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MarRINav – Maritime Resilience and Integrity in Navigation
Work Package 1 – Maritime Context and Requirements v2.0 (Section 8 updated)

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<th>Date</th>
<th>Author</th>
<th>Reason for change</th>
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## Document Information

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<th>Section</th>
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<tbody>
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Executive Summary

This document is the output deliverable D1 of Work Package 1 – Maritime Requirements and Context of the MarRINav project.

The aim of WP1 was to establish just how dependent shipping, port and port hinterland operations are on GNSS (and PNT information in general) and so the potential impact of GNSS vulnerabilities. It builds on previous work by the General Lighthouse Authorities of the United Kingdom and Ireland (GLA) plus the London Economics report [1]. A variety of shipping, ports, applications and operations are included in the investigation, ensuring that the whole diverse ecosystem of maritime and associated activities is represented along the entire shipping logistics chain from ocean to port hinterland. This summary report identifies the reliance of maritime and port Critical National Infrastructure (CNI) on Global Navigation Satellite Systems (GNSS), the most prevalent of which is the United States’ Global Positioning System (GPS), informing UK Government actions in addressing Recommendation 1 of the Blackett Report:

‘Operators of CNI should review their reliance on GNSS, whether direct or through other GNSS-dependent systems, and report it to the lead government department for their sector. The Cabinet Office should assess overall dependence of CNI on GNSS’

This work package captures and analyses the maritime context for future CNI in the timeframe to 2030. Stakeholders and actors are identified and stakeholder requirements gathered, encompassing as wide a variety of maritime operations and applications as possible including those applicable to General Navigation (ocean, coastal, port approach voyage phases.), e-Navigation, autonomous vessels, the Blue Economy, port/pilot operations at sea and the land/sea interface.

The work draws upon information available within GLA strategy documentation, including the GLA Marine Navigation Plan [2], and other documentation that describes maritime applications in sufficient detail for analysis.

Implications for Resilient PNT systems and their supporting data communications infrastructure, including the Maritime Connectivity Platform (MCP) and VHF Data Exchange System (VDES), are considered against the identified requirements.

In summary, the report introduces the concepts of maritime resilience and integrity, outlines the stakeholders involved from a maritime perspective and draws upon IMO and other documentation to identify functional, non-functional and performance related technical requirements for Resilient PNT. In regard to performance level requirements the focus is on the four commonly used Required Navigation Performance (RNP) parameters **accuracy, integrity, availability** and **continuity**; and each of these terms is defined from a maritime perspective.

The document’s main aim is to present the maritime requirements and context for the work of the other work packages of the project and any subsequent follow-on Phases. Maritime
Context is presented from several points of view, including maritime Critical National Infrastructure (CNI) which encompasses vessels, ports, systems, aids to navigation etc. We consider the evolution of the core source of PNT, multi-constellation, multi-frequency GNSS, and identify sources of policy regarding this from GLA and Department for Transport strategy documentation to the wider European perspective of the European Radionavigation Plan (ERNP).

We identify the overall need for resilient PNT from the point of view of the dependence of the maritime domain on GNSS as sole means provision of PNT information. The European Radionavigation Plan clearly states that even the provision of the multi-constellation and multi-frequency GNSS of the future, a complementary backup is still required.

The aim for MarRINav WP1 is to understand where PNT information, primarily derived from GNSS, is used within the maritime activities and applications undertaken aboard ship and within shore-side support systems and services, for example Vessel Traffic Service (VTS) and Port Collaborative Decision making (PCDM), through to port and pilot operations at sea, and the land side of the port/sea interface. We also identify, where applicable, the Required Navigation Performance (RNP) parameter values for those activities in terms of accuracy, integrity, continuity and availability.

We begin by considering the requirements and context from the point of view of the human being on the bridge of the ship, and draw upon the International Chamber of Shipping’s Bridge Procedure Guide including aspects of voyage planning and execution to understand the procedures and the systems employed by the mariner in determining position and navigating the vessel. A useful method of eliciting requirements is to employ scenarios in order to determine Use Cases.

MarRINav employs the scenario of a single cargo container travelling aboard a large cargo container vessel from mid-ocean to berth in a UK port. We identify all of the electronic systems aboard ship that employ PNT information, and then the scenario is segmented into a number of activities. During each activity PNT information will be used by a particular subset of the total equipment aboard ship; these are the PNT Use Cases. In this way we break down the PNT requirements from General Navigation (Ocean, Coastal and Port Approach voyage phases) through to port phase, berthing and manoeuvring, and finally the PNT requirements for unloading the cargo container and moving the container through the port to the exit gate on the trailer of a truck.

We also consider the above scenario from the point of view of upcoming technology including the rise of autonomy; Maritime Autonomous Surface Ships (MASS) and automated port systems and e-Navigation.

In addition, we identify existing and emerging applications developed to protect the maritime environment and its resources (known as the Blue Economy) that employ PNT information. We consider the geographical diversity of those applications around the coastline of the UK and Ireland and note the requirement to provide adequate coverage of those applications, in terms of the RNP parameters, with whatever mix of Resilient PNT systems is to be provided.
Another geographically related requirement is to consider the degree of risk of collision and grounding based on the analysis of historic marine traffic flow information. For these geographical requirements we introduce the idea of the MarRINav Geographical Information System (GIS), and freely available GIS shapefiles together with the overlaid output of coverage performance prediction software developed by the GLAs.

Once we are satisfied that we have sufficiently captured the requirements, we will be able to determine what mix of backup and complementary PNT systems can provide Resilient PNT, with sufficient performance, for those activities and applications. This will be the subject of the later work of the project.
Contents

Table of Contents

Glossary

1 Introduction

1.1 Context

1.1.1 Maritime CNI
1.1.2 Resource Management and Control
1.1.3 Situational Awareness
1.1.4 Resilient PNT
1.1.5 Robust Communication
1.1.6 User Interfaces

1.2 PNT in the Maritime Context

1.3 The Mariner – The Human Context

1.4 The Provision of Maritime Aids to Navigation

1.5 The Overarching Needs for Resilience and Integrity in PNT Provision

2 Definitions

2.1 Accuracy
2.2 Availability
2.3 Integrity
2.3.1 User Level Integrity
2.4 Continuity
2.5 Resilience

3 Technical Rationale and Context

3.1 GNSS – The Core, Primary Source of PNT
3.1.1 GNSS Augmentation systems

3.1.2 Timing - The ‘T’ in ‘PNT’
3.2 VHF Data Exchange System (VDES) 52

3.3 e-Navigation 53
   3.3.1 The Service Based Approach 55
   3.3.2 The e-Navigation System-of-Systems 56
   3.3.3 Potential Users of e-Navigation and Their High-Level Needs 58
   3.3.4 e-Navigation’s Service Orientated Architecture 60
   3.3.5 The Maritime Connectivity Platform 62
   3.3.6 e-Navigation Services 64
   3.3.7 Roadmap Summary 65
   3.3.8 Example Maritime Services (in the Context of e-Navigation) and Requirements for PNT Information 66

3.4 Autonomous Vessels 74
   3.4.1 Regulatory Work 75
   3.4.2 Example Project - MUNIN 77

3.5 The IMO’s Multi-system Receiver 78

3.6 Integrity Threats and Mitigations 80

3.7 Sources of Resilience 81

3.8 Harmonisation 82

4 PNT Information in Use Aboard Ship and Ashore 83

4.1 Systems Aboard Ship that Use PNT Information 84
   4.1.1 The Maritime GNSS Receiver and Regulatory Context 84
   4.1.2 ECDIS 84
   4.1.3 GMDSS 86
   4.1.4 Voyage Data Recorder (VDR) 91
   4.1.5 Gyrocompass 92
   4.1.6 Radar 93
   4.1.7 Engine Management 94
   4.1.8 Satellite communications – VSAT, Inmarsat etc. 94
   4.1.9 Dynamic Positioning systems 94
   4.1.10 VHF Data Exchange System (VDES) 95
   4.1.11 Hydrographic Surveying Equipment 96
   4.1.12 Heli-deck Stability Monitoring 96
   4.1.13 Pilot’s Portable Pilot Unit (PPU) 96
   4.1.14 Oil Discharge Monitoring Equipment (ODME) 97
   4.1.15 Ballast Water Discharge Management System (BDM) 97
   4.1.16 Ship’s Clocks and Other Uses of Time Aboard Ship 97
   4.1.17 Track Control System 98
   4.1.18 NAVTEX 98
   4.1.19 The Use of Timing Information 99

4.2 Systems and Services Ashore that Use PNT Information 101
   4.2.1 AIS Service 101
   4.2.2 Vessel Traffic Services (VTS) 102
4.2.3 Ship Reporting Systems
4.2.4 Port Collaborative Decision Making (PCDM)
4.2.5 Vessel Monitoring System (VMS)
4.2.6 Consolidated European Reporting System (CERS)
4.2.7 SafeSeaNet (SSN)
4.2.8 Mobile AtoN Marking
4.2.9 Floating Aid to Navigation (AtoN) Monitoring

5 Systems and Equipment Aboard Ship that are currently Perceived as a Backup

5.1 Visual Techniques
5.2 Radar
  5.2.1 Radar Parallel Indexing
5.3 The Gyrocompass
5.4 Magnetic Compass
5.5 Speed log
5.6 Inertial Navigation Systems
5.7 Sextant and Other Celestial Systems

6 Requirements Capture

6.1 Introduction
6.2 Requirements Gathering Process
  6.2.1 Requirements Software Tools
6.3 Stakeholders
6.4 Sources of Requirements
  6.4.1 International Maritime Organisation (IMO)
  6.4.2 IALA
  6.4.3 European Radio Navigation Plan (ERNP)
  6.4.4 GLA Marine Navigation Plan
  6.4.5 DfT Strategy

7 User Requirements for (Resilient) PNT

7.1 The Organisation of User Requirements
7.2 User Applications (or Use Cases)
  7.2.1 General Navigation
  7.2.2 e-Navigation
  7.2.3 Autonomous/Unmanned Vessels
  7.2.4 The Blue Economy

8 The Scenario and Use Cases

8.1 Passage Planning
  8.1.1 Appraisal
8.1.2 Planning
8.1.3 Execution and Monitoring

8.2 The Scenario – Large Container Vessel Executing a Passage Plan
8.2.1 Introduction
8.2.2 Ocean Voyage Phase
8.2.3 Coastal Voyage Phase
8.2.4 Port Approach Voyage Phase
8.2.5 Port Phase
8.2.6 Example - Port and Pilot Operations Use Cases

8.3 Port Shore-side Container Operations
8.3.1 Container Handling Equipment
8.3.2 Position Information in Ports
8.3.3 GNSS Outages at Ports and The Effects
8.3.4 Summary

9 Summary and Conclusions

10 Reference Documents

Appendix A – General Operational Requirements

Appendix B – Maritime Required Navigation Performance Requirements from IMO A.915

