A more developed digital model, in addition, includes real-time waterway and/or individual infrastructure component information, observations on environmental conditions and information on vessel traffic: This type of digital model may be called digital shadow, and it would require appropriate sensors at, and communication means from its physical entities.

When the digital model is also capable of automatically providing ‘feedback’ to its physical entities by appropriate communication means and actuators, such a digital model can be called a digital twin. A digital twin thus can be used for effecting real-time changes at its physical entities remotely initiated in the virtual domain. Hence, a digital twin becomes a tool for higher control processes in the virtual domain ashore, which in turn can be informed by (even automatic) evaluation of simulated future scenarios, forecasts and predictions.

A digital twin of a waterway and/or of its individual infrastructure components can be applied to support more optimized and predictive maintenance of individual waterway infrastructure components such as AtoNs proper. A digital twin of the vessel traffic within a given waterway can be applied to initiate any proactive corrective actions necessary to individual vessels or waterborne vehicles, to specific kinds of vessels, such as traditionally operated, remotely-controlled or autonomous vessels, or to the vessel traffic in the context of that waterway and taking into account its prevailing conditions in real-time.

From this introduction, it becomes clear, that digital twins are a feature of higher digitalisation maturity degrees, only. In addition, digital twins are required for any implementation of the concept of the Physical Internet (PI) within a waterway grid under consideration.

### Digital Model – Definition in international standards

[content to be added]

### Digital Shadow – Definition in international standards

[content to be added]

### Digital Twin - Definition in international standards – the ITU example

#### ITU

[content derived from ITU-T Rec. Y.4600 on the digital twin of “smart cities” to be added [17]

#### ISO/IEC

[contents to be added, noting the existence of for example ISO/IEC 30173:2023 “Digital twin – concepts and terminology”]

## The specific Relevance of the S-100 world

[content to be added]

### Specific relevant features of the S-100 World

[content to be added]

## Digitalisation Maturity of Waterway entities

[content to be added]

### IALA Digital Maturity Categories

[content to be added]

### Model under development at IEC applied

[content to be added]

# Digital Services for navigation in waterways

## Introduction

The increase of provision of digital services to individual vessels or waterborne vehicles, to specific kinds of vessels and/or to vessel traffic at large is the major factor of any digitalisation of waterways: Certain digital services use the digital models, digital shadows, and – at a high digital maturity level – the digital twins for their respective purposes. Certain other digital services are necessary to interact with vessels or waterborne vehicles, and thus are also required for both any digital shadow (to receive data ashore) and/or for digital twin implementation (to also convey actuator data from ashore). Some of the digital services may require that there is a real-time digital model, shadow, or even twin of the waterway already available. Internationally harmonised or even standardised digital services would allow broad participation in a traditionally open system that waterways constitute. IMO, as an outcome of its e-navigation strategy, has defined certain ‘Maritime Services in the context of e-navigation’ that operate in an overarching architectural framework, called ‘overarching e-navigation architecture’. IALA has also defined certain digital services in support of IMO.

It should be noted, though, that the notion of digital services is not confined to those services defined by IMO or IALA, not even in the maritime domain alone: In proximity to shore, but in particular in harbour approaches and estuaries connecting to the hinterland via inland waterways, for example, there regularly is to be expected a ‘mixed traffic’ of various kinds of vessels/waterborne vehicles. This eventually results in portfolios of digital services provision beyond the scope of IMO alone, including for example also internationally defined River Information Services (RIS).

## digital services for Waterways as defined by IMO

[content to be added]

## Digital services for Waterways as defined by PIANC

[content to be added]

## Digital services stemming from S-100-World data products

[contents to be added, for example Under Keel Clearance service (to individual vessels)

## Digitalisation Maturity concepts applied to Digital Services for navigation in waterways

The usefulness of digital navigational services depends on the ability of vessels to use the provided services. Therefore, the definition of target maturity level may need to include considerations related to adaptability of the services.

[content to added]

### IALA Digital Maturity Categories applied

[content to be added]

### Model under development at IEC applied

[content to be added]

# Architectures for Digitalisation of waterways

[content to be added]

# CONSEQUENTIAL REQUIREMENTS

## Introduction

Digitalisation of waterways is strongly dependent on the availability of adequate connectivity between all actors involved (e.g. vessels/waterborne vehicles, field infrastructure like AtoNs, land-based centers).

[content to be added]

## Connectivity Requirements in general

[content to be added]

## Specific Digital Twin (System) requirements

[content derived for example from ITU-T Rec. Y.4600 on the digital twin of “smart cities” to be added]

## Generic functionality requirements

[content to be added]

## Keeping an overview on the consequential Requirements – Requirement traceability

Managing a complex system like a digital waterway with numerous interacting technical sub-systems and features puts demands on a given system architecture but also requirement traceability. In G1133 the concept of requirement traceability is described, the capability of defining and following the life of a requirement as it changes over time. Here “requirements” is meant in very broad terms, originating from political, managerial and regulatory requirements to requirements set out by the end user’s needs of the provided maritime services. Several software tools for managing requirement traceability exist, such as Microsoft Azure DevOps and Jira Atlassian.

