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RESEARCH ARTICLE

Radio navigation systems: definitions and classifications

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Abstract

Radio navigation systems (RNSs) are commonly applied in air, land and marine navigation. They are most often used for position determination. However, when comparing the definitions of this concept provided by global organisations, such as the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA), International Civil Aviation Organization (ICAO), International Maritime Organization (IMO) or International Telecommunication Union (ITU), it should be noted that the definitions presented differ significantly. Due to the ambiguity and numerous contradictions, the RNS classification varies depending on the definition of the term 'radio navigation' adopted, which poses serious interpretation problems. This article analyses the concept of radio navigation based on the most important global documents and legal acts on this issue. It points to fundamental differences in the understanding of the term and proposes the adoption of a new, uniform definition for air, land and marine navigation. Based on this definition, the current paper proposes a uniform RNS classification. The proposed definition of the concept of radio navigation and the resulting RNS classification are essential for the understanding of this term to achieve global uniformity and fundamental to the harmonious development of the scientific discipline of navigation. The current proposal should initiate a discussion on the meaning of the concept of radio navigation and the RNS classification.

1. Introduction

Terminological consistency, based on definitions of basic axioms and concepts, is the very foundation of any scientific discipline. However, divergences in the definition of various important, and even basic, terms have been observed in the navigation literature for many years. This does not apply exclusively to specialist concepts. It also applies to new terms, which need clarification as a result of pushing the boundaries of knowledge. It would seem, however, that after decades of development such a scientific discipline as navigation should work out clear definitions of concepts that are fundamental to it. Nevertheless, this is not the case. The incessant development of navigation techniques certainly explains this state of affairs to a certain degree, but on the other hand, it is worth noting that the fundamental terms of this discipline should at least be consistent, if not identical. The concept of radio navigation is among such unclear or even disputable (defined in different ways) basic terms. In various documents (IMO, 1989, 1997; IALA, 2004, 2018; ITU, 2016; ICAO, 2018; U.S. DoD, 2019), it is presented in various manners. The lack of clarity on this issue causes difficulties in classifying a particular system among radio navigation systems (RNSs) and makes RNS classification difficult.

Many scientific publications (Giuliani, 1972; Walton, 2005; Hansson, 2006; Zarefsky, 2006; Macagno, 2010) have been devoted to the definition of concepts which constitute the methodological basis for the considerations in this discipline. It should be stressed that this article is not a scientific discussion on the methods of defining various terms, hence the concept of a definition, which was

defined by Aristotle as 'a phrase signifying a thing's essence' (Giuliani, 1972), has been adopted for the purposes of this paper. This is adequate for further methodological considerations.

There are two kinds of definitions: lexical (descriptive) or stipulative. The former is commonly used, as true or false values can be unequivocally attributed to it. The latter determines how the defining person would like the concept defined by them to be understood. A stipulative definition cannot be correct or incorrect, but it can be enlightening or confusing, fruitful or barren, adequate or inadequate (Hansson, 2006). Since the term RNS has been widely used in the technical literature for a long time, it should have a lexical (descriptive), so true or false values can be assigned.

A definition consists of three essential components: *definiendum* (what is defined, i.e., the terms 'radio navigation' and 'radio navigation system'), *definiens* (a description of what is defined) and a defining link. The term RNS consists of two constituents: the words 'system' and 'radio navigation'.

The word 'system' is part of the concept of RNS. The term 'system' has been defined similarly by many authors and does not give rise to major interpretative doubts. Due to the technical nature of the concept of radio navigation, it is reasonable for the definition of the word 'system' also to be situated in a technical context. It appears that, from among the many definitions of this term, which differ slightly from one another, two of them merit mention since they define the concept of system from a technical perspective. The first term was defined in INCOSE (2015). It is descriptive in nature, determining a system as an integrated set of elements, subsystems or assemblies that accomplish a defined objective. These elements include products (hardware, software, firmware), processes, people, information, techniques, facilities, services and other support elements. A very similar definition of system is presented in the standardisation document ISO (2015), which describes this concept as a combination of interacting elements organised to achieve one or more stated purposes. As it follows from the definition, the essence of the term 'system' lies in a set of elements that jointly serve a given function.