Appendix C – IMO’s Maritime Services in the Context of e-Navigation
Glossary

ACU - Antenna Control Unit
AGCS - Allianz Global Corporate and Speciality
AI - Artificial Intelligence
AIS - Automatic Identification System
ANS - Autonomous Navigation System
API - Application Programming Interface
ARPA - Automatic Radar Plotting Aid
ASM - Application Specific Messages
ATA - Actual Time of Arrival
ATD - Actual Time of Departure
AtoN - Aids-to-Navigation
BDM - Business Development Management
BDSBAS - BeiDou Satellite-Based Augmentation System
BEIS - Department for Business, Energy and Industrial Strategy
BIS - Business, Innovation and Skills
C4ISR - Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance
CSI - Command, Control, Communications, Computers, Collaboration, and Intelligence
CAF - Cost of Averting a Fatality
CATZOC - Category Zone of Confidence
CBA - Cost Benefit Analysis
CCS - Carbon Capture Storage
CDF - Cumulative Distribution Function
CDMA - Code Division Multiple Access
CERS - Consolidated European Reporting System
CHC - Canadian Helicopter Corporation
CHE - Container Handling Equipment
CIRM - Comité International Radio-Maritime
CMDS - Common Maritime Data Structure
C/No - Carrier to Noise Ratio
CNI - Critical National Infrastructure
COG - Course Over Ground
COLREGS - Convention on the International Regulations for the Prevention of Collisions at Sea
CORS - Continuously Operating Reference Stations
COSPAS-SARSAT - Cosmicheskaya Sisteyama Poiska Avariynich Sudov - Search and Rescue-Satellite-Aided Tracking
CPA - Closest Point of Approach
CW - Coastal Waters (or Continuous Wave in radio technology)
DFT - Department for Transport
DGPS - Differential Global Positioning Systems
DNP - Digital Nautical Publication
DNV - Det Norske Veritas
<table>
<thead>
<tr>
<th>Abbreviation</th>
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</tr>
</thead>
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<td>Data Processing</td>
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<td>DP</td>
<td>Dynamic Positioning</td>
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<td>DSC</td>
<td>Digital Selective Calling</td>
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<td>EC</td>
<td>European Commission</td>
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<td>ECA</td>
<td>Emission Control Areas</td>
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<td>ECDIS</td>
<td>Electronic Chart Display and Information System</td>
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<td>ECSs</td>
<td>Electronic Chart Systems</td>
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<td>EDAS</td>
<td>EGNOS Data Access Service</td>
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<td>EEZ</td>
<td>Exclusive Economic Zone</td>
</tr>
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<td>EGNOS</td>
<td>European Geostationary Navigation Overlay Service</td>
</tr>
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<td>ELT</td>
<td>Emergency Locator Transmitters</td>
</tr>
<tr>
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<td>European Maritime Safety Agency</td>
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<td>ENC</td>
<td>Electronic Navigational Charts</td>
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<td>EPD</td>
<td>e-Navigation Prototype Display</td>
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<td>EPIRB</td>
<td>Electronic Position Indicating Radio Beacon</td>
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<td>ERNP</td>
<td>European Radionavigation Plan</td>
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<td>ESA</td>
<td>European Space Agency</td>
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<td>ESSP</td>
<td>European Satellite Service Provider</td>
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<td>ETA</td>
<td>Estimated Time of Arrival</td>
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<td>ETD</td>
<td>Estimated Time of Departure</td>
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<td>EU</td>
<td>European Union</td>
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<td>EU SWD</td>
<td>European Union Staff Working Document</td>
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<td>FD/E</td>
<td>Fault Detection and Exclusion</td>
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<td>FDMA</td>
<td>Frequency Division Multiple Access</td>
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<td>FLNG</td>
<td>Floating Liquefied Natural Gas</td>
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<td>FOC</td>
<td>Full Operational Capacity</td>
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<td>FPSOs</td>
<td>Floating Production and Storage Vessels</td>
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<td>FSRU</td>
<td>Floating Storage Regasification Unit</td>
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<td>FSU</td>
<td>Floating Storage Unit</td>
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<td>GAGAN</td>
<td>Geo-Augmented Navigation</td>
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<td>GBAS</td>
<td>Ground Based Augmentation Systems</td>
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<td>GDPR</td>
<td>General Data Protection Regulation</td>
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<td>GI</td>
<td>Geospatial Information</td>
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<td>Geographical Information System</td>
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<td>GLA</td>
<td>General Lighthouse Authorities of the UK and Ireland</td>
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<td>GLONASS</td>
<td>Globalnaya Navigazionnaya Sputnikovaya Sistema (or Global Navigation Satellite System)</td>
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<td>GMDSS</td>
<td>Global Maritime Distress and Safety System</td>
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<td>GMSK</td>
<td>Gaussian Minimum Shift Keying</td>
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<td>GNSS</td>
<td>Global Navigation Satellite System</td>
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<td>GPS</td>
<td>Global Positioning System</td>
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<td>GSA</td>
<td>European GNSS Agency</td>
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<td>GVA</td>
<td>Gross Value Added</td>
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<tr>
<td>HAL</td>
<td>Horizon Alert Limit</td>
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<td>HCA</td>
<td>Helideck Certification Agency</td>
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<tr>
<td>HF</td>
<td>High Frequency</td>
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HMI Hazardously Misleading Information
HMS Helideck Monitoring System
HPL Horizontal Protection Level
IALA International Association of Marine Aids to Navigation and Lighthouse Authorities
IAMSAR International Aeronautical and Maritime Search and Rescue Manual
IBPL Isotropy Based Protection Level
ICAO International Civil Aviation Organisation
ICT Information and Communications Technology
IEC International Electrotechnical Commission
IHMA International Harbour Masters Association
IHO International Hydrographic Organisation
IMO International Maritime Organisation
IMU Inertial Measurement Unit
INS Integrated Navigation System
INTL International
IP Internet Protocol (or Intellectual Property)
IS Information Service
IT Information Technology
ITU International Telecommunications Union
ITZ Inter-Tidal Zone
IWRAP IALA Waterway Risk Assessment Program
KASS Korean Augmentation Satellite System
KML Keyhole Markup Language
KRISO Korean Research Institute for Ships and Ocean
LAN Local Area Network
LEO Low-Earth Orbit
LIDAR Light Detection and Ranging
LNG Liquid Natural Gas
LOP Lines of Position
LPS Local Port Service
LRIT Long Range Information and Tracking
M-RAIM Maritime Receiver Autonomous Integrity Monitoring
MAAS Maritime Autonomous Surface Ships
MAIB Maritime Accident Investigation Board
MARPOL MARitime POLution
MAS Maritime Assistance Service
MASRWG Maritime Autonomous Ship Regulatory Working Group
MASS Maritime Autonomous Surface Ships
MAtoN Mobile Aids-to-Navigation
MBE Member of the Order of the British Empire
MCA Maritime Coastguard Agency
MCC Maritime Connectivity Consortium
MCP Maritime Connectivity Platform
MF Medium Frequency
MFMC Multi-Frequency Multi-Constellation
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<td>MF R-Mode</td>
<td>Medium Frequency Ranging-Mode</td>
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<td>MIR</td>
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<td>MMS</td>
<td>Maritime Messaging Service</td>
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<td>MMSI</td>
<td>Maritime Mobile Service Identity</td>
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<td>MOPS</td>
<td>Minimum Operational Performance Standards</td>
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<td>MPA</td>
<td>Marine Protected Area</td>
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<td>MRCC</td>
<td>Maritime Rescue Co-ordination Centre</td>
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<td>MSA</td>
<td>Merchant Shipping Act</td>
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<tr>
<td>MSAS</td>
<td>Multi-function Satellite Augmentation System</td>
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<td>MSC</td>
<td>Maritime Safety Committee</td>
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<td>MSF</td>
<td>Three letter code designation of the UK National Physical Laboratory’s radio time signal broadcast from Anthorn, Cumbria, UK</td>
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<td>MSI</td>
<td>Maritime Safety Information Service</td>
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<td>MSPD</td>
<td>European Commission’s Maritime Spatial Planning Directive</td>
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<tr>
<td>MSR</td>
<td>Multi System Receiver</td>
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<td>MSR</td>
<td>Maritime Service Registry</td>
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<tr>
<td>MTBF</td>
<td>Mean Time Between Failure</td>
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<td>MTTR</td>
<td>Mean Time To Repair</td>
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<td>MUNIN</td>
<td>Maritime Unmanned Navigation through Intelligence in Networks</td>
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<td>MUSES</td>
<td>European Union’s Multi-Uses in European Seas project</td>
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<td>NACE</td>
<td>Nomenclature statistique des activies economiques dans la Communauté Européenne</td>
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<td>NAS</td>
<td>Navigational Assistance Service</td>
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<tr>
<td>NAVAREA</td>
<td>Geographic areas in which various governments are responsible for navigation and weather warnings</td>
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<td>NAVTEX</td>
<td>Navigational Telex</td>
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<td>NLOS</td>
<td>Non-line of Sight</td>
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<td>NM</td>
<td>nautical mile</td>
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<td>NM</td>
<td>Notices to Mariners</td>
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<td>Notices to Mariners Temporary &amp; Preliminary</td>
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<tr>
<td>NMEA</td>
<td>National Marine Electronics Association</td>
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<td>National Oceanography Centre</td>
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<td>National Physical Laboratory</td>
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<td>National Time Centre</td>
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<td>Ocean Data Acquisition System</td>
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<td>Oil Discharge Monitoring Equipment</td>
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<td>OECD</td>
<td>Organisation for Economic Co-operation and Development</td>
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<td>OOW</td>
<td>Officer of the Watch</td>
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<td>OSC</td>
<td>On Scene Coordinator</td>
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<td>OSPAR</td>
<td>Oslo/Paris convention for the protection of the marine environment of the North East Atlantic</td>
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<td>PC</td>
<td>Personal Computer</td>
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<td>PCDM</td>
<td>Port Collaborative Decision Making</td>
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<td>PCZ</td>
<td>Pollution Control Zone</td>
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<td>PEC</td>
<td>Pilotage Exemption Certificate</td>
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<td>Abbreviation</td>
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<td>PLA</td>
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<td>PLBs</td>
<td>Personal Location Beacons</td>
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<td>PNT</td>
<td>Position, Navigation, and Timing</td>
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<td>PPM</td>
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<td>Portable Pilot Unit</td>
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<td>Particularly Sensitive Sea Areas</td>
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<td>REZ</td>
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<td>Radio Frequency</td>
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<td>RIMS</td>
<td>Reference and Integrity Monitoring Stations</td>
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<td>Radio Image Overlay</td>
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<td>RMG</td>
<td>Rail Mounted Gantry crane</td>
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<td>RNC</td>
<td>Raster Navigation Charts</td>
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<td>RNP</td>
<td>Required Navigation Performance</td>
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<td>Roll on-Roll off</td>
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<td>RPM</td>
<td>Revolutions Per Minute</td>
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<td>Resilient Position, Navigation and Timing</td>
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<td>RTCM</td>
<td>Radio Technical Commission for Maritime Services</td>
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<td>RTG</td>
<td>Rubber Tyred Gantry crane</td>
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<td>RTK</td>
<td>Real Time Kinematic</td>
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<td>Receiver Time Synchronisation</td>
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<td>Search and Rescue</td>
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<td>Standards and Recommended Practices</td>
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<td>Search and Rescue Transponders</td>
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<td>System for Differential Correction and Monitoring</td>
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<td>Submarine EPIRBs</td>
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<td>Service Oriented Architecture</td>
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<td>Safety of Life at Sea</td>
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<td>Service Simulator</td>
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<td>Ship Security Alert System</td>
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<td>SafeSeaNet</td>
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<td>Standards of Training Certification and Watch-keeping</td>
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<td>STM</td>
<td>Sea Traffic Management</td>
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<tr>
<td>STS</td>
<td>Ship To Ship or Ship To Shore</td>
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<tr>
<td>STW</td>
<td>Speed Through Water</td>
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<td>Twenty-foot Equivalent Units</td>
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<td>Telemedical Assistance Service</td>
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<td>Terminal Operating System</td>
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<td>Traffic Organisation Service</td>
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<td>Traffic Separation Scheme</td>
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<td>Time To Alarm</td>
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<td>TW</td>
<td>Territorial Waters</td>
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<td>TWSTFT</td>
<td>Two Way Satellite Time and Frequency Transfer</td>
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<td>UK Civil Aviation Authority</td>
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<td>United Kingdom Marine Accident Investigation Branch</td>
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<td>UKC</td>
<td>Under Keel Clearance</td>
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<td>ULCV</td>
<td>Ultra Large Container Vessel</td>
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<td>UML</td>
<td>Unified Modelling Language</td>
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<td>UN</td>
<td>United Nations</td>
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<td>UNCTAD</td>
<td>United Nations Conference in Trad and Development</td>
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<td>UNEP TEEB</td>
<td>United Nations Environment Programme - The Economics of Ecosystems and Biodiversity</td>
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<td>United States Federal Radionavigation Plan</td>
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<td>United States National Transportation Safety Board</td>
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<td>USV</td>
<td>Unmanned Surface Vessel</td>
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<td>Coordinated Universal Time</td>
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<td>VHF Data Exchange</td>
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<td>VHF Data Exchange System</td>
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<td>Voyage Data Recorder</td>
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<td>Very High Frequency</td>
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<td>VMS</td>
<td>Vessel Monitoring System</td>
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<td>VOCT</td>
<td>Vessel Operational Coordination Tool</td>
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<td>VSAT</td>
<td>Very Small Aperture terminal</td>
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<td>Vessel Traffic Monitoring Directive</td>
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<td>WAAS</td>
<td>Wide Area Augmentation System</td>
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<tr>
<td>WETREP</td>
<td>Western European Tanker Reporting System</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>WFD</td>
<td>European Union’s Water Framework Directive</td>
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<td>WP</td>
<td>Work Package</td>
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<td>WRC</td>
<td>World Radiocommunication Conference</td>
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<td>WWNWS</td>
<td>World-Wide Navigational Warning Service</td>
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<td>WWRNS</td>
<td>World-Wide Radionavigation System</td>
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<tr>
<td>XTD</td>
<td>cross track distance</td>
</tr>
<tr>
<td>XTE</td>
<td>cross track error</td>
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</table>
1 Introduction

This document is the output deliverable D1 of Work Package 1 – Maritime Requirements and Context of the MarRINav project.