# Putting existing generic AtoN and VTS applications into the picture

This chapter shows how existing and well-understood AtoN applications fit into the larger picture of digitalisation of waterways and how they can be progressed by applying the concepts described in previous chapters.

## Introduction

AtoN authorities have launched [Smart |Digital] AtoN projects with the purpose of marine environmental data collection and broadcast as well as for supporting regional navigation systems. It was recognised that in particular the notion of [Smart |Digital] AtoN has potential to support the digitalisation of waterways as follows:

* The digitalisation of traditional AtoNs can provide digital information of the characteristics and status on the AtoN as such. That can be achieved through implementing of, for example, AIS AtoN devices in conjunction with remote monitoring and control systems. It is also necessary to evaluate the current degree of such monitored AtoNs and develop future development goals. This kind of application would render digital shadow to the monitored AtoN.
* Certain data can be collected and transmitted by [Smart |Digital] AtoNs which thus acts as an outpost of the waterway authority towards shipping. For example, collection and dissemination of environmental information such as channel water depth, hydrology and meteorology, identification and monitoring of above water objects information, and marking and early warning of construction, operations and buildings around waterways. The [Smart |Digital] AtoNs may also carry related sensors, developing service and data system, and updating structure, power system and communications links, as needed. Such [Smart|Digital] AtoN can contribute to electronic fence application in port areas.

Consequentially, the development of such digitalised AtoNs, especially the construction of multi-functional [Smart | Digital] AtoNs, have to meet new requirements in terms of availability, reliability, and their maintenance scheme needs to to pay special attention to this during implementation. These topics will be addressed in some more detail below.

## Digital shadows of remotely monitored floating visual Aids

Systems for remotely monitoring the status of floating AtoNs and their equipment has been widely used over a decade now (Figure 6). These systems provide data flow from physical object (floating AtoN) to a digital monitoring system and may also prove means to remotely control (manually) the status and configuration of the physical object, thus creating a digital shadow (Figure 5, 22). The digital shadow in this case is limited to the status of AtoN and its equipment, excluding for example the physical condition of the AtoN structures. This type of digital shadow of an AtoN is updated frequently but usually not continuously due to the energy and data link limitations. [The IALA G1008 gives extensive introduction on remote control and monitoring of marine AtoNs, [18]]



1. Example of AtoN monitoring information.

The AtoN on-demand concept opens possibilities for upgrading the type of AtoN digital shadow described in the previous paragraph further to a digital twin. The AtoN on-demand concept has been introduced related to the use of occasional lights in low traffic areas and the possible need to increase intensity of AtoN lights in poor visibility conditions [and is described in more detail in IALA G1038, [19]]. Activation method for an on-demand AtoN can be automated based on for example AIS information and/or information from visibility sensors (Figure 10) [20]. The automated on-demand AtoN will have automatic bi-directional data flow between physical objects in the waterway (i.e. AtoN, AIS, visibility sensors) and the digital model (Figure 5, 22) thus it can be seen to form a limited scale digital twin.



1. Example of an on-demand AtoN used for increasing the intensity of AtoN lights based on traffic information from AIS (yellow trigger areas) and prevailing visibility (blue visibility meter).

## [Smart | Digital] aton as outposts of the waterway authority towards shipping

[content to be added]

## AV-Adapted and AV-Supportive AtoNs

MASS are coming sooner or later – waterway authorities may be inclined (or even driven in the future by events) to provide AtoNs specifically geared towards autonomous vehicles/vessels in the waterway with the goal to provide them digital AtoN precision and reliability support for their navigation (again learning from aviation ILS concept) ontop/instead of the visual service provision.

### ‘AV-Supportive’ AtoNs -Why should an AV require Any aid from AtoNs?

When observing current projects, test beds, and discussions regarding AVs and ROVs it seems, that attention mainly lies with the shipboard automation and the challenges for automation to arrive at autonomy. The *pendula thus seems to have swung almost exclusively towards navigational aids supporting the decision making and execution functionality of the AV.* The envisaged PNT Data Processing as embedded in the generic shipboard navigation system architecture as introduced above serves as an example here.

When considering *the ‘AV-compatibility of an AtoN’ like in this paper, the point of view is from the outside towards the automated or even autonomous vessel, however.* It exhibits to the onlooker a certain behaviour as a consistent entity – that is a ‘black box’ characteristic perceivable from the outside. So, what requirements originate from this ‘black box’ relevant for the future role of AtoNs for AVs?