Contrary to the concept of system, the other part of the term RNS, referring to the words 'radio navigation', is not as easily defined. The first part of this paper presents the definitions of radio navigation used in documents of key importance for world navigation (IMO, 1989, 1997; IALA, 2004, 2018; ITU, 2016; ICAO, 2018; U.S. DoD, 2019). An analysis showed that they exhibit significant variations. In addition to position determination (used in all definitions), different definitions of radio navigation describe various systems using radio waves related to navigation to a greater or lesser degree. Therefore, this paper proposes the author's own definition of the concepts of 'radio navigation' and 'radio navigation system' and, based on these definitions, a classification of RNSs is also determined.

2. Materials, methods and results

2.1. Definition of the concept of radio navigation

Radio navigation and RNSs use radio waves. The International Telecommunication Union (ITU) defines radio waves or hertzian waves as electro-magnetic waves of frequencies arbitrarily lower than 3,000 GHz, propagated in space without artificial guide (ITU, 2016). This concept is unambiguous and does not give rise to any uncertainty of interpretation or definition. For this reason, it will not be discussed further in this paper.

Let us start the terminological discussion with the concept of radio navigation. To this end, one should recall the definition of this term from one of the most influential global radio navigation documents, which is the U.S. Federal Radionavigation Plan (FRP) (U.S. DoD, 2019). The FRP is the official source of positioning, navigation, and timing (PNT) policy and planning for the U.S. Federal Government, which states:

Radionavigation – The determination of position, or the obtaining of information relating to position, for the purposes of navigation by means of the propagation properties of radio waves.

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Table 1. *Positioning, navigation and timing information services and systems.*

Positioning, navigation, and timing (PNT) information services	PNT systems

• United States Coast Guard (USCG) Navigation Center (NAVCEN) Navigation Information Service
• GPS Notice to Airmen (NOTAM)/Aeronautical Information System
• Wide Area Augmentation System (WAAS) NOTAM/Aeronautical Information System
• Maritime information systems
• National Aeronautics and Space Administration (NASA) GPS Monitoring and Space-User Services
  ° International GNSS Service (IGS)
  ° GPS metric tracking for space lift vehicles
  ° Global differential GPS (GDGPS)
  ° Next generation beacon service (NGBS)
• National Oceanic and Atmospheric Administration (NOAA) Continuously Operating Reference Station (CORS) Network
	• Global Positioning System (GPS)
	• Augmentations to GPS
	• Instrument landing system (ILS)
	• Very high frequency (VHF) omnidirectional range (VOR)
	• Distance measuring equipment (DME)
	• Tactical air navigation (TACAN)
	• Nondirectional beacon (NDB)
	• Internet time service (ITS)
	• Radio station WWVB signal
	• Two-way satellite time transfer (TWSTT)
	• Network time protocol (NTP)
	• Automatic dependent surveillance – broadcast (ADS-B)

Since the FRP does not include electronic non-RNSs that are used primarily for communication and surveillance (e.g., cell phone, radar), it cannot be considered as a document only describing RNSs. PNT information services and systems, to which the document pertains, are mentioned in Table 1. The concept of radio navigation presented in the FRP covers PNT systems, which include positioning systems, surveillance systems and time transfer systems. There is no doubt that the systems listed in Table 1 use radio waves for navigation purposes and can thus be considered RNSs. However, the inclusion of the PNT information services from Table 1 in the RNSs would require that they also use radio waves for transmitting information from these services to navigation objects, which is only the case with selected systems of this group.

Note that the FRP does not include navigation radar in the RNSs, classifying it as a non-radio navigation system, despite it using radio waves for collision avoidance and positioning. Radars have long been used in air, marine and, more recently, land (automotive) navigation. However, in the FRP, radar is included in the group of surveillance systems related to the observation of an area or space to determine the position and movements of craft or vehicles in that area or space. The view expressed in the FRP, stipulating that navigation radar is not a radio navigation device as determining a position

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(of an aircraft or a ship or, generally speaking, an object) is just one of its two (apart from collision avoidance) fundamental functions, seems difficult to defend.