The aim of WP1 was to establish just how dependent shipping, port and port hinterland operations are on GNSS (and PNT information in general) and so the potential impact of GNSS vulnerabilities. It builds on previous work by the GLA plus the London Economics report [1].

A variety of shipping, ports, applications and operations are included in the investigation, ensuring that the whole diverse system of maritime and associated activities is represented. This summary report identifies the reliance of maritime and port Critical National Infrastructure (CNI) on GNSS informing UK Government actions in addressing Recommendation 1 of the Blackett Report [3]:

‘Operators of CNI should review their reliance on GNSS, whether direct or through other GNSS-dependent systems, and report it to the lead government department for their sector. The Cabinet Office should assess overall dependence of CNI on GNSS’

This work package captures and analyses the maritime context for future CNI in the timeframe of 2030. Stakeholders and actors are identified and stakeholder requirements gathered, encompassing as wide a variety of maritime operations and applications as possible including those applicable to General Navigation (ocean, coastal, port approach voyage phases.), e-Navigation, autonomous vessels, the Blue Economy, port/pilot operations at sea and the land/sea interface.

The work draws upon information available within GLA strategy documentation, including the GLA Marine Navigation Plan, and other documentation that describes maritime applications in sufficient detail for analysis.

Implications for Resilient PNT systems and their supporting data communications infrastructure, considering the benefits of the Maritime Connectivity Platform (MCP) and VHF Data Exchange System (VDES), are considered against the identified requirements.

In summary then the report introduces the concepts of maritime resilience and integrity, outlines the stakeholders involved from a maritime perspective and draws upon IMO and other documentation to identify functional, non-functional and performance related technical requirements. In regard to performance level requirements the focus is on the four commonly used Required Navigation Performance (RNP) parameters accuracy, integrity, availability and continuity; and each of these terms is defined from a maritime perspective.

We begin by establishing the maritime context as outlined in the original project proposal, and this is then expanded upon further.
1.1 Context

The improvement of Infrastructures (sic) is one of the seventeen UN Sustainable Development Goals [4] which includes statements such as:

‘We will adopt policies which increase... sustainable transport systems; and quality and resilient infrastructure’

The most recent 3 year report [5] assesses world progress against these goals. These global goals referenced in the UNCTAD Review of Maritime Transport for 2017 and 2018 [6] [7] and as such member states are given a mandate to improve their Infrastructures. For example, the 2018 report states:

‘Enhancing port and terminal performance in all market segments is increasingly recognized as critical for port planning, investment and strategic positioning, as well as for meeting globally established sustainability benchmarks and objectives such as the Sustainable Development Goals. Ports and their stakeholders, including operators, users and Governments, should collaborate to identify and enable key levers for improving port productivity, profitability and operational efficiencies.’

Critical National Infrastructure in the UK covers a number of elements of Maritime Trade, each needing resilience and Integrity. In Figure 1 the relationship between underlying elements of Maritime CNI is presented as a logical Venn type diagram to illustrate the interactions involved. As can be seen all elements considered overlap in some ways and this larger underlying picture provides some context in which MarRINav, although not addressing everything, can operate.
Figure 1 – Maritime CNI Context.

A brief explanation of some elements of the diagram in Figure 1 is provided as follows:

1.1.1 Maritime CNI

This is the overall concept and encompasses all items involved in Maritime activities including vessels, ports, systems, aids to navigation etc.

This Infrastructure will form part of the overall Critical National Infrastructure, for which the inner boxes have possible wider application beyond Maritime, covering all transport modes, services and systems, some of which will also be critical.

1.1.2 Resource Management and Control

Resource Management and Control is associated with C4ISR and C5I concepts and these may be mutually inclusive, depending on the scenario. Derived from knowledge of resource situation and the users’ intent, it is necessary to formulate plans and, by controlling information, enable these to be executed. This will also need to adapt to dynamically changing circumstances.
1.1.3 Situational Awareness

The Situational Awareness layer includes users and intelligent systems having knowledge of status and resources of vessels and ports (including forward prediction). It is necessary to form a clear and unambiguous picture of the past, current and expected state and function of the elements comprising the Maritime facilities. This will be underpinned by the identified PNT capabilities that MarRINav will particularly address.

1.1.4 Resilient PNT

A key contributor to Situational Awareness is Resilient PNT that must robustly provide continuity of correct information (integrity) concerning where, when and how to proceed to all entities. Indeed, Resilience and Integrity (R&I) of PNT is fundamental throughout this diagram. There is an endeavour recognised by the MarRINav project to make sure all information is true and all exchanges are suitably protected to appropriate threat levels.

The Resilient PNT, Robust Communication, User Interfaces overlap area acknowledges a high degree of commonality of PNT/Communication/User Interface functions, for example:

- Conveyance of R&I information for PNT to users and user equipment via PNT signals
- Use of data channels on terrestrial PNT systems to support their application (e.g., eLoran)
- Potential use of communication bearers for ranging (e.g., Ranging Mode on DGPS marine beacon Medium Frequency transmissions) as a component of multilateration.

1.1.5 Robust Communication

Communication provides means for PNT information to be distributed and Command and Control to be exercised hence it overlaps these areas. Without a means of exchanging information between entities it is not possible to exercise Management and Control of the situation and its effectiveness for any co-ordinated action will be minimal. This will impact many areas, not least safety and efficiency. Communication needs, therefore, to be dependable and robust, itself with high resilience and integrity. The extension of Robust Communication to Resource Management and Control acknowledges that part of it can be used for messaging between various resources. This will become important in the future context of e-Navigation and the Maritime Connectivity Platform (MCP).

1.1.6 User Interfaces

These will be many-fold and diverse, ranging from electronic bridge systems, Port Community Systems (PCS), links to complex systems such as those for coordinated decision making (PortCDM) in integrated logistics through to hand-held devices (e.g., Portable Pilot Units). They are the necessary portals for interaction with many types of maritime system elements in which awareness of the quality and resilience of underlying PNT information will be of crucial importance to human users and autonomous systems.
1.2 PNT in the Maritime Context

GNSS has become ubiquitous in the maritime domain both for safety and business-critical professional applications and for non-critical leisure use. The maritime sector was one of the early professional adopters of GNSS, which has become its principal source of position, navigation and timing (PNT) information. Maritime requirements for GNSS were among the first to be formally proposed and adopted at an international level. They now cover a wide range of maritime applications, though not all. Further, there is a continuing debate about the validity of some of the current standards such as IMO recommendation A.915, which at time of writing was adopted 17 years ago and drafted more than 20 years ago. Standards will need to evolve and expand to encompass new applications, notably marine autonomous systems including autonomous vessels, and e-Navigation. In addition, standards should also be updated to reflect the vast changes to the GNSS signal in space over the past 20 years - more constellations, more signals, better clocks, better monitoring networks.

The current standards are maritime-only and so do not encompass the multi-modal integration of services and applications as goods flow from the sea, through a port, to the hinterland. Standards will also need to expand to support any improved efficiency and effectiveness of this vital logistics supply chain.

The two most important PNT performance parameters for critical maritime applications are Integrity (at the user level) and Resilience. While Integrity is rather well defined (by reference to an “alert limit” and a “confidence interval”), resilience is not.

1.3 The Mariner – The Human Context

What do we mean by “The Mariner”? For our purposes we mean the human bridge team aboard a vessel or, in the age of autonomy, at a remote operations centre. The team has numerous duties in ensuring the safe passage of a vessel. Procedures aboard the ship’s bridge are well documented by the International Chamber of Shipping in its Bridge Procedures Guide document [8], and it is with reference to that document that we describe herein the duties of the mariner, in particular the Officer of the Watch (OOW), as part of the bridge team.

Later on in this report we introduce The Scenario, for requirements capture purposes, which describes a large cargo container vessel making way from mid-ocean to its berth at a destination port and a single container being unloaded from the vessel and transported through the port to the port gate. Our PNT requirements capture will be posed within the framework of that scenario for the purposes of breaking up the requirements into the various PNT related activities (or Use Cases) that take place during the various voyage phases within which the vessel operates.

In parallel we consider the scenario in the human context of the “Passage Plan” – the information required to be gathered by the Master of the vessel, before the vessel departs its origin port, encompassing routing, safety, environmental considerations, sailing directions, port information, charting, weather routing, requirements for ship reporting, among other things. We introduce the Passage Plan in Section 8.1, but further detail can be found in [8]. It
is the responsibility of the OOW to monitor and execute this Passage Plan (or seek guidance on modification of the plan) throughout the vessel’s voyage in the absence of the Master’s presence on the bridge.

The bridge team should be sufficiently resourced and trained to meet the operational requirements of the passage plan. When considering the composition of the Bridge Team and ensuring that the bridge is never left unattended at sea, the Master should take into account the following:

- Visibility, sea state and weather conditions
- Traffic density
- Activities occurring in the area in which the ship is navigating
- Navigation in or near traffic separation schemes or other routeing measures
- Navigation in or near fixed and mobile installations
- Ship operating requirements, activities and anticipated manoeuvres
- Operational status of bridge equipment including alarm systems
- Whether manual or automatic steering is anticipated
- Any demands on the navigational watch that may arise as a result of exceptional circumstances
- Any other relevant standard, procedure or guideline relating to watch keeping arrangements or the activities of the vessel

Figure 1 shows an example of the general construction of the Bridge Team.

The OOW is the Master’s representative and is responsible at all times for the safe navigation of the ship in full compliance with the Convention on the International Regulations for the Prevention of Collisions at Sea (COLREGSs). Under the Standards of Training Certification and Watch-keeping (STCW) Code, the OOW may, in certain circumstances, be the sole look-out in daylight conditions. Note that the Helmsman (although “looking out of the window” cannot also be the look-out.
The primary duty of the OOW is to maintain a safe navigational watch at sea or at anchor, which will require ensuring:

- Compliance with the Company’s navigational policies and requirements
- Effective watch handovers
- Management of the Bridge Team
- Keeping a proper lookout
- Familiarity with the bridge layout and equipment
- Familiarity with bridge procedures
- Maintaining situational awareness
- Surveillance of the ship
- Execution of the passage plan
- Navigation and control of the vessel
- Collision avoidance in compliance with the COLREGSs
- GMDSS watchkeeping
- Compliance with environmental requirements
- Monitoring the performance of navigational equipment
- Recording bridge activities
- Management of emergency situations
- Security awareness

Further details of the OOW’s duties will be described in the context of the Scenario later on in this report, but it is clear that there is much to do on a busy ship’s bridge!

The Bridge Procedure Guide was first published in 1977, however, it is still widely acknowledged that the majority of collisions and groundings at sea have human error as a contributory factor – and the costs associated with these accidents are rising each year. There
are numerous examples where subsequent investigation and analysis has suggested that accidents might have been avoided, had there been appropriate input to the navigational decision-making process. Despite advances in bridge resource management training, it is evident that many watch-keeping officers make critical decisions for navigation and collision avoidance in isolation [9]. This is almost entirely due to reduced manning and can result in insufficient assessment of the situation, poor or no look-out and the lack of good watch-keeping practices.