There is one last term to be introduced here, a term that appears to be broadly used. That term is **‘smart vessel’.** ‘Smart vessel’ seems to be a synonym for at least very highly automated vessels or even – or maybe only – AVs. Reading documents dealing with ‘smart vessels’ construed as AVs, the *underlying assumption seems to be that ‘smart vessels’ and thereby AVs are required to be ‘smarter than humans’.[[13]](#footnote-13)* Which would also imply, that any AV would recognise *at least* the same data, information, guidance etc. of the world outside the AV that a human would recognise. This in turn, of course, explains why the focus of attention is on (‘smart’ or ‘intelligent’) sensory equipment of an AV in the ‘smart vessel’ camp. *All of which are navigational aids!*

According to ISO, AtoNs – on the other hand - ‘are various physical or virtual devices that are installed to directly assist in the ship’s navigation. It can be lighthouses, markers and buoys, or virtual AIS-based AtoN’ ([7], A.2.2). While this introduction is formally correct, no real value of AtoN for the AV is apparent in that definition: AtoNs seem to be represented in the ‘context of the autonomous ship system’ only as entities that context just traditionally seems to contain and that therefore are to be mentioned. Despite that, one important truth needs to be captured from that definition, though, namely that ***AtoNs are the – only – entity from the outside of the automated or even autonomous vessel that is capable of ‘directly assisting’ in its navigation.*** This is important for any determination of a future role of AtoNs for AVs.

Going back to the AV as such, the question must be raised, whether the bias towards an AV being a ‘smart vessel’ and thus being ‘intelligent’ or ‘smart’ (in the common sense of those terms) is really helpful for the successful – meaning broadly accepted – introduction of AVs? This bias may even stand in the way of a graceful introduction of AVs. That is, because ***the definition of autonomy does not mean ‘intelligent’ by default;*** the definition of autonomy would allow for ‘dull’ (in common sense), too. Which prompts the following question:*Are there maritime or inland waterway business cases, use cases, or applications that would benefit using only even ‘less than smart’ AVs?*Of course, ‘less than smart’ is not an appropriate designation. A more appropriate designation will be found further down below.

While the identification or even specification of specific such applications is beyond the scope of this paper, the following use cases should be given to eventually identify them:

* **Reasonable expenditure constraint**:All AVs, including the anticipated ‘smart’ AVs, will remain ‘less than smart’ if *the required or even desired level of ‘smartness’* *cannot be accomplished reliably* in the harsh environments of the maritime and/or inland waterway domains *within reasonable expenditure constraints*. This holds true for equipment in R&D stage, which tends to be costly, but potentially also for mass produced commercial products eventually.
* **Expenditure trade-offs between shipboard navigational aids and shore-based AtoNs in an economy of scale**: All AVs would be required to have whatever shipboard functionality in terms of the generic shipboard navigation system architecture with the Autonomous Onboard Controller on top. The specific functionality profile of these entities may be negotiated as follows, however: There may be an economical incentive to use many ‘less than smart’ AVs in combination with a smaller or even small set of shore-provided high-profile AtoNs *instead of* the same number of ‘smart’ AVs equipped with high-profile navigational aids in combination with present-state AtoNs. Even more so, if this trade-off may cover not only one kind of business case, use case or application at the same time.[[14]](#footnote-14)
* **Shore-based AtoNs to pre-empt impositions due to ‘smartness-induced’ accidents**: Despite all good efforts, ‘smartness-induced’ accidents will happen – which is just a matter of time. Accident investigations and/or the public may potentially *conclude that sole reliance on (shipboard) navigational aids for AVs may not be acceptable (any more)*. Reverting to traditionally operated – meaning crewed – vessels might not be possible, however, due to reasons like the demographic change. One way to avoid this reverting to crewed vessels would be the co-operative system approach, *where (shore-based)* ***‘AV-supportive’ AtoNs*** *would support AVs’ navigational aids – however ‘smart’ –* ***by default****.* If the above reaction to ‘smartness-induced’ accidents is to be anticipated as a ‘sure event’, *why not anticipate it and start with such a co-operative system approach from the outset?* Such an approach will likely also qualify as a risk mitigation measure in any Formal Safety Assessment.
* **AV operation outside Operational Envelope – falling back to remote operation:** Autonomous operation takes place only within an Operational Envelope, which contains a temporal dimension, too, as introduced above. When situations occur that renders the AV as being outside its pre-defined Operational Envelope, the AV will revert to a ROV as a first stage. *Operating the ROV under way by a human operator from the (remote) RCC could benefit from AV-supportive AtoNs in the proximity of the AV-reverted-to-ROV, too,* and potentially extend this mode of operation before re-crewing the AV or AV-reverted-to-ROV as a final stage.
* **Malfunction fall-back shore-support:**A shipboard navigational aids simply can fail, either at individual AVs or – even worse – system-wide for **common modes of failure.** While failure may lead to AVs leaving their Operational Envelopes as discussed above*, AV-supportive AtoNs may serve as shore-provided fall-back in order to* ***keep the AVs affected within their Operational Envelops,*** *otherwise impossible solely with just shipboard navigational aids.* This scenario does not depend on the unpredictable timing of the occurrence of any future ‘smartness-induced’ accident; rather, the need for fall-back as a shore-support can be recognised by a risk consideration at planning time already. This would also be the case, if the required or even desired level of ‘smartness’ can and will be accomplished reliably within reasonable expenditure constraints. Again, a co-operative system approach where AV-supportive AtoNs would support the remaining operational AVs’ navigational aids may offer a solution before reverting to ROV or crewed operation.

Common to all characteristics for potential business cases, use cases, and applications is **the ‘directly assisting’ capability** of the AV-supportive AtoN made instrumental to AVs here. For the same reason, this renders also a better term than the ‘less than smart’ AV, as promised above, namely **‘AtoN-Assisted’ AV**. Using these terms, the co-operative system postulated above would thus reside on the relationship shown in Table 2.