The International Maritime Organization (IMO) presents a significantly different definition of the concept of radio navigation from the FRP, defined as (IMO, 1997):

Radionavigation – The use of radio waves in navigation for the determination of position or direction, or for obstruction warning.

The definition of the concept of radio navigation as presented in IMO (1997) seems narrower and more precise than that of the FRP. To determine a position, the IMO definition adds a direction determination and an obstruction warning (IMO, 1997). Direction determination is a very broad term, since it can be both related to positioning, i.e., the establishment of a position line by radio direction finding, as well as the determination of the direction of movement of an object along a given path, as is the case in air or marine navigation. Moreover, this definition includes a new concept – obstruction warning. According to this definition, a navigation radar becomes a radio navigation device, contrary to the definition presented in the FRP.

When analysing the IMO's position on the definition of radio navigation, it should be noted that its fundamental resolution (IMO, 1989) does not explicitly define the concept of radio navigation or a RNS. However, the statement: 'RECOGNIZING the need for a world-wide radionavigation system to provide ships with navigational position-fixing throughout the world' also indicates that only systems that determine the position of a ship are considered RNSs. What is noteworthy in the IMO resolution is that it includes the following systems among world-wide RNSs: Global Positioning System (GPS), Transit (turned off in 1996), GLObal NAvigation Satellite System (GLONASS), differential OMEGA (turned off in 1997), Decca Navigator System (turned off in 2000), Loran-C and Tchaika (Specht et al., 2016). Obviously, due to its publication date, IMO (1997) does not include other (contemporary) positioning systems. However, it should be stressed that it only lists positioning systems. Other systems using radio waves for navigation without positioning capability have been omitted. Furthermore, restricting the definition to a ship may be justified by the type of organisation, dealing exclusively with sea-related matters, but the fact that radio navigation has only been linked to positioning deserves some attention.

Another definition of the concept radio navigation has been presented by the ITU (ITU, 2016). Compared with other definitions, this one is the broadest, because it covers many more areas that can be classed as radio navigation due to the system's use. According to ITU (2016):

Radionavigation – Radiodetermination used for the purposes of navigation, including obstruction warning, where:
Radiodetermination – The determination of the position, velocity and/or other characteristics of an object, or the obtaining of information relating to these parameters, by means of the propagation properties of radio waves.

Just like the IMO definition, the ITU definition covers obstruction warning and radiodetermination (position determination). However, unlike the definitions provided in IMO (1997) and U.S. DoD (2019), in the ITU definition, radiodetermination is no longer equivalent only to determination of position coordinates. New, additional areas of radio wave application have been added to this concept. These include:

- Velocity determination;
- Determination of other characteristics of an object related to position and/or velocity;
- Obtaining information relating to position, velocity and/or other characteristics of an object.

The International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) presents yet another definition of the concept radio navigation, much different from the others. According to IALA (2004):

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Table 2. *Comparison of the conceptual range of radio navigation definitions across normative documents.*

Document	Determination of					Obtaining information relating to	
	Position	Position line	Direction	Velocity	Obstruction warning	Position	Velocity
U.S. DoD (2019)	✓	×	×	×	×	✓	×
IMO (1997)	✓	×	✓	×	✓	×	×
IMO (1989)	✓	×	×	×	×	×	×
ITU (2016)	✓	×	×	✓	✓	✓	✓
IALA (2004)	✓	×	✓	×	✓	×	×
IALA (2018)	✓	✓	×	×	×	×	×

Radionavigation – The use of radio signals to support navigation for the determination of position or direction, or for obstruction warning.

However, a dozen years later, in another document very important for marine navigators (IALA, 2018), the IALA provided a different definition of the concept of radio navigation, which is:

Radionavigation – Navigation using radio signals to determine a position or a line of position (e.g. eLORAN, GNSS, DGNSS etc.).

The earlier IALA definition (IALA, 2004) is identical to the IMO definition (IMO, 1997). However, the IALA definition from 2018 (IALA, 2018) limits radio navigation to the positioning and determination of the position line.