IMO principles on the human element stipulate that in the process of developing regulations, it must be recognised that adequate safeguards must be in place to ensure that a “single person error” will not cause an accident through the application of such regulations. A UK Marine Accident Investigation Branch (MAIB) study has found that a check on the decision-making process on board can improve human reliability by a factor of 10. This calls for well-designed on-board systems and close cooperation with Vessel Traffic Management (VTM) systems ashore.

In 2006, seven IMO Member States made a join submission to the Maritime Safety Committee to “develop a strategic vision for the utilisation of existing and new navigational tools, in particular electronic tools, in a holistic and systematic manner”.

That strategic vision became the e-Navigation concept.

1.4 The Provision of Maritime Aids to Navigation

The mariner is supported in his/her navigational duties by a system of international maritime regulations and standards, including the provision of marine Aids to Navigation (AtoN). The Governments of the UK and Ireland are signatories to the IMO’s Safety of Life at Sea (SOLAS) Convention with the associated obligations, inter alia:

“...provide...such aids-to-navigation as the volume of traffic justifies and the degree of risk requires...”
“...take into account the international recommendations and guidelines...”
“...arrange for information relating to Aids to Navigation to be made available to all concerned...”

Through the Merchant Shipping Act (MSA) and other legislation, the UK and Irish Governments have empowered the GLA to meet their AtoN obligations under the SOLAS Convention and to carry out other functions in relation to wrecks. Individual ports provide their own AtoN. The GLA and port responsibilities apply equally to all types of mariner and vessels: from the highly trained professional navigator on-board large, sophisticated ships through to the amateur leisure user sailing small boats. Although the precise institutional arrangements for provision of AtoN vary from country-to-country, the same basic principles and obligations apply through IMO membership.

Traditionally the AtoN provided for use by mariners have been based on the establishment, operation and maintenance of infrastructure comprising a mix of visual and electronic
facilities, such as lighthouses, buoys, radar beacons (racons) and the differential GPS system (DGPS). As shipping is a worldwide activity, standardisation and global interoperability are critical requirements for AtoN provision and operation.

Standardisation of AtoN is performed at supranational level, with development coordinated principally through IALA, the International Association of Marine Aids to Navigation and Lighthouse Authorities. The IMO is the governing body setting on-board carriage requirements, while IALA has the role of harmonising onshore infrastructure and AtoN.

The International Telecommunication Union (ITU) allocates the global radio frequency spectrum and develops technical standards for information and communications technology (ICT), applicable to maritime communications/navigation.

The International Hydrographic Organisation (IHO) coordinates standards for nautical charts, hydrographic documents and maritime data, including Maritime Safety Information (MSI).

The Radio Technical Commission for Maritime Services (RTCM) and the International Electrotechnical Commission (IEC) are tasked with technical standardisation and type-approval of equipment.

Comité International Radio-Maritime (CIRM), the international association for marine electronics companies, promotes the application of electronic technology to the safety of life and efficient conduct of vessels at sea, representing the global base of equipment suppliers/manufacturers.

1.5 The Overarching Needs for Resilience and Integrity in PNT Provision

There are several points to consider when analysing the need for resilient PNT and the AtoN that provide and support it.

1.5.1 GNSS is not just used for plotting a position on a chart

GNSS has become the principal (and often the only) aid to navigation for ships. It is not, however, a system solely used for plotting the ship’s location on an electronic chart. An oft-quoted paraphrase that “any mariner worth his salt should be able to navigate without GPS” is somewhat misplaced when talking within the context of a modern vessel.

On most large modern vessels GNSS is integrated deeply within multiple digital systems on the bridge and wider ship’s systems, not only in portraying the vessel’s position and motion on the screen of the Electronic Chart Display and Information System (ECDIS). Other systems aboard ship, and ashore, present and future, depend on the provision of automatic, electronic position, navigation and timing solutions derived from GNSS. These include:

- Global Maritime Distress and Safety System (GMDSS), including its components:
  - Automatic Identification System (AIS)
  - Long Range Information and Tracking (LRIT) system
Digital Selective Calling (DSC) on MF, HF and VHF communications
Electronic Position Indicating Radio Beacon (EPIRB) – a GNSS receiver may or may not be included to speed up beacon location and thus Search and Rescue Response
Search and Rescue Transponders (SART) - a GNSS receiver may or may not be included to speed up beacon location and thus Search and Rescue Response
Satellite Earth Stations (SES) aboard ship
- Vessel Traffic Service (VTS)
- Port Collaborative Decision Making (PCDM), including just-in-time arrival logistics
- Ship Security Alert System (SSAS)
- Voyage Data Recorder (VDR)
- Vessel Monitoring System (VMS)
- Gyro compass
- Radar
- Consolidated European Reporting System (CERS)
- Vessel Traffic Monitoring supported by the European Vessel Traffic Monitoring Directive
- SafeSeaNet (SSN)
- Engine Management
- Satellite communications – VSAT, Inmarsat etc.
- Dynamic Positioning systems
- The upcoming VHF Data Exchange System (VDES)
- Hydrographic surveying
- Heli-deck stabilisation
- Pilot’s Portable Pilot Unit (PPU)
- Oil Discharge Monitoring Equipment (ODME)
- Ballast Water Discharge Management (BDM)
- Ship Security Alert System (SSAS)
- Ship’s clocks
- Floating Aid to Navigation (AtoN) monitoring
- Mobile AtoN marking
- e-Navigation
- Track Control System
- NAVTEX

These will be further expanded upon in Section 4.

1.5.2 The GNSS radio signal is weak

Unfortunately, all GNSS are vulnerable to unintentional RF interference, solar weather events, intentional jamming and spoofing because of their low received signal strength and their need to share the same radio frequency bands. Jamming trials [10] [11] at sea have demonstrated the complete failure of multiple systems aboard ships when GNSS is denied, creating numerous alarms from the various systems whose GNSS input is affected. A more insidious effect occurs when a GNSS receiver is interfered with so that it delivers hazardously misleading
information (HMI) – positioning information that is incorrect, it is not obvious that it is incorrect and the mariner is not informed that it is incorrect. Not only does this have a serious impact on safety, but it may have extremely costly implications for the flow of goods, including potential economic loss and environmental damage.

1.5.3 UK sea areas are busy and complex

Traffic complexity and density is increasing in many areas. Figure 3 shows the traffic traversing the Dover Straits in the summer of 2018.

![Figure 3](image)

Figure 3 – 28 days’ worth of AIS data showing example traffic density in the region of the southern North Sea, Dover Strait, and Eastern part of the English Channel. *Courtesy Trinity House, Director of Navigational Requirements, ANATEC analysis.*

Not only does Figure 3 show the complexity of the traffic, with many crossing and convergence points, it also shows how well-defined and dense the ships’ tracks have become (darker lines equate to more vessels). Vessels follow the most economically advantageous route, taking distance, weather and other factors into account. Often this route is also the least environmentally damaging as it is based on minimum fuel burn, for financial reasons. This means that the majority of vessels are concentrated on the same track with little lateral divergence. In busy areas of dense track, vessels will also follow each other closely; in the Dover Straits, for example, the spacing between vessels has reduced to very low margins, placing greater reliance on accurate navigation and automated systems to avoid collisions. Offshore wind generation capacity has increased by a factor of eight around the UK over the past 10 years (Figure 4). The capacity of wave and tidal power generation is small relative to that of wind but has risen by a factor of 37 over the same period.
Figure 4: Evolution of UK offshore renewable energy generation. Source: Table 6.4 of [12].

Figure 5 shows the location of actual and planned wind farms, many of which can be seen to be in areas of high traffic density, further increasing traffic complexity and affecting navigation requirements. Although not increasing at the same rate as offshore renewables, there is a considerable amount of oil and gas related infrastructure situated in the North Sea, again sometimes interacting with high density shipping lanes.
Finally, Figure 6 shows the location of marine protected areas (MPA), illustrating that these are not only situated in coastal regions, but also in the high seas. See Figure 47 later on for an illustration of the combined effect of all the offshore installations and other restrictions on the freedom of maritime navigation.
1.5.4 Ships are getting bigger and more numerous

Currently 95% of goods are transported by sea, and trends in the maritime sector are driving change in navigation requirements.

Ship size is increasing; for example, the container vessel OOCL Hong Kong (Figure 7) has a capacity of 21,413 twenty-foot equivalent units (TEU), is approximately 400 m long and 60 m wide. The cruise ship Harmony of the Seas is 361 m long and 226,000 Gross Tonnes. On average, the size of container vessels has increased by 32% since 2011. Over the same period, the average increase in size of tankers and bulk carriers has been 30% and 11% respectively. Figure 7 illustrates the increase in size in container ships over the past 50 years.

Figure 6: Marine protected areas [14].
It is thought this increase in ship size, together with a larger the global fleet, will result in a doubling of seaborne trade by 2030 [16]. With reduced sea-space, as outlined above, there will likely be an increase in the need for management of sea traffic, and the associated requirement for resilient and high integrity position reporting.

**Figure 8 – The Marco Polo is 396m long and can carry 16,000 TEUs.**

1.5.5 The Development of e-Navigation

To meet the increasing navigation challenges outlined above and to take advantage of digital technology, the IMO has developed its e-Navigation strategy for the benefit of maritime safety, security and protection of the marine environment, reducing the administrative burden and increasing the efficiency of maritime trade and transport. e-Navigation is defined by the IMO [17] and IALA as:
'The harmonised collection, integration, exchange, presentation and analysis of maritime information onboard and ashore by electronic means to enhance berth to berth navigation and related services, for safety and security at sea and protection of the marine environment.'

The IMO SIP [18] clearly states that “Position fixing systems will need to be provided that meet user needs in terms of accuracy, integrity, reliability and system redundancy in accordance with the level of risk and volume of traffic”

e-Navigation will be presented in more detail in Section 3.3.

1.5.6 The Drive for More Efficient Ports

The need for resilient PNT does not end once the ship reaches port. It is a key enabler for multiple elements of the logistics chain from crane control for loading and unloading ships, through container handling and tracking within the port, to vehicle fleet management in the hinterland. Close integration of vessel, port and land transport operations is becoming vital in supporting the efficient and seamless flow of goods internationally. There will therefore be increased reliance on smart multimodal information services for coordinated decision support, through such initiatives as Port Collaborative Decision Making (PCDM) [19]. The aim will be to increase safety, reduce congestion, increase efficiency, improve environmental protection and reduce emissions.

1.5.7 The dawn of the autonomous ship

Maritime Autonomous Surface Ships (MASS) are nearing reality. Such vessels will be guided by automated on-board decision systems, controlled and monitored by a remote operator (shore station), who may be in charge of an entire fleet of such vessels.

Figure 9 – The Yara Birkland is expected to be in operation in 2020, and will be the world’s first autonomous ship. Picture courtesy www.yara.com.
Yara Birkeland [20] is the world’s first autonomous and zero-emission container vessel (Figure 9), aimed for launch in 2020. Initially Yara Birkeland will be manned, but will move to fully autonomous operation by 2022. The 120 TEU-capacity vessel will incorporate a ballast-free design and run on battery power. The vessel will be deployed on routes between its Yara’s fertiliser plant at Porsgrunn and the ports of Brevik (to the south) and Larvik (to the south-east). The ship will replace 40,000 truck journeys a year completely removing harmful emissions and improving safety on Norway’s roads.

1.5.8 Cross-sector considerations

Vulnerability of GNSS is not just a maritime problem. This same vulnerability is found throughout many sectors of Critical National Infrastructure (CNI), for example land-mobile, aviation, power distribution and monitoring, communications, as has been clearly set out in the recent UK Blackett Report [3].
2 Definitions

No project on resilience and integrity can begin without at least some form of definition of these two terms. In this section we attempt a definition of these and other important concepts specifically for the maritime domain; there may very well be alternative definitions for other domains and sectors, for example land mobile, aviation and timing.

The four most important concepts to be defined when specifying performance requirements and assessing the performance of a maritime navigation system are the Required Navigation Performance (RNP) parameters: accuracy, availability, integrity and continuity; and so we begin with those.