1. Fundamental relationship for AtoN supportive of AtoN-Assisted AVs

**AtoN-assisted Autonomous Vessel ⬄ AV-supportive Aid(s)-to-Navigation**

### Principle Capabilities of AV-Supportive AtoNs for AtoN-Assisted AVs

From the preceding the following question follow suit: What would be the implications for AV-supportive AtoNs when being designed for support of AtoN-Assisted AVs? As part of the shore infrastructure, an AtoN, as the very name implies, is supposed to *provide aid* to the navigation of vessels in its coverage area or within range. AtoNs were traditionally deployed at critical locations along a coast, within an approach or along a waterway to benefit humans operating a vessel on the bridge *at these locations*– to be *physically seen by the human master*at the helm. In addition, there have been deployed AtoNs, that, upon being triggered by an appropriate electronic shipboard device carried by the vessel passing those locations, would send data by radio transmissions *physically* *to that electronic shipboard devices*to be displayed directly and immediately to the human master at the helm. All visual AtoNs would fall into the first category, while Racons would serve as an example for the second category ([13], figure 4 refers).

In addition, AtoN *for the large area provision*and therefore – by very definition not confined to any single critical location – of navigation-supportive data by radio transmissions have been deployed. Their radio transmissions are received and used by certain electronic shipboard devices, which in turn forward the *abstract data*received to other shipboard systems to be displayed eventually, but not necessary immediately, to the human master at the helm. Well-understood examples for this category would be PNT augmentation and/or backup provisions by terrestrial radio services; virtual AIS AtoNs may also serve as an example.

It is in principle the first two cases of traditional deployments ***where transforming the underlying ideas of the traditional aids renders the new class of the AtoN-assisted AV:*** Their functional requirements may be relaxed regarding the requirements to correctly and reliably analyse the AV’s navigational environment in the visual domain similarly or even better than human capabilities. This can be achieved, if and when the traditional visual *functionalities* are amended by radio transmissions that *emulate* the visual functionalities by ***direct*** *delivery at an appropriate shipboard radio receiver at their Sensor Layer in an appropriate machine-readable format* (instead of the detour via the visual domain). In other words*, the fundamental idea would be to emulate the combined functionalities of in particular leading lights and sector lights by providing* ***directional and highly beam-focussed short-range radio transmissions****. Together they would create* ***a shore-provided radio transmitted high-precision trajectory to the AtoN-Assisted AV******through the approach or waterway, i.e. an ‘invisible high-precision vessel track’ or ‘electronic tow path’ provided from ashore.***

* NB: The AV’s functionalities to autonomously and dynamically position and motion itself to whatever degree of precision would still be required.

Since these essentially short-range radio transmissions would preferably predominantly operate in the Short Range Devices (SRD)[[15]](#footnote-15) or cellular land mobile frequency bands dedicated by the International Telecommunication Union (ITU), this would require and allow also using their mass market commercial off-the-shelve electronics for their radio front ends. Relaxed infrastructural requirements for supporting short-range radio transmissions sites (see discussion below) even would allow to increase the number of sites with the goal *to provide bended and approximately curved trajectories* than just straight lines or simple polygons.

* NB: Since uniquely identifiable, the spot locations marked by the short-range radio emissions could potentially be used for supporting shipboard PNT at the AtoN-assisted AV, by e.g. shipboard map matching applications or even short-range R-Mode implementations.
* NB: This is *not* a Racon functionality, although Racons come close to it. While Racons are located at locations critical for navigation, Racons are specifically designed to operate on the radar bands in such a way that their radar transmissions are directly displayed and therefore visible on the radar screen for the human at the helm in a human-readable signature, i.e. they directly serve the shipboard HMI. Racons require more sophisticated and therefore more expensive technology for their operation in the radar band(s) with also a limited market size.
* NB: This is *not* a virtual AtoN application by a shore-based AIS Service because the radio beacons envisaged are situated directly adjacent to navigation critical locations; as opposed to a large(r) area coverage provided by an AIS Service.
* NB: The motion dynamics of a buoy would regularly *disallow* them to be used as infrastructure sites for the envisaged directional short-range radio transmissions. Conversely, the envisaged short-range radio transmissions may put certain buoy positions into disposition.

While science fiction regularly employs this kind of invisible tracks for space station-guided automated landing of spacecraft, it is no ‘rocket science’. A proven example of this approach since long is the well-established combination of the ‘Autoland’ functionality and the Instrument Landing System (ILS) in aviation, which allows for autonomous landing of an appropriately equipped airplane at an appropriately equipped airport under even severe weather conditions [21], [22].

The above variety of AV-supportive AtoNs do not need to be necessarily digital: High-precision can be achieved also just with analogue transmissions. However, progress in beam-forming technologies as developed specifically for latest digital land mobile radio communication technologies, such as IMT-2020 (aka ‘5G’), may be useful for AV-supportive AtoNs, in combination with bi-directional digital data communications via the same digital technology.