Since IMO and IALA are organisations primarily involved in marine radio navigation, it seems justified to cite a definition of this concept provided by an organisation involved in another type of navigation, i.e., air navigation. In a document fundamental to aviation, the Chicago Convention on International Civil Aviation, the concept of radio navigation is not given explicitly. However, it includes a very similar term – radio navigation service. According to the International Civil Aviation Organization (ICAO) (ICAO, 2018):

Radio navigation service – A service providing guidance information or position data for the efficient and safe operation of aircraft supported by one or more radio navigation aids, where:
Radio navigation aid – A facility or system external to the aircraft that generates electro-magnetic signals to be used by aircraft navigation systems for position determination or flight path guidance.

In the ICAO definition, radio navigation, in addition to providing position data, includes a broad concept from aviation, i.e., flight guidance information. It also stresses that the ICAO definition only refers to the term RNS in relation to air navigation, which is justified by the type of organisation.

In conclusion, the concept of radio navigation does not have a uniform definition, not only globally, but even in individual industries, as marine institutions (IALA and IMO) define the term differently. Table 2 synthesises the different definitions of the concept of radio navigation, taking into account the areas of RNS application mentioned in these definitions.

In Table 2 the ICAO definition has been omitted due to its very broad scope of application, which is significantly different from other definitions. The comparison of the definition of the concept of radio navigation presented in Table 2 illustrates the discrepancies in the areas in which RNSs are used. The table shows that, apart from position determination, the term radio navigation covers different areas in various definitions.

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The six different definitions of the concept radio navigation presented in Table 2 should be assessed from the point of view of definition theory. As mentioned above, the definition of this term is lexical (descriptive). This means that it can be only attributed to one of two logical conditions: 'true' or 'false'. Other valuations, such as: 'almost true', 'almost false', 'half-true' or similar statements are incompatible with the definition theory. Thus, if the six definitions presented differ, it means that only one of them can be true and the other five definitions must be considered false. To put it simply: five of the definitions presented in Table 2 are not true. The author does not intend to resolve which are untrue and which one is true because this does not solve the problem in question.

To solve it, another question needs to be asked instead: what strategy should be adopted in defining the concept of radio navigation to be able to state that a given sentence is true? There seem to be two methods of assessing whether a definition is correct:

1. The definition of the term radio navigation should cover all areas of the application of radio waves in navigation.
2. When defining the concept of radio navigation, no areas of the application of radio waves in navigation should be explicitly pointed to, but it is sufficient to describe their common characteristic, which is certainly the use of radio waves in navigation.

Since it is very difficult, if not practically impossible, to list all areas of use of radio waves in navigation, no other solution than the one mentioned in point 2 is practicable. To conclude, for the definition of the concept radio navigation to be true, it cannot be other than:

Radionavigation – The use of radio waves in navigation.

Hence, the definition of the term RNS is derived from the adopted definition of radio navigation. It must take the following form:

Radio navigation system – A system that uses radio waves in navigation.

2.2. RNS classification

The classification and division of RNSs is a complex process, as these systems are applied in navigation in many different areas and some of them are of local character (e.g. national) or used in military applications. This diversity makes it very difficult, or even impossible, to find a single, logically consistent criterion for their classification.

It seems that the type of navigation and the phases in which these systems are applied are the most obvious criteria for classifying RNSs. This division was used in the FRP (U.S. DoD, 2019), which describes specific systems. The following phases have been identified for each type of navigation:

- Marine navigation: inland waterway, harbour entrance and approach, coastal navigation and ocean navigation;
- Aviation navigation: en route, oceanic en route, terminal, takeoff and approach-to-landing, as well as aviation surface operations;
- Land navigation: highways, transit and rail.

By dividing RNSs according to the phase and type of navigation, a new problem with defining phases for land navigation emerges, as they have not yet been identified in the scientific literature. Land navigation is commonly divided into the following types: highways, rail and transit (U.S. DoD, 2019), but not into land phases of navigation. This results in a lack of a uniform criterion for system classification at this stage.

The division into three types of navigation is probably the most obvious division criterion for RNSs. However, there are systems that are used for all types of navigation (GPS, Inmarsat, Loran-C, radar and others). Thus, it would be incorrect to list them repeatedly in each type of navigation.