2.1 Accuracy

According to the IMO [21] accuracy is the degree of conformance between the estimated or measured parameter of a vessel at a given time and its true value at that time. In the context of navigation parameters may be position co-ordinates, velocity, time, angle etc. There are several types of accuracy:

Predictable Accuracy – also called Absolute, Geographic, or Geodetic accuracy is the accuracy of a position estimate with respect to the geographic or geodetic co-ordinates of the Earth. In performance measurement trials absolute accuracy is typically measured with reference to a ground truth (the true position), with geographic latitude and longitude referenced to a reference ellipsoid, a mathematical model of the earth. WGS-84 (World Geodetic System - 1984) is the reference ellipsoid used in GPS; differences between this and other reference ellipsoids are usually published but for some applications are so minor that equivalence to WGS-84 can be shown. For our work we will use WGS-84.

Relative Accuracy – The accuracy with which a user can determine position relative to that of another user of the same navigation system at the same time.

Repeatable Accuracy – The accuracy with which a user can return to a position whose co-ordinates have been measured at a previous time using uncorrelated measurements from the same navigation system.

For the purposes of MarRINav Absolute Accuracy will be used. An accuracy requirement states the average accuracy across all conditions that the navigation system must meet and is typically expressed as 95% bounds for the radial horizontal (and vertical) position errors; in other words the position errors that must not be exceeded more than 5% of the time.

In a navigation system there are two main components of position (and velocity) error in whatever system is being used to determine a navigation solution; bias and variance. Variance is sometimes also referred to as “noise”. Bias is an offset from the mean position solution affecting predictable accuracy, whereas variance or noise determines the scatter around that biased solution and is therefore a component of repeatable accuracy.
The left hand side of Figure 10 shows a scatter plot of position solutions from a radionavigation system. The central red dot shows the location of ground truth, the actual location of, say, a radionavigation system’s receiver antenna. The blue dots are the computed positions, which are scattered around the central true location, due to the variances of the pseudorange measurements. Such variances are caused by signal propagation effects, local interference, atmospheric noise, multipath, transmitter and receiver timing errors. Looking closely we can see that the scatter plot is slightly biased to the west of the true position, bias effects are typically due to unaccounted for propagation delays, signal and receiver timing offsets.

Some examples of how these biases and variances manifest themselves in various types of navigation system include:

1. Biases and variances in the input pseudorange measurements from radionavigation systems from which the position solution is computed;
2. Biases and variances in the bearing and ranging measurements made by radar;
3. Biases and variances in heading, and axis alignment errors, in accelerometers and gyroscopes.

The accuracy performance of the system is determined by forming the cumulative distribution function (CDF) of the position errors and identifying the 95‘%ile value as shown on the right hand side of the plot.

Figure 10 – Example scatter plot illustrating bias, variance and the method of computing accuracy.

### 2.2 Availability

Availability is the percentage of time that system or device is performing its function as required under stated conditions. Non-availability can be caused by scheduled and/or unscheduled interruptions. Signal availability is the availability of a radio signal in a specified coverage area. System availability is the availability of a system to a user, including signal availability and the performance of the user’s receiver.
Traditionally we can represent availability mathematically as:

$$A = \frac{MTBF}{(MTTR + MTBF)}$$

Where $MTTR^1$ is the Mean Time To Repair and $MTBF^2$ is Mean Time Between Failure. $A$ is usually expressed as a percentage and the figure is computed over a period of 2 years.

Availability must include the capability to provide a position solution with integrity.

### 2.3 Integrity

The IMO [21] defines integrity as: The ability to provide users with warnings within a specified time when the system should not be used for navigation.

Integrity is provided through *integrity monitoring*, which is the process of determining whether the system performance (or individual observations) allows use for navigation purposes.

Integrity monitoring can be:

- *Internal integrity monitoring* – integrity monitoring performed within the receivers (and possibly other systems) aboard the vessel – this can also be referred to as *user level* integrity, and this important concept is presented further below.

- *External integrity monitoring* – sometimes also referred to as *infrastructure based* integrity monitoring, or *system integrity* – integrity monitoring provided by external stations or other parts of the service provider side of the system, for example RIMS (Reference and Integrity Monitoring Stations) in EGNOS. GNSS satellite health status messages are also an example of the provision of *system integrity*. Infrastructure based integrity monitoring monitors the integrity of certain signals at the monitor locations; it does not monitor the integrity of the vessel's position solution, so can never protect against all causes of HMI.

Integrity may be described by three parameters:

1. The *threshold value* (or alert limit) – the maximum allowable error in the measured position, or some other variable derived from positioning - during integrity monitoring – before an alarm is triggered.

---

1 Mean Time to Repair refers to the amount of time required to repair a system and restore it to full functionality.
2 Mean Time Between Failures measures the predicted time that passes between one previous failure of a system to the next failure during normal operation.
2. The **time to alarm** – the time elapsed between the occurrence of a failure in the system and its presentation on the user (the mariner on the bridge).

3. The **integrity risk** - the probability that a user will experience a position error larger than the threshold value without an alarm being raised within the specified time to alarm at any instant of time at any location in the coverage area of the service.

2.3.1 **User Level Integrity**

The concept of user-level integrity is that responsibility for determining the validity of a position-solution lies also with the user’s navigation receiver, not just the system. Figure 11. The level of position error considered intolerable is called the Horizontal Alert Limit (HAL).

![Diagram](image.png)

Figure 11 - Existing IMO requirements specify only the signal-in-space performance. Effects local to the user’s receiver are not in scope; they are therefore **system-level requirements** rather than **user-level**.

Each operation or application would have its own HAL requirement. The receiver is tasked with issuing an alert to the user should it determine that there is the possibility of a position fix with a position error that exceeds the HAL. Whether the HAL is breached or not is determined through modelling the accuracy of the position-solution, and monitoring for various potential failings that could affect the quality of the output fix, according to some **threat models**. Additional data from the system itself (GNSS, eLoran, LOCATA, STL, and potentially Dead Reckoning sensors) and/or any augmentation system may aid this determination, but the final decision is made by the user’s equipment. The receiver thus presents to the mariner a **yes or no** decision as to whether the navigation system can be trusted at any position fix.

If ever the algorithm determines that a fix should not be used, an alert should be issued to the user. Any fix for which the actual error exceeds the HAL, but is still declared usable, is referred to as Hazardously Misleading Information (HMI). The **integrity risk** requirement specifies a maximum probability of HMI over a nominal time-frame in order to limit the possibility of the equipment misleading the user.

Part of the integrity monitoring process will be to determine the validity of the yes/no decision by estimating the probability of HMI (or integrity risk) for each position-fix. In practice it can be a much tougher task to estimate integrity-risk than to provide the yes/no decision in the first place. Good algorithm design is essential to this process.
If the system determines that the probability of HMI on a position-fix is larger than the requirement then the fix cannot be trusted. In this case the receiver may output an ‘Integrity un-monitored’ alarm, or may err on the side of caution and provide the ‘do-not-use’ decision for that particular position-fix. We may use an intuitive ‘traffic light’ system to describe the output:

- **Red-Light** = a fault has been detected, do not use the fix.
- **Green-Light** = the fix is acceptable, and the integrity risk is within the requirement.
- **Yellow-Light** = the fix seems acceptable, but since integrity risk is not below the required level, this decision cannot be trusted. Use at own risk.

To avoid confusion the yellow-light condition may be replaced with a red-light ‘do-not-use’ warning. The algorithm’s “snapshot” risk per-epoch is related to the total risk over the given time-frame – an estimate of the correlation time of GNSS errors for example is used to relate individual epochs to the cumulative risk over a longer time-frame; for example a correlation time of 150 seconds is assumed for GPS as this is the figure adopted in aviation SBAS standards [22].

More details on user-level integrity will be provided in the Work Package 2 output deliverable in the context of the IMO’s multi-system receiver, including a discussion on RAIM (Receiver Autonomous Integrity Monitoring), and Fault Detection and Exclusion (FD/E), a method of detecting faults on ranging measurements and removing such faulted inputs. Indeed in the latter if a fault is detected and can be isolated and the new solution can be shown to meet the integrity requirements, then the fix is deemed acceptable. If no faults are detected, but there is insufficient information to verify that the solution meets the integrity requirements, then the fix is not acceptable. Where different ship subsystems have different PNT requirements, a fix can potentially be acceptable for some requirements and not for others.

### 2.4 Continuity

Continuity is the probability that a user will be able to determine a navigation solution with specified accuracy and is able to monitor the integrity of the determined solution over the (short) time interval applicable for a particular operation, within a limited part of the coverage area given that the solution is available at the start of the period. The original IMO definition assumes a fault-free receiver, however, for the sake of resilience, it is necessary to take into account knowledge of the probability of receiver faults when apportioning continuity budgets across the system.

In [21], the IMO state that continuity is a Service Level parameter – this is equivalent to saying “User Level”. Consider that continuity can be expressed as a Mean Time Between Failure (MTBF) recognising that:

\[
MTBF = \frac{1}{\text{Failure Rate}}
\]
Where Failure Rate can be expressed in terms of the continuity requirement, $R_C$, and time period over which continuity is determined, $T_C$, thus:

$$\text{Failure Rate} = \frac{1 - R_C}{T_C}$$

$$\text{MTBF} = \frac{T_C}{1 - R_C}$$

Thus for the IMO’s 99.97% (0.9997) continuity requirement over 3 hours we would expect the system to have an MTBF of 10,000 hours, or 1.14 years.

The IMO has now reduced $T_C$ to 15 minutes and now we have an MTBF of approximately 35 days.

However, [23] suggests a continuity requirement of 99.95% per 15 minutes, which gives an MTBF of 20 days.

This implies that the mariner should only expect to have his operation interrupted by a navigation system once every 20 days, however, it may be that the mariner is operating within a sea area, such as a port, where local effects like multipath, Non-Line Of Sight (NLOS) reception and interference create integrity alarms much more often than 20 days. We suggest that the continuity requirement as expressed in [21] is inconsistent with what is experienced by the mariner; Work Package 2 of MarRINav discusses continuity further.

The last paragraph eludes to the fact that an integrity alarm, whether true or false, is a continuity failure. When considering the assignment of continuity and integrity risk budgets to the various components of a navigation system it is important to understand that continuity and integrity are interlinked; they are not separate parameters and one RNP requirement cannot in fact be assigned to an application in isolation from the other. See also Table 3 later for Blue Economy operations where continuity is considered critical.
2.5 Resilience

Resilience is:

*The ability to anticipate, mitigate and recover from disruption.*

From a maritime perspective the activities of resilience includes:

1. The provision of a **user-level integrity** guarantee, which makes a position solution robust to any arbitrary fault, or disruption, likely to occur in the real world, e.g. cyber threat, space weather, deliberate jamming.

2. The provision of sufficient hold-over capability from alternative systems and sensors that the **continuity** guarantee is not undermined by loss of GNSS, for example due to an integrity-alert, jamming or interference.

Let us examine more closely what these two statements mean.

Point 1 of the definition talks about **user-level integrity**. As mentioned, this is the ability of the user to be provided with warnings of failure of the navigation system due to problems, faults or issues as seen by the user’s receiver at the point of use of the navigation system. Compare this to **system-level integrity**, which is the provision of such things as satellite health warnings, system wide error status messages and other information that informs the user community that there is an issue with the whole system or individual transmitters/satellites.

User-level integrity issues can include such things as local interference and jamming, the effects of multipath signals, non-line of sight propagation; effects that cause bias errors on the pseudorange measurements made by the user’s receiver. Should there be such user-level effects (and for that matter system-level effects), we would expect the receiver to inform the user about the problem, perhaps take some action to remove faulty measurements from the navigation solution, and maybe even fail over to an alternative navigation system.

The reason we would want the receiver to operate in this way is encompassed in Point 2 of the definition of Resilience, and is the **fundamental rationale for Resilient PNT**. The maritime stakeholder would like to **continue** his or her operation, whether that operation is bringing a vessel into port, laying an electricity transmission cable, engaging in a search and rescue operation, positioning a navigation buoy or unloading cargo containers, to list several examples. **ALL** of these applications rely on the **continued** existence of a PNT signal.