### ‘AV-Adapted’ AtoNs to support shipboard automation

While the preceding discussions focused on the AtoN-assisted AV, it is now necessary to address the traditionally operated vessels at an intermediate degree of automation and the truly ‘smart’ AV.

#### Benefits of AV-supportive AtoNs for all degrees of shipboard automation

Would the above AV-supportive AtoNs, i.e. the invisible high-precision vessel track feature, originally introduced for AtoN-assisted AVs benefit traditionally operated vessels with intermediate degree of automation or for truly ‘smart’ AVs, too? Both would not need the AV-supportive AtoNs for their navigation tasks in regular operations – strictly speaking. However, *once implemented* the AV-supportive AtoNs may provide required support for operation outside the ‘smart’ AV’s Operational Envelope, for the RCC when operating an ROV remotely and generally as fall-back arrangements as indicated above. Traditionally operated vessels may benefit by the re-assurance provided potentially by the AV-supportive AtoNs as soon as their functionality would have crept into the appropriate HMI’s at the helm.

#### Principle capabilities of an AV-Adapted AtoN

While the previous option would be just a spin-off, it is necessary now to take the potential assistance of AtoNs for traditionally operated vessel with intermediate degrees of automation and for truly ‘smart’ AVs into focus. This assistance to these vessels categories can be provided, if the traditionally human-focused AtoN would be amended *by a machine-focused functionality,* i.e. if the traditionally human-focused AtoN would become an **AV-Adapted AtoN** (Table 3). This would mean that the traditional AtoN would be *equipped with an additional Machine-to-Machine (M2M) interface directly communicating with shipboard peer equipment.*

* NB: ‘To be amended’ as opposed to ‘to be replaced’ would be required in general due to the mixed traffic target fleet. Traditionally operated vessels would still require AtoNs with a HMI, namely visual aids. This does not exclude the deployment of AV-Adapted AtoNs solely equipped with M2M interfaces as required locally.
* NB: Increased automation and AVs both would allow and require increased data telegram communications, even as an operational key element, which was labelled **Nautical Datalink Communication (NDLC)** in a relevant project [23].
* NB: An AV-Adaptive AtoN becomes an **adaptive AtoN** (compare the IALA workshop findings in the introduction), if designed to be capable of changing its support for automated or AVs at run-time.

1. Fundamental relationship for AtoN(s) adapted for vessels with different degree of automation

**Traditionally operated vessel at intermediate automation degree**

**(optional: truly ‘smart’ AV)**

**(for supplementary and fall-back purposes, only: AtoN-assisted AV)**

**⬄**

**AV-Adapted Aid(s)-to-Navigation**

#### AV-adapted and AV-supportive AtoNs as two functional types of AV-compatible AtoNs

Concluding, the preceding discussions have rendered **two functional types of AV-compatible AtoNs**, namely the **AV-supportive AtoNs** that were designed specifically for the needs of **AtoN-assisted AVs** and the **AV-adapted AtoNs** designed to support intermediate degrees of shipboard automation on traditionally operated vessels or truly ‘smart’ AVs. The AV-supportive AtoNs may be used by traditionally operated and truly ‘smart’ vessels alike, once implemented, of course.

### General Technical Considerations regarding AV-compatible AtoNs

This section will consider some technical aspects for the AV-compatible AtoNs. They are applicable in principle to both AV-adapted AtoNs and AV-supportive AtoNs likewise, but the AV-supportive AtoN may be subject to additional requirements as given above regarding e.g. high-precision.

#### Introducing the Infrastructure Site Architecture

In vicinity of shore, the distances between the vessel and an AV-compatible AtoN can be considered sufficiently short range everywhere for any kind of *direct* data communications, which is short-range by default. To cover a variety of options, the consideration of a generic **Infrastructure Site Architecture** for the AV-compatible AtoNs might be helpful. It supports at least the following three different use cases:

* *co-operative position determination* of the vessel passing by the AV-compatible AtoN, which is also *electronically identified* in the process;
* *upload of data relevant for navigation from AV-compatible AtoN to vessel,* such as locally gained sensor data or remotely received data for broadcast to all passing vessel or remotely retrieved data for identified vessel, if sufficient time available for retrieval process;
* *download of vessel data to AV-compatible AtoN,* such as vessel sensor data at the time of passing of site or data stored by the vessel on-board equipment for a period prior to passing by.

The interaction of the AV-compatible AtoN with a vessel is illustrated by the Figure 8.



1. Working principle of interactions between vessel and AV-compatible AtoN [12].

In order to give an indication for timing requirements when selecting any suitable communication technology to support the above use cases, the following example calculations for vessels of different speeds over ground at an example maximal distance usable for data communications are given.