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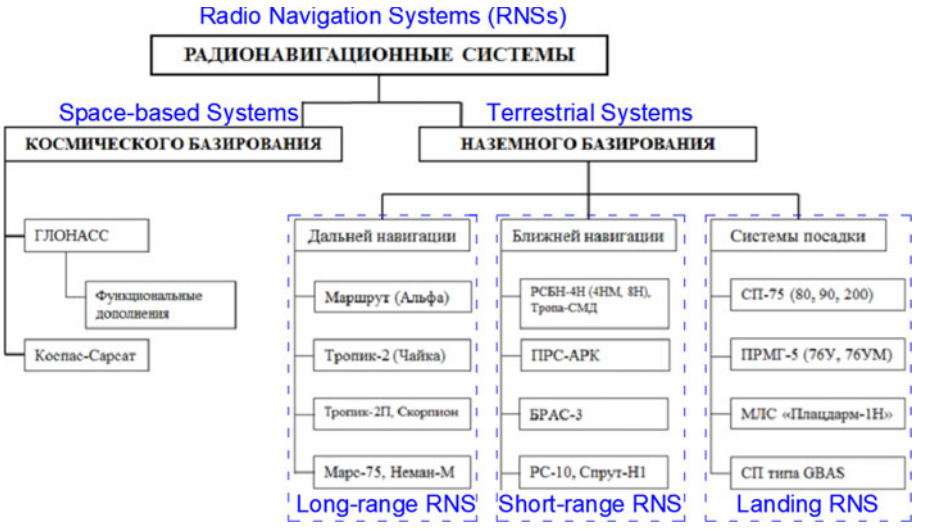

Figure 1. *Radio navigation system (RNS) classification according to CIS (CIS, 2019).*

System coverage constitutes another division criterion for RNSs. If the coverage of a RNS is taken as a classification criterion, the RNS can be divided into the following categories: global systems, long-, medium- and short-range systems. This is undoubtedly a single-criterion division and appears to be correct, homogenous and simple. A method similar to this proposal was used in the Russian radio navigation plan (CIS, 2019). Since there is no English version of this document, the Russian RNS classification is presented in Figure 1 supplemented by translation of the most important terms into English (blue).

Note that in the FRP (U.S. DoD, 2019) the criterion of RNS coverage was not applied to all groups and systems. The appearance of the additional landing RNS group (Figure 1), incompatible with the adopted classification criterion, i.e., the range, seems debatable. Moreover, it should be stressed that with such a division, RNSs used in aviation, on land and at sea belong to the same group. Aviation systems, such as instrument landing system (ILS) will be in the same group (short-range systems) as global navigation satellite system (GNSS) real time kinematic stations. Systems such as automatic identification system and VDL transponders, Bluetooth and Wi-Fi also fall into this group. There is no rational justification for such a 'mixing' of RNSs with different intended uses, as such classification would only be understandable at the level of system coverage, and RNSs from different types of navigation would fall into the same group (e.g., long-range systems).

From the analysis carried out, it follows that it is not possible to use a single criterion (positioning accuracy, system coverage, type of navigation, etc.) which would allow the division of RNSs clearly and logically. Therefore, it is proposed to divide RNSs into five types: terrestrial systems (common systems, systems for aviation, systems for land and systems for marine), satellite systems, GNSS augmentation systems, onboard systems and support systems. This approach was inspired by the Swedish Radio Navigation Plan (SRNP) (SMA, 2009), where RNSs were divided into four types: terrestrial systems (common systems, systems for aviation, systems for maritime use and systems for land navigation/positioning), onboard systems, satellite-based systems, and support and augmentation systems. The main differences between the SRNP and the proposed approach to RNS classification include designation of a separate system group (GNSS augmentation systems), leaving out commercial and military systems, as well as supplementing the classification with other global systems not included in the SRNP (SMA, 2009). Figure 2 presents the author's original RNS classification. It is supplemented with the indication of application areas: aviation, land, marine and rail.