For true resilience, requirements need to be specified at the **user-level**, not the **system-level**, but proving that a system, or system of systems, can meet those user-level requirements can be very difficult, if not impossible. This is because so much evidence, in the form of measurement data, is required to adequately model the probabilistic nature of threats and hazards to integrity and continuity – for example, the effect of multipath propagation of radionavigation signals. This important point is missing from the IMO requirements but they are the best requirements available and they will serve as a starting point for further analysis. In practice, a set of standard simulator-based tests would have to be specified that the system is expected to meet.
In Work Package 3 we will show that the IMO RNP requirements should refer to a PNT system-of-systems comprising a core GNSS system AND a resilient PNT system. The continuity and integrity risk budgets of these two main system components can be much higher (less conservative) than if we consider them as requiring to meet the RNP requirements individually.

2.6 The Interdependence of the RNP Parameters

It is important to bear in mind that the RNP parameters from a user perspective (user level) are interdependent with a hierarchy shown in Figure 12 [23]. Positioning accuracy is the basic performance parameter (and is usually the easiest to model and demonstrate). Integrity depends on the accuracy requirement compared to the actual accuracy demonstrated by the system in operation, either under normal un-faulted operation or faulted; continuity depends both on accuracy and integrity; while availability means the availability of both accuracy and integrity.

![Figure 12 – Dependency and hierarchy of RNP parameters. Source: [23].](image)

By comparison, system-level integrity (health flags and status alarms), that is integrity not determined at the user level by the user’s receiver, is less dependent on the probabilistic (noise like) nature of the accuracy of the system as seen by the user.

As mentioned at the end of Section 2.4 Continuity and Integrity are deeply intertwined – the requirements and the statistical processes that define them need to be mutually compatible. The navigation-solution is considered usable only if accompanied by the green-light integrity guarantee. Mariners wish to see the green-light preserved for a long enough time to allow them to do their job safely. A stipulation is made that the probability of losing the green-light each epoch is kept to a very low figure to maximise the usability of the system – thus maximising continuity. The probability of a switch to the red-light condition each epoch has to be quite precisely controlled by the receiver to preserve user-level continuity.
Part of the integrity-monitoring process to detect possible HMI is to set detection thresholds. A detection threshold is set such that if it is breached an integrity alarm is raised. Various parameters may be used to detect faults, such as the range-residuals produced from a position solution, or the separation between fixes found using different sub-sets of pseudorange measurements. If the fault-detection threshold is set low then even small errors trigger detection and HMI is very unlikely, however alarms will be frequent and perhaps raised unnecessarily – these would be false-alarms, which also of course cause dis-continuity events.

As a priority, continuity should be preserved by raising detection thresholds such that false-alarm probability is tightly controlled. Setting thresholds too high guarantees good continuity, but at the cost of faults not being detected – increasing the probability of missed detection. Integrity and continuity are like either end of a see-saw, the trick is to establish the right balance through careful budgeting of both continuity and integrity risk probabilities. These budgets need to be agreed as part of the performance specification of any navigation system. As mentioned earlier this will be discussed further in Work Package 3.
3 Technical Rationale and Context

This section highlights some of the technical context around the work that will be considered within MarRINav.

3.1 GNSS – The Core, Primary Source of PNT

GNSS is at the core of e-Navigation. Currently, for a vast number of vessels, maritime GNSS is effectively the GPS L1 signal alone, but MarRINav needs to account for the capabilities provided by the multiple constellations that will be available in the near future as well as the enhancements that will be possible due to the provision of multi-frequency signals from these constellations. The availability of signals from the core constellations is illustrated in the diagrams that follow in the paragraphs below, which have been taken from the European Radionavigation Plan (ERNP) [24].

According to the ERNP the following are the technology roadmaps for the various GNSS. Note that the dates indicative and correct at the time of the publication of the ERNP and may have slipped to the right.

**GPS development roadmap**

GPS was recognised by IMO as a component of the World-Wide Radionavigation System (WWRNS) in 1996. The GPS Modernization Program will introduce three new signals designed for civilian use: L2C, L5, and L1C. The legacy civil signal, L1, will continue broadcasting in the future, as will the military L2 signal. GPS is expected to become a two-frequency system (L1 and L2C) at around the end of 2019 and a three-frequency system (L1, L2C and L5) by 2026. The evolution of GPS signal availability is illustrated in Figure 13.

![Figure 13: Availability of GPS signals. Source: ERNP.](image-url)

**GLONASS development roadmap**

GLONASS was recognised by IMO as a component of the WWRNS in 1996. GLONASS already broadcasts two signals, L1 and L2, using its traditional frequency division multiple access (FDMA) modulation scheme. There are currently some satellites broadcasting on a third frequency, L3, using code division multiple access (CDMA) modulation for improved compatibility with other core GNSS constellations. The first of a new generation of GLONASS
satellites broadcasting CDMA signals on L1 and L2 is expected to be launched in 2019, adding two new signals to the system, L1 C and L2 C. The L3 CDMA signal is expected to reach full operational capability (FOC) around 2023 and GLONASS will become a three-signal system, albeit mixed FDMA and CDMA modulation schemes. Two signals, L2 and L3, solely using CDMA will be available from around 2025.

The evolution of GLONASS signal availability is illustrated in Figure 14.

![Figure 14: Availability of GLONASS signals. Source: ERNP.](image)

**Galileo development roadmap**

Galileo is currently in its deployment phase and is expected to be fully deployed and operational in 2020. The satellites transmit signals in three frequencies, E1, E5 and E6. Galileo was recognised by IMO as a component of the WWRNS in 2016.

The evolution of Galileo signal availability is illustrated in Figure 15.

![Figure 15: Availability of Galileo signals. Source: ERNP.](image)

**Beidou development roadmap**

BeiDou, like Galileo, is still in its development phase. The satellites also transmit signals on three frequencies, B1, B2 and B3. The Chinese authorities plan to declare Full Operational Capability (FOC) for BeiDou in 2020. Up until FOC, Beidou is operating with a reduced constellation and its services only cover China. At FOC the constellation will be complete and it will provide global coverage. Beidou was recognised by IMO as a component of the WWRNS in 2014.
The evolution of Beidou signal availability is illustrated in Figure 16.

![Figure 16: Availability of Beidou signals. Source: ERNP.](image)

**Multi system shipborne receiver**

In June 2015, IMO’s Maritime Safety Committee adopted performance standards [25] for a multi-system shipborne radionavigation receiver (MSR) equipment to ensure that ships are provided with resilient position-fixing equipment suitable for use with available radionavigation systems throughout their voyage. The aim of the performance standard is to allow the combined use of current and future radionavigation as well as augmentation systems for the provision of position, velocity and time data within the maritime navigation system. The design and implementation of the optimum receiver autonomous integrity monitoring (RAIM) algorithm tailored to the maritime environment, will be a critical element of the development of the MSR.

Although, the performance standard for the MSR exists, there are challenges for receivers to be developed, not least the need for them to go through the maritime receiver standardisation process. There is currently no roadmap for the development of a true MSR.

3.1.1 GNSS Augmentation systems

3.1.1.1 Ground Based Augmentation Systems (GBAS)

The IALA marine radiobeacon Differential GNSS (DGNSS) system is the principal GNSS augmentation system used in the maritime sector. Figures Figure 17, Figure 18 and Figure 19 show the location of stations derived from the current IALA database, noting that some countries have not reported since 2014. These figures emphasise the ubiquity of the system.
Figure 17: Worldwide locations of operational IALA DGNSS stations. Source: IALA, e-Navigation Netherlands.

Figure 18: European locations of operational IALA DGNSS stations. Source: IALA, e-Navigation Netherlands.
Currently there is no roadmap for the future of the IALA DGNSS system. However, there are several considerations to be taken into account:

- In general, IALA DGNSS equipment was recapitalised around 2008-2012, based on guidance and recommendations from IALA (IALA Guideline 1060, recapitalisation of DGNSS, edition 2.0, June 2011). Based on the assumption of a 10-15-year life for the equipment, a further recapitalisation will be required in around five to 10 years.
- The IALA DGNSS equipment will require upgrade to provide augmentation to the multiple constellations and multiple frequencies that are due to come online from 2020 onwards.

### 3.1.1.2 Space Based Augmentation Systems (SBAS)

Much of the world is either covered, or planned, to be covered by SBAS systems:

- WAAS, commissioned in 2003, covers much of North America
- EGNOS, commissioned in 2011, covers western and central Europe and most of the Mediterranean
- The multi-function satellite augmentation system (MSAS, commissioned in 2007) and the quasi-zenith satellite system (QZSS – a non-geostationary system with services started in December 2018) covers Japan
- The GPS-aided geo-augmented navigation (GAGAN), commissioned in 2013, provides coverage of India
- The Russian system for differential correction and monitoring (SDCM) is currently under development and will provide global augmentation for GPS and GLONASS
- The BeiDou satellite-based augmentation system (BDSBA) will service China and its surrounding area and is planned for initial operation in 2020
- The Korean augmentation Satellite System (KASS) is planned for aviation use in South Korea by 2022
- Australia and New Zealand commenced work in 2018 on a multi-constellation, multi-frequency, second generation SBAS.

The coverage of these systems is illustrated in Figure 20.

![Global coverage of SBAS systems. Source: EGNOS safety of life, service definition document (SDD), European GNSS Agency.](image)

To ensure seamless interoperability for aviation, SBAS systems are designed to the same standards as defined by the International Civil Aviation Organisation (ICAO) standards and recommended practices (SARPs) and minimum operational performance standards (MOPS) defined by the Radio Technical Commission for Aeronautics (RTCA) [22]. SBAS service providers coordinate within an Interoperability Working Group to ensure continued interoperability.

These SBAS have been developed as aviation systems and, as far as is known, only EGNOS is being developed and considered for a dedicated maritime service. The roadmap for EGNOS maritime services is illustrated in Figure 21 below.
The EC maritime development of EGNOS is being progressed in three steps [26]:

- **Step 1**, where EGNOS is re-broadcast using IALA DGNSS beacons and/or the automatic identification system (AIS). EGNOS is provided to the re-transmitting station either via the signal-in-space or via ground links using the EGNOS Data Access Service (EDAS).

- **Step 2**, where EGNOS version 2 is designed to provide a safety service via the signal-in-space compliant with IMO Resolution A.1046 augmenting GPS on a single frequency (L1) and providing system level integrity (i.e. reporting GPS system failures). This service is very similar in scope (and performance) to that provided by the IALA DGPS system.

- **Step 3**, where EGNOS version 3 is designed to be a dual-frequency, multi-constellation safety service compliant with IMO Resolution A.915 augmenting both GPS and Galileo and providing a user-level integrity service (i.e. considering local factors such as multipath, shadowing and interference).

Whilst this European work has mostly been driven by requirements for European GNSS, they would be mirroring the requirements and implementation that could be performed worldwide.

### 3.1.2 Timing - The ‘T’ in ‘PNT’

Currently GPS is the *de facto* source of time and frequency used in maritime applications. From a resilience point of view, time therefore suffers from the same vulnerabilities as position and
navigation. The UK national time scale, UTC(NPL), is operated by the National Physical Laboratory and is disseminated to the user using the MSF radio time signal (accurate to approximately 1 ms), an Internet time service referred to as Precision Time Protocol (PTP), and the NPLTime® service for the financial sector.

Plans at NPL for a UK National Time Centre (NTC) are underway, although details are not yet entirely in the public domain. When implemented, the NTC will address the risk of a single point of failure for the UK time source. Currently, the high precision methods of time and frequency transfer, independent of GPS are achieved using two-way satellite time and frequency transfer (TWSTFT) or using dedicated optical fibres, so called “dark fibre”. Both methods are expensive in terms of hardware and service provision, and more affordable mechanisms are likely to be needed for general maritime use and to support the provision of Resilient PNT AtoN.