1. Example calculations for time available for data communications at infrastructure site/AtoN.

|  |  |  |
| --- | --- | --- |
| Max. time available for data communications V2I [s] | [min] | Max. distance usable for data communications V2I [m] | Vessel speed over ground [km/h] | [m/s] |
| 360 | 6 | 100 | 10 | 2,8 |
| 10 | 0,18 | 100 | 36 | 10 |

#### Physical links using High bandwidth Visual Light Communications (VLC)

Besides the physical links that use radio communication technologies as introduced above, the **use of light for high bandwidth data communications** may be interesting as a short-range communications means in general but in particular for adapting traditional visual AtoN to render AV-adapted AtoNs. ITU recently has conducted a survey on the emerging technology enabling ‘short distance broadband communication via visible light’ ([24], para. 5), which precisely expresses the idea. This is labelled ‘(near) visible light communication (VLC)’ or alternatively ‘Optical Wireless Communication’ ([24], para. 1). The latest developments regarding modulation of light for establishing high-bandwidth physical links are introduced there: ‘Visible light optical wireless access data rates ranging from a few b/s to excess of 10 Gbit/s are possible at standard indoor illumination levels. VLC has the potential capability to ease congestion with low radio frequency (RF) spectrum bands since light spectrum can be used as an additional spectrum resource for broadband communications.’ ([24], para. 3.1). Use cases of relevance here are identified as follows ([24], para. 3.4), most of which are self-explanatory:

* ‘Location-based services / indoor positioning and navigation’ - VLC would be an option to support PNT.
* ‘Vehicular communications’ and ‘Point-to-(multi)point/relay/communications’ – this implies both Vessel-to-Vessel (V2V) as Vessel-to-(AtoN) Infrastructure (V2I) options.
* ‘LED based tag applications’ – When either a vessel carries such a tag it can be detected as ‘being there’ (by another vessel or by an infrastructure sensor) or vice versa when an infrastructure position can be detected as ‘being there’ by a vessel. Slightly more specifically but still relevant would be the use case: ‘Digital signage and location based content delivery’.
* ‘In-Vehicle data services (flight, train, ship, bus, etc.)’ – e.g. for local VLC link in the bridge/wheelhouse.
* ‘Connected-cars and Autonomous Vehicles‘
* ’Underwater/Seaside Communications‘
* ‘Internet of Things (IoT)’.

Hence, wherever data must be exchanged in short distances in spot-like situations between a fixed and a moving position, VLC may offer an emerging solution, even if it is only ‘one bit’ – namely the detection of presence of an (expected) object. But also V2V data exchange at short distances might be an option specifically in fairways with their regularly close encounters. Finally, the motivation to shift communications from a radio link to a visual link may be helpful also in the light of the congestion of the VHF Maritime Mobile Service frequency band. For the application in the outdoor domain, the requirements to be met by any VLC application are given as ‘coexistence with ambient light [and] coexistence with other lighting systems’ ([24], para. 3.4). Since a number of products and application domain projects employing VLC are given worldwide ([24], para. 5.4) and standardisation is under way already, it may be assumed that the VLC technology as such has reached the ‘testing prototype in user environment’ stage in a technology maturity model.

#### The ‘Smart Hectometre Stone’ as a basic variety of an AV-compatible AtoN for many locations

Considering a deployment of *many instances of the same or similar such AV-compatible AtoNs* would allow for ***steady*** *direct communication* with vessels during their (entire) voyage under land but in particular in waterways. Sites with a high affinity to that would be (existing) hectometre stones and/or other passive AtoN positions (signs), thus rendering ‘Smart Hectometre Stones’ and/or ‘Smart AtoNs’, and bridges thus rendering ‘Smart Bridges’. The figure overleaf gives an engineering sketch for the functional setup of such ‘smart’ infrastructure sites.

* NB: A ‘smart’ infrastructure site would lend itself as a contribution to Resilient PNT, if and when its precisely known position is used in combination with a precise time kept and being transmitted by any relevant radio or light communication technology or technologies. The deployment of many ‘Smart Hectometre Stones’ along relevant waterways may resolve the challenge of providing R-Mode indicated above.
* NB: The remoteness of the sites equipped, would require local energy generation and storage, if and when no fixed electricity line would be available. Alternatively, the substantial experience with integration of solar powered low-power electronics gained in the maritime domain could be used.
* NB: The degree of integration of electronics will likely further increase over time while size and energy consumption of individual components will decrease, thus allowing for more functionality to be integrated and/or the dimensions of the ‘Smart Hectometre Stone’ being reduced.



1. Functional block diagram of a ‘Smart Hectometre Stone’ [12]

*Legend to above figure:*

M2M-NDLC = Machine-to-Machine-Nautical Datalink Communications ([23], paras 3.2 and 4.2);

IMT-2020 = International Mobile Telecommunication for 2020 and beyond (aka ‘5G’) [25];

LPWAN = Low Power Wide Area Network [26].

#### Benefits for infrastructure/waterway providers

While deploying the AV-compatible AtoNs along an approach or a waterway may be a considerable investment, it may provide an option to arrive at a **new system or service mix** thus allowing to exploit the trade-off with other Aids-to-Navigation and/or VTS services. In addition, with increasing number of those AV-compatible AtoNs deployed, the potential benefit of **swarm collection of relevant waterway and environmental data** for operation and maintenance of the waterway itself will increase. Such data is gathered by the AVs on the waterway for their own reasons, anyway; to that end, the AV-compatible AtoNs need to have bi-directional radio communications.