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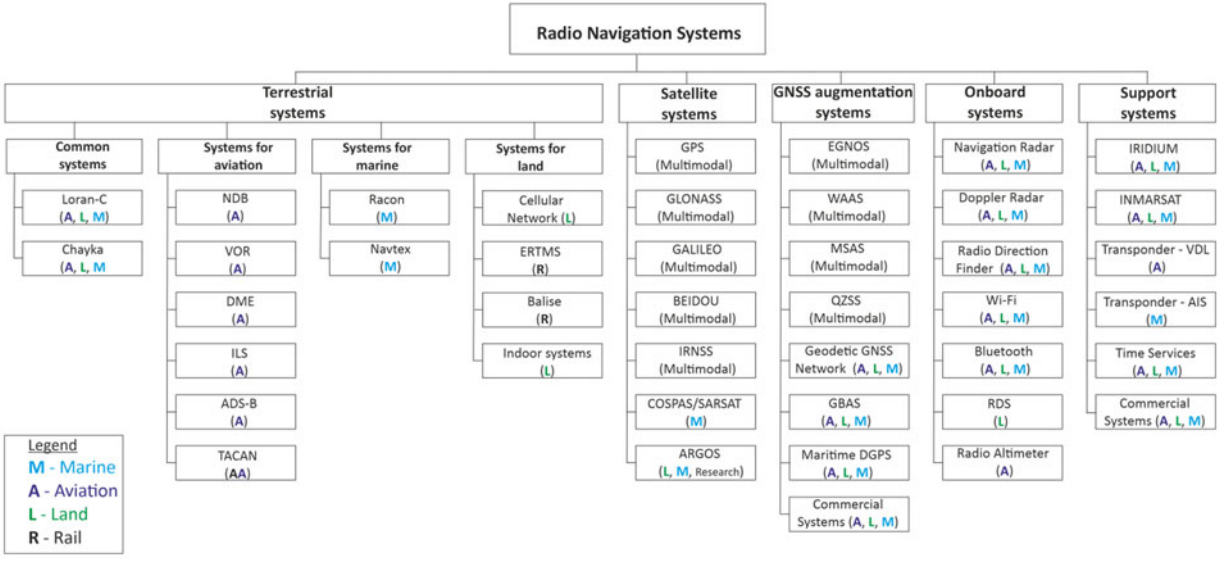

Figure 2. *Radio navigation system (RNS) classification.*

3. Discussion

From the analysis of RNS definitions presented in Table 2, it follows that:

- The concept of radio navigation is always associated with radiodetermination (position determination) and it may sometimes also refer to systems that dispatch obstruction warnings.
- Other areas of use for the navigation systems based on radio waves (determination of position, position line, direction or velocity, obstruction warning and obtaining information relating to position or velocity) are only occasionally mentioned in definitions and therefore should not be included in the definition of radio navigation.
- Analysis also shows that defining the term radio navigation through a detailed list of the areas of application of RNSs has led to such significant discrepancies across specific definitions.

Taking into account the conclusions presented above indicates the following:

- The definition of the concept of radio navigation should be as general as possible and it can be possible to assign true or false values, in a logical sense, to such a sentence.
- It is not justified to list the areas of application of RNSs in the definition, as it is very difficult, if not practically impossible, to list them all.
- Although position determination is found across all the definitions of the term radio navigation, it is not true that RNSs only serve the purpose of determining position.
- The definition of radio navigation should be consistent with that of navigation, for which exactly the same phenomenon is observed: different definitions can be found in various documents of global organisations and scientific publications. This is an issue to be discussed in a separate paper.

4. Conclusions

The paper discusses two concepts important for navigation: radio navigation and RNS. This study has shown that there are large discrepancies in the definition of the term 'radio navigation' in publications of international organisations, such as IALA, ICAO, IMO or ITU. As these definitions are lexical, it must be possible to assign true and false values to them and that is why it is very difficult, if not practically impossible, to list all of them when defining areas of application of radio waves in navigation.

The definition of the concept of radio navigation proposed in this paper reflects its essence and it is a true sentence (in a logical sense). On this basis, the RNS classification is made. Since it is extremely difficult to list all the applications of navigation using radio waves, the presented RNS classification, which is the author's position, should start a discussion on this issue.

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