3.2 VHF Data Exchange System (VDES)

The VHF Data Exchange System (VDES) [27] is an effective and efficient use of radio spectrum, building on the capabilities of AIS and addressing the increasing requirements for data throughput. VDES is built on new techniques providing higher data rates than those used for AIS. The VDES network protocol is optimised for data communication so that each VDES message is transmitted with a high confidence of reception. VDES increases the capability for digital data exchange in a manner similar to AIS, which includes provision of data to vessels in a geographic area (broadcast), to a specific vessel or a group of vessels in a geographic area (addressed) or to a fleet of vessels (addressed). The roadmap for the introduction of VDES is illustrated in Figure 22.

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**Figure 22:** VDES implementation roadmap. Source: IALA Guideline G1117 VHF data exchange system (VDES) overview, 2017.
VDES is being introduced through the following phases [27]:

- (2016) AIS exists as defined by ITU.R M.1371-5 on the AIS frequencies, and Coastal Stations use the ASM and VDE frequencies for Voice VHF.

- (2017-2018) Post World Radiocommunication Conference (WRC)-15 - AIS+ASM: Regionally, where there is an urgent need for offloading significant ASM traffic from AIS, it is recommended to allow the introduction of 4-channel AIS + ASM devices. These devices may receive and transmit ASM on the ASM1 and ASM2 frequencies, but shall discontinue their transmit capability, using the existing GMSK modulation after January 1st 2019 unless a software upgrade enables them to participate in the modulation and access scheme agreed for the ASM frequencies. Note that the ASM frequencies will need to be shared with the VHF voice service from Coast Stations in many areas during this time frame.

- (2019) the WRC-19 will consider and decide regarding VDE-SAT.

- (2019-2020) Post WRC-19 operational capability established. Note that both the ASM and VDE frequencies may still need to be shared with the voice VHF service in many areas.

- (2021+) When a satellite service is developed, full operational capability of the VDES including the Satellite frequencies can be achieved.

3.3 e-Navigation

e-Navigation is IMO’s future digital concept for the maritime sector that responds to structural changes and will have a profound and long-term impact on the way the maritime sector operates. It is an International Maritime Organization (IMO) led concept based on the harmonisation of marine navigation systems and supporting shore services driven by user needs. The current definition [18] states that:

“e-Navigation is the harmonised collection, integration, exchange, presentation and analysis of maritime information onboard and ashore by electronic means to enhance berth to berth navigation and related services, for safety and security at sea and protection of the marine environment”

The e-Navigation concept also overlaps with the e-Maritime initiative developed by the European Commission [28]. The objective of the e-Maritime initiative is to promote:

“coherent, transparent, efficient and simplified solutions in support of cooperation, interoperability and consistency between member States, sectors, business and systems involved in the European Transport System”

It is foreseen that e-Navigation will provide new capabilities both to ship operations and to shore operations; some of these new capabilities will be explored later in this document. For ship operations e-Navigation will develop onboard navigation systems that benefit from the
integration of the ship’s own sensors, supporting information, a standard user interface, and a comprehensive system for managing guard zones and alerts – so called volumetric navigation [29]. Core technologies of such a system will include high integrity electronic positioning, e.g. multi-constellation, multi-frequency GNSS, with terrestrial backups, electronic Navigational Charts (ENC) and an analysis capability to reduce human error, actively engaging the mariner in the process of navigation while reducing distraction and overburdening.

On the shore side the management of vessel traffic and related services will be enhanced through better provision, co-ordination, and exchange of comprehensive data in formats that will be more easily understood (based on the Common Maritime Data Structure (CMDS), itself based on the International Hydrographic Office (IHO) S-100 format, and utilised by shore-based operators in support of vessel safety and efficiency. This is perceived as a major commercial benefit by port operators.

These e-Navigation capabilities will be underpinned by a communications infrastructure designed to enable authorised seamless information transfer onboard ship, between ships, between ship and shore and between shore authorities and other parties. The importance of this infrastructure cannot be overstated. The focus of the e-Navigation concept would appear to be oriented entirely at the end user and stakeholder benefits but in practice the task of making it work rests largely on the ability of the maritime community to develop a comprehensive, future proof communications architecture.

In 2008 IMO approved the development of an e-Navigation Strategy Implementation Plan (SIP). This includes the development of a technical architecture, gap analysis, cost benefit analysis and the creation of a detailed implementation plan. The SIP includes priorities for deliverables, a schedule for implementation and provision for the continual assessment of user needs. The architecture of e-Navigation encompasses hardware, data, information, communications technology and software.

The e-Navigation Strategy Implementation Plan (SIP) [18], which was approved at IMO Maritime Safety Committee (MSC) meeting number 94 in November 2014, contains a list of tasks required to be conducted in order to address five prioritized e-navigation solutions, namely:

- improved, harmonized and user-friendly bridge design;
- means for standardized and automated reporting;
- improved reliability, resilience and integrity of bridge equipment and navigation information;
- integration and presentation of available information in graphical displays received via communication equipment; and
- improved Communication of VTS Service Portfolio (not limited to VTS stations).

It is expected that these tasks, when completed, should provide the industry with harmonized information in order to start designing products and services to meet the e-navigation solutions.
3.3.1 The Service Based Approach

e-Navigation is based on the overarching architecture illustrated in Figure 23. This architecture is based on the Common Maritime Data Structure (CMDS) that spans the whole of the horizontal axis and the World Wide Radio Navigation System (WWRNS), which includes GNSS, GNSS augmentation and terrestrial backups.

As well as making the best use of digital technologies to the benefit of maritime transport, e-Navigation is moving the focus of AtoN providers from infrastructure operations and maintenance to the provision of services. IMO’s initial identification of services is provided in Annex C but it should be noted that the final set of e-Navigation services is likely to be much wider than this initial list.

A number of initiatives worldwide are building core e-Navigation technologies, and developing, prototyping and demonstrating e-Navigation services. These initiatives include:

- The EfficienSea2 project, led by the Danish Maritime Authority. This project ran for three years, finishing in April 2018. It had 32 partners from 12 countries and an overall budget of €11.5M. The overall aim was to create and implement innovative and smart solutions for efficient, safe and sustainable traffic at sea through improved connectivity for ships.
- The **Sea Traffic Management** (STM) series of projects, led by the Swedish Maritime Administration with 39 partners from 13 countries. STM ran from 2015 to 2018 and had a budget of €21M. STM’s aims were:
  - to enable efficient exchange of information between maritime stakeholders through common standards
  - establish a decentralised service ecosystem for ships, ports and authorities
  - facilitate secure and authenticated access to authorised parties.
- The **SMART-Navigation** project, funded by the Ministry of Oceans and Fisheries of the Republic of Korea. This project is running from 2016 through to 2020. This project is developing core technologies for e-Navigation services; developing an e-Navigation operating system and digital maritime communication and developing the maritime digital communications standard for e-Navigation.

Figure 24 illustrates STM’s set of services underpinned by secure, system-wide information management.

![Figure 24: STM services and infrastructure. Source:](https://www.stmvalidation.eu/image-gallery/)

### 3.3.2 The e-Navigation System-of-Systems

As a consequence of technological development and the move to a service-based rather than infrastructure-based philosophy, e-Navigation is based on a system-of-systems as illustrated in Figure 25.
This system-of-systems comprises:

- **Traditional visual AtoN**, such as lighthouses, buoys, beacons, etc. These are already in place and will continue to be required and operate for the foreseeable future.

- The **Maritime Connectivity Platform (MCP)**, which essentially serves as an “App Store”, pointing to the location of instances of the services that are advertised, and providing documentation on the specification and design of services for potential providers to implement. The MCP is described further fully in Section 3.3.5.

- **Resilient PNT**, as indicated by IMO, based on core multi-frequency multi-constellation (MFMC) GNSS, GNSS augmentation and terrestrial, complementary, back-up. The evolution of the core GNSS systems and augmentation systems as it is currently understood was described in Section 3.1. **The identification of the optimal suite of terrestrial back-up systems to provide resilience (and integrity) in PNT is MarRINav’s principal objective.**

- A **service portfolio**, derived from and building on the services identified by IMO (Annex C) and the e-Navigation projects, such as EfficienSea2, STM and SMART-navigation, introduced above. This service portfolio is just starting to emerge and will likely be developed continuously as new services emerge both to meet requirements (user pull) and to take advantage of technological advancement (technology push).
• The VHF Data Exchange System (VDES), which is a concept developed by IALA and the ITU, supported by the IMO, in order to:
  o overcome the capacity shortcomings of the Automatic Identification System (AIS)
  o provide data exchange capability to enable e-Navigation applications
  o support modernisation of the Global Maritime Distress and Safety System (GMDSS)
  o ensure the effective and efficient use of the maritime VHF band.
  The roadmap for the development of VDES was outlined in section 3.2.

• The data needed to support e-Navigation.

  e-Navigation will rely on resilient electronic position fixing for the location context based dissemination of information via a myriad of e-Navigation services. e-Navigation requires resilient and high integrity PNT because:

  • Vessels will obtain information pertinent only to their location, reducing workload and confusion on the bridge.

  • Information presented on evolved ECDIS will need to be portrayed correctly in the correct location relative to own ship and others.

  • e-Navigation is intended to assist in the reduction of crew, by limiting the workload of those crew members remaining.

  • e-Navigation will support the development of autonomy, including autonomous ships.

3.3.3 Potential Users of e-Navigation and Their High-Level Needs

User needs for e-Navigation can be found in [18], and are presented here for completeness.

3.3.3.1 Common Maritime Information Structure

Mariners require information pertaining to the planning and execution of voyages, the assessment of navigation risk and compliance with regulation. This information should be accessible from a single integrated system. Shore users require information pertaining to their maritime domain, including static and dynamic information on vessels and their voyages. This information should be provided in an internationally agreed common data structure format. Such a data structure is essential for the sharing of information amongst shore authorities on a regional and international basis. The IHO S-100 data format [30] has been adopted by the e-Navigation community to serve as the CMDs. Several data products have already been produced and are in the process of standardisation, for example the S-124 - Area Message data model has been developed to support e-Navigation services that provide Maritime Safety Information (MSI).
3.3.3.2 Automated and Standardised Reporting Functions

We have seen how the OOW is responsible for numerous activities as a member of the Bridge Team. One of the OOW’s responsibilities is ship reporting. e-Navigation should provide automated and standardized reporting functions for optimal communication of ship and voyage information. This includes safety-related information that is transmitted ashore, sent from shore to shipborne users and information pertaining to security and environmental protection to be communicated amongst all users. Reporting requirements should be automated or pre-prepared to the greatest extent possible both in terms of content and communications technology. Information exchange should be harmonised and simplified to reduce reporting requirements.

3.3.3.3 Effective and Robust Communications

A clear need was expressed for there to be an effective and robust means of communications for ship and shore users. Shore-based users require an effective means of communicating with vessels to facilitate safety, security and environmental protection and to provide operational information. To be effective, communication with and between vessels should make best use of audio visual aids and standard phrases to minimise linguistic challenges and distractions to operators.

e-Navigation includes the concept of seamless data communication, with the in-use physical electronic data communication system changing as and when systems come in and out of coverage. For example when moving from Coastal Voyage phase to Ocean phase we would expect e-Navigation data communication channels to change from those provided by relatively short range VDES, to the wider area coverage satellite based communications seamlessly with no interruption in the performance of the e-Navigation services.

3.3.3.4 Human Centred Presentation Needs

Navigation displays should be designed to clearly indicate risk and to optimise support or decision making. There is a need for an integrated “alert management system” as contained in the revised recommendation on performance standards for Integrated Navigation Systems (INS) [31]. Consideration should be given to the use of decision support systems that offer suggested responses to certain alerts, and the integration of navigation alerts on board ships within a whole ship alert management system. Users require uniform and consistent presentation and operation functionality to enhance the effectiveness of internationally standardised training, certification and familiarisation. All displays should be designed to limit the possibility of confusion and misinterpretation when sharing safety-related information.

3.3.3.5 Human Machine Interface

As electronic systems take on a greater role, facilities need to be developed for the capture and presentation of information from visual observations, as well as use knowledge and experience. The presentation of information for all users should be designed to reduce “single person errors” and enhance team operations. There is a clear need for the application of ergonomic principles both in the physical layout of equipment and in the use of light, colour,
symbology and language. Portrayal of digital information on user displays is part of the Product Specification for a digital Maritime Service in the context of e-Navigation.