### Conclusions

From the discussions, it can be concluded that AtoN infrastructure will be needed in the future with increased numbers of AVs, (highly) automated, traditionally operated vessels operating both in coastal waters and in inland waterways. AtoN concepts must be amended compared with the present situation to become **AV-compatible AtoNs**. As one variety of those, the concept of an ***AV-adapted AtoN***has been defined, that would be specifically geared towardstraditionally operated vessels with mixed intermediate degrees of automation as well as for truly ‘smart’ AVs. Another variety of AV-compatible AtoNs were defined as ***AV-supportive AtoNs*** for certain applications benefitting from AVs, labelled ***AtoN-assisted AVs,*** which are dependent on those AV-supportive AtoNs for their navigation. Both AV-compatible AtoN varieties could co-exist. They would be designed to provide ***direct*** *on-site shore-range data exchange* AtoN with AV and vice versa in M2M communication while potentially maintaining a human-readable AtoN functionality to cater for the mixed target fleet. The data communication of both varieties could be done by short-range radio links and/or high-bandwidth visual links; potentially even being adaptive at run-time to different degrees of shipboard automation encountered. The AV-supportive AtoN infrastructure would provide a high-precision trajectory to the AtoN-assisted AV through the approach or waterway, i.e. *an ‘invisible high-precision vessel track’ or ‘electronic tow path’.*

## Other application scenarios under discussion

[content to be added]

## Vessel Traffic management by using digital twins

Creating a digital twin of a fairway can significantly enhance vessel traffic management, as it allows the simulation of various scenarios involving different types of vessels safely navigating the fairway. This can include the selection of hydrological or weather conditions and traffic scenarios, including both routine and emergency situations. A digital twin is especially valuable during the construction or renovation of a fairway, as it enables the simulation and analysis of vessel traffic management in the early design stages.

For existing fairways, the digital twin also serves as a valuable training tool. It allows port personnel, such as pilots or VTS operators, to simulate and practice managing vessel traffic in a safe environment.

# OUTLOOK ON FUTURE, BUT IMMINENT PARADIGMATIC DEVELOPMENTS

This chapter introduces some further steps in the digitalisation of waterways that may or will be taken in the future. While the maturing of the development and/or implementation of these *paradigmatic concepts* is still future as seen from the date of the publication of this edition of this guideline, international standardisation work on them has already started or has gained already a certain degree of maturity even. Hence, these paradigmatic concepts are to be considered imminent. Therefore, the following developments are introduced here as an outlook together with references to the international standardisation domains dealing with them presently. These paradigmatic concepts will be further elaborated in future editions of this guideline as they gain higher degrees of maturity.

## Introduction to THE Concept of THE Metaverse and its derivatives

So far, this guideline has introduced the generic paradigmatic concepts of a data model, a data shadow, and a digital twin. These concepts have in common, that they create a digital data representation ***about*** physical or virtual entities of whatever kind which may be used for certain improvements regarding the functioning of those physical or virtual entities. The concept of the metaverse uses this digital data representation together with further amendments to allow humans (and potentially their avatars) ***to enter into*** a virtual representation of – both real physical and virtual environments and imagined or projected such environments – that is, the metaverse.

It is assumed, that by entering into the metaverse interactions of humans (and potentially their avatars) with functions of the (physical and virtual) entities represented there can be even more efficient – whatever this may mean specifically.

To cater with the complexities of this concept when applied to the whole of reality, certain subset derivatives of the metaverse have been defined, such as the citiverse. *Regarding waterways as the topic at hand, it is certainly not far fetched that there may be established in some future a derivative of the metaverse for waterways [– maybe dubbed “waterverse” by then.]*

Technologies needed to enter into the metaverse range from augmented reality displays via virtual reality headsets to cyber-human implants, all of which are already under standardisation in international organisations.

## Introduction to the Concept of the Physical Internet

So far, this guideline has concerned itself with ***concepts of digitalisation*** of the waterways and of its individual infrastructure components. The paradigmatic concept of the Physical Internet (PI) builds on these but reverts back to the ***original purpose of waterways – even if digitalised eventually –, that is the transport of cargo*** ***and persons*** in the case of vessel traffic (as opposed to the purpose of operating waterborne vehicles). In a nutshell, the idea of the PI is to enable an appropriate and standardised container (of cargo, to start with) ***to be routed or even route itself*** through the whole of the intermodal transport network from consigner to consignee ***using any available mode of transport.*** That resembles the idea of the Internet with the routing of data containers applied (back) to physical containers. Because any mode of transport can be employed to that end, if and when the different modes of transport are transparent to the decision making of the cargo containers routeing themselves through the transport network at a certain point in time, this concept is sometimes also called ***synchromodality***.

It should be noted, that the containers as mentioned above, should ***not*** be construed as TEU sea containers by default, but may be much smaller, and that the vessels – in the case of the waterway transport part – may be quite small while still having all features of vessels.

While conceptionally speaking not strictly necessary, in practice the PI requires a ***high degree of automation or even autonomous entities throughout,*** e.g. at points of change of mode of transport but also en-route within a specific mode of transport. Regarding the waterway this would mean specific support for approaching vessels to berths along the waterways and in ports

# DEFINITIONS

The definitions of terms used in this Guideline can be found in the *International Dictionary of Marine Aids to Navigation* (IALA dictionary) at <http://www.iala-aism.org/wiki/dictionary> and were checked as correct at the time of going to print. Where conflict arises, the IALA Dictionary should be considered as the authoritative source of definitions used in IALA documents.

# abbreviations

IMO International Maritime Organization

PI Physical Internet

[content to be added]

# references

[to be checked]

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27. [to be checked] International Telecommunication Union. (2022). Report ITU-R SM.2153-9. Technical and operating parameters and spectrum use for short-range radiocommunication devices. Last edition 9: July 2022.

# Further reading

1. [Reference on Physical Internet introduction]

# Index

**No index entries found.**

1. That backdrop to the DIWA Maturity Model has developed over several decades now into a science of its own. For an introduction to the Capability Maturity Model compare [Wikipedia2022c]. [↑](#footnote-ref-1)
2. Note to above figure: The entities shown will be introduced soon in more detail. [↑](#footnote-ref-2)
3. The entities that an organisation may be composed of are depicted as examples; a very important entity within any organisation providing service to the IWT fairway & navigation domain is the operations centre which therefore features prominently. [↑](#footnote-ref-3)
4. This holds true even with the advent of digital technologies such as Fuzzy Logic or AI algorithms that deliberately create the impression of permissible ambiguity to the human user or to applications using them. [↑](#footnote-ref-4)
5. To that end, the International Maritime Organization (IMO) has set up a *Harmonisation Group on Data Modelling (HGDM)* as a consequence of their e-navigation strategy. [↑](#footnote-ref-5)
6. The notion of a co-operative digital technology is not new at all: There are well known examples of co-operative digital radio communication technologies, such as the Digital Selective Calling (DSC) and AIS. Also, in principle, visual aids flashing a light-on-off sequence as a code for identification form a co-operative digital (visual light) communication link with the human eye as the other ‘terminal’. But also ECDIS is an example of digital technology because there is not only the digital co-operative technology needed to exchange chart data but also the close and unambiguous co-operation of several organisations involved in creating the chart data on one hand (i.e. for example chart providing authorities) and displaying it on the shipboard side on the other hand (i.e. for example equipment manufacturers). [↑](#footnote-ref-6)
7. Some of the proposed scales of ‘degree of autonomy’ resolve the issue to designate the autonomy of the entity in its above philosophical sense by introducing terms like ‘fully autonomous’ ([4], [5]), and thus the prudence of language – obviously perceived need for adding the prefix ‘full’ – reveals the issue at hand. At Sheridan levels of autonomy, the term ‘autonomy’ appears only at Level 10, while the term ‘automatic execution’ appears last at Level 6. The intermediate levels 7, 8, and 9, are neither labelled automatic nor autonomous, and it can be debated what is implied by ‘computer executes action’ in this regard ([6], 11). [↑](#footnote-ref-7)
8. ISO defines ‘uncrewed’ as a ‘ship with no crew onboard’, while ‘crew does not include passengers, special personnel etc.’ ([auton2], 3.1.9). [↑](#footnote-ref-8)
9. ISO defines autonomy as ‘processes or equipment in a ship system which, under certain conditions, are designed and verified to be controlled by automation, *without human assistance*’ ([6], 3.1.3, emphasis added). Sheridan Level 10 defines autonomy in respect to a computer as ‘Computer does everything autonomously*, ignores the human’* ([10], 11, emphasis added). [↑](#footnote-ref-9)
10. Consequentially, this fundamental distinction may or even should be clearly stated by the vessel to the outside world by setting an appropriate flag visually and electronically dynamically at run-time, if the state ‘autonomy’ would imply any operational difference to other vessel traffic participants compared to any other degree of automation. [↑](#footnote-ref-10)
11. The functions of the RCC and of the AVCC can be merged. This is indicated by ISO, by positioning the functionality of the ‘Autonomous Remote Controller’ into the RCC ([6], 3.2.5 and Figure A.1). [↑](#footnote-ref-11)
12. Which do not need to be radio communication technologies exclusively; see further down below. [↑](#footnote-ref-12)
13. A ‘smart vessel’ was not incorporated in ISO’s comprehensive AV terminology definition work [2], although ISO hosts a dedicated working group on the topic labelled by that term. Maybe ‘smart vessel’ (or any correlate term for that matter) was not included in the ISO AV definitions, because of the obvious difficulties to define that term. [↑](#footnote-ref-13)
14. This is ***not*** to advocate ‘sub-standard’ AVs. Quite the contrary. *All functionality that* ***is*** *implemented in an AV for* navigation *must adhere to the high quality standards likely in place in due course for navigational aids and must demonstrate their compliance, too,* by e.g. type approval procedures. Since both requirements will add to the expenditure of shipboard equipment of the AV, this even adds weight to this expenditure trade-off use case. [↑](#footnote-ref-14)
15. This technical term is defined by ITU as an umbrella term and comprises a number of diverse short-range radio communication technologies. For further details, refer to e.g. [11]. [↑](#footnote-ref-15)