### 3.3.3.6 Data and System Integrity

The IMO has made a clear statement that e-Navigation systems should be resilient and take into account issues of data validity, plausibility and integrity for the systems to be robust, reliable and dependable. Requirements for redundancy, particularly in relation to **position fixing systems**, should be considered.

The IMO Strategy Implementation Plan [18] states that:

“Position fixing systems will need to be provided that meet user needs in terms of accuracy, integrity, reliability and system redundancy in accordance with the level of risk and volume of traffic”

### 3.3.3.7 Analysis

e-Navigation systems should support good decision making, improve performance and prevent single person error. To do so, shipboard systems should include analysis functions that support the user in complying with regulations, voyage planning, risk assessment, and avoiding collisions and groundings including calculation of Under Keel Clearance (UKC) and air draughts. Shore-based systems should support environmental impact analysis, forward planning of vessel movements, hazard/risk assessment, reporting indicators and incident prevention. Consideration should also be given to the use of analysis for incident response and recovery, risk assessment and response planning, environment protection measures, incident detection and prevention, risk mitigation, preparedness, resource and asset management and communication.

### 3.3.4 e-Navigation’s Service Orientated Architecture

The digital Maritime Services developed under e-Navigation follow the principles of Service Oriented Architecture. e-Navigation is a distributed Service Oriented Approach (SOA) based Information Technology system. Services can be developed, published and advertised via a Yellow Pages type system called The Maritime Connectivity Platform (MCP). The MCP essentially serves as an “App Store”, pointing to the location of instances of the services that are advertised, and providing documentation on the specification and design of services for potential providers to implement.

Instances of services are typically hosted on servers **external** to the MCP. The MCP has no storage, however it eventually will contain a bespoke service, the Maritime Messaging Service (MMS), that allows agnostic and seamless data transfer between users of digital Maritime Services and contains a store and forward messaging system for times when actors are out of coverage of any of the multiple data communication systems. The use of the MMS would be optional, and service providers would be free to employ independent communications services instead, although the need for **resilience, authentication** and **security** should still be considered.
A number of mutually interacting parts of the e-Navigation architecture can be identified: 

**Shipboard technical infrastructure** - Shipboard communication, navigation and display and processing equipment is integrated to exchange information seamlessly, using harmonized data formats.

**Shore based technical infrastructure** - Shore based information is made available through harmonized data/information services. The architecture integrates a variety of shore-based technologies and data processing devices.

**Application-to-application (services)** - Data exchange via physical links ship-to-shore and shore-to-ship, and ship-to-ship.

**Communications** - A concept of generic communication links providing the logical connections that allow data/information flow between the shipboard and the shore based systems - or at a higher logical level: the people operating/using these systems. Communications may be aided by the Maritime Messaging Service of The Maritime Connectivity Platform. Communications is needed to be seamless and employs several different technologies depending on where the vessel is along its voyage. TCP/IP will be the main transport/network protocol employed but scope will be included to allow the use of non-IP related technologies.

**Common Maritime Data Structure (CMDS)** – The CMDS is a method by which data is modelled, and formatted in order to make data transfer interoperable and promote common understanding, among the various e-Navigation stakeholders, of the data structures involved in service specification, design, development and their subsequent implementation as instances (service endpoints). It is based on IHO S-100 and S-200 series Product Specification and Data Modelling. It provides standardised methods of information exchange between stakeholders (ships, VTS, AtoN providers, service providers). The International Hydrographic Office (IHO) Geospatial Information (GI) Registry (Figure 26) provides a common baseline for the CMDS, and provides the methods for producing Product Specifications based on standardised data models. The work of the IHO also considers the important aspect of portrayal of the results of services on maritime displays.
The IHO Geospatial Information (GI) Registry contains Product Specifications and Data Models that have been adopted by the e-Navigation community as the Common Maritime Data Structure for specifying services. Note that DNP = Digital nautical Publications.

**e-Navigation Services** – There are currently 16 groups of Maritime Services defined by the International Maritime Organisation (IMO) [4]. These are summarised in Annex C.

### 3.3.5 The Maritime Connectivity Platform

The Maritime Connectivity Platform (MCP) is a digital Information Technology (IT) framework consisting of standards, infrastructure and governance that facilitates secure interoperable information exchange between stakeholders in the maritime community by the principles of Service Oriented Architectures (SOA). The Maritime Connectivity concept is intended to face the demand for interoperability among existing and upcoming maritime systems and is being developed to establish “a communication framework, enabling efficient, secure, reliable and seamless electronic information exchange between all authorized maritime stakeholders across available communication systems”. 
The objective of the Maritime Connectivity Platform (MCP) is to provide a secure platform to enable maritime stakeholders to securely access technical services to gain further information for decision-making onboard and ashore during a voyage from berth-to-berth (Figure 27). The Maritime Connectivity Platform shall not be considered as a product but as a common communication framework for maritime users to register, discover, and use maritime services such as route optimization or weather forecast. Clients and Services communicate by standardized web service technologies supported by standard services to set up and facilitate the communication. The MCP does not host services, but points to where service consumers can find instances (or endpoints) of services.

The foundation for the technical concept of the MCP is based upon three main contributions as depicted in Figure 27 to enable and support service oriented communication:

1. The **Maritime Identity Registry (MIR)** - deals with managing users, vessels, devices and organizations as well as provide information to be used for controlling their access to resources within the MCP. Thus ensuring authentication of users and therefore assuring users of the trustworthiness of the source of information.

2. The **Maritime Service Registry (MSR)** - enables service providers to register the location of instances of their services and allows the end-user to discover and use those services, or developers to access specifications and designs and implement instances of the services.

3. The **Maritime Messaging Service (MMS)** enables transparent and seamless transfer of information across different communication links in a carrier agnostic and geolocation context sensitive manner.
The governance structure has been established for the MCP, via the Maritime Connectivity Platform Consortium (MCC), which is a follow-on from the Maritime Connectivity Platform Development Forum. The GLAs are members of the MCC with liaison taking place through their Research and Development directorate and their membership of the Board of the consortium.

Currently there is a test instance of the MCP running, and plans for the development of the first operational instance and ongoing operations are being made through the establishment of a number of Working Groups within the MCC. A Working Group on the Maritime Identity Registry (MIR) has been formed, and plans are underway to establish the same for the Maritime Service Registry (MSR). Work on the Maritime Messaging Service is being led by KRISO (the Korean Research Institute for Ships and Ocean).

More information about the Maritime Connectivity Platform can be found at https://maritimeconnectivity.net/.

3.3.6 e-Navigation Services

In the context of service-oriented architecture, a service usually refers to a set of related software functionalities that can be reused for different purposes together with policies that govern and control its usage. The MCP comprises a much broader scope that also includes services, which do not solely rely on machine-to-machine communication such as services delivered over telephone calls (voice or fax), email, websites, NAVTEX and other “primitive” solutions. The Maritime Service Registry may also be used to advertise these services; it does not provide actual maritime information but a specification of various services, the information they carry, and the technical means to obtain it. A Maritime Service Registry instance contains service specifications according to an envisaged Service Specification Standard and provisioned service instances implemented according to these service specifications.

A registered service always includes the following specifications:

1. **A service specification**, which describes one dedicated service (e.g. a weather service) at logical level.

2. **A technical design**, which follows the technology-agnostic service specification of a dedicated service and provides information about the actual realization of the service, so that a developer/service provider can develop software that implements the service.

3. **A service instance description**, which follows the specifications of (1) and (2) and contains the description of one specific implementation (or instance) of a service. The service instance description also contains the endpoint of the service, in other words where to access it.
Figure 28 – MCP usage concepts.

Figure 28 illustrates these concepts as used by various stakeholders.

The functionality of the Maritime Service Registry, as it is defined so far, can be separated into the two areas: service discovery and service management. The first objective of the MSR is to enable the discovery of a specific service. A service shall be discovered either via a human actor using the MCP Portal or via an artificial device such as an ECDIS. Services and service instances shall be searched via different criteria such as keywords, publishing organizations or combinations, locations and more, and may appear as a drop-down list at pertinent locations along a voyage plan.

The second objective of the Maritime Service Registry is service management. As seen in Figure 28, the management of a service encapsulates the functions to publish a service specification and register/publish a service instance. While publishing a service specification is handled by the service specification producer, following the envisaged service specification standard, the service implementer uses a service specification discovered in the MSR to implement a service instance. The service provider is consequently responsible for hosting a service instance and publishes the related service instance specification to the MSR.

3.3.7 Roadmap Summary

The development roadmaps for each of the systems within the e-Navigation system-of-systems (Figure 25) are overlaid in Figure 29.
The figure highlights some mismatches in timing and gaps for the development of the foundations needed to support e-Navigation:

- Around 2020, there will be three core constellation frequencies available from each of Galileo and Beidou, as well as two frequencies from GPS and GLONASS, albeit with the latter using FDMA rather than CDMA. However, there is no obvious plan to develop and certify an MSR, with suitable RAIM, to enable the maritime community to take advantage of these signals.

- The EGNOS V2 service will be available in early 2021 but will only provide augmentation for GPS on the L1 frequency and will only monitor the integrity of GPS, although signals will be available on multiple frequencies from multiple constellations at that time.

- Similarly, EGNOS V3 will be limited to augmentation of GPS and Galileo on L1/E1 and L5/E5 frequencies even though additional frequencies and constellations will be available.

- The IALA DGNSS system only augments GPS on the L1 frequency. There are no plans in place to further develop this system to augment multiple constellations on multiple frequencies. This is an item of work in the current IALA work plan, so this is an area under consideration and IALA is due to update related Recommendations and Guidelines later in 2019.

3.3.8 Example Maritime Services (in the Context of e-Navigation) and Requirements for PNT Information

A number of international projects have worked on developing prototype e-Navigation services. Some services have had their data products standardised by the IHO, but there is still ongoing development regarding the exact structure and methodology of e-Navigation. For
example, the Maritime Messaging Service, part of the MCP, is being worked upon by the SMART-navigation project in South Korea. A selection of these projects and the services of interest are captured in Table 1. A more comprehensive list of e-Navigation projects and testbeds is maintained by IALA [32].

The work of e-Navigation is international in its extent, and is intended to provide interoperability and scalability of the services.

Next, we consider three example e-Navigation services and outline how PNT is vital to their functioning, we consider:

1. Maritime Safety Information/Notice to Mariners service;
2. Tactical Route Suggestion service;
3. Vessel Operational Coordination Service for search and rescue operations.
### Table 1 – Some e-Navigation projects and testbeds.

<table>
<thead>
<tr>
<th>Project name</th>
<th>Web address</th>
<th>Information available</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACCSEAS</td>
<td><a href="http://www.iala-ais.org/products-projects/e-navigation/test-bedsprojects/accseas/">http://www.iala-ais.org/products-projects/e-navigation/test-bedsprojects/accseas/</a></td>
<td>Full details on the project. Reference documents for each service, including detailed descriptions and data formats, and use with the EPD. Videos of the demonstrated services are also available, which are a good start to understand what they can do.</td>
</tr>
<tr>
<td>ACCSEAS</td>
<td><a href="https://github.com/dma-enav/EPD">https://github.com/dma-enav/EPD</a></td>
<td>Open source software for the e-Navigation Prototype Display (EPD). The CAPITALS project may wish to re-use</td>
</tr>
<tr>
<td>EfficienSea2</td>
<td><a href="http://efficiensea2.org/">http://efficiensea2.org/</a></td>
<td>Project overview and reference documents.</td>
</tr>
<tr>
<td>STM Validation project</td>
<td>stmvalidation.eu</td>
<td>Various project information aspects related to Port Call information, time stamping data across the logistic chain, including vessels, port systems and vehicles.</td>
</tr>
<tr>
<td>SMART-Navigation</td>
<td><a href="http://www.smartnav.org">www.smartnav.org</a></td>
<td>A South Korean initiative, the work involves core technology development of e-Navigation, the development of e-Navigation operating system and digital maritime communications, in addition to ensuring harmonisation with e-Navigation international standards.</td>
</tr>
</tbody>
</table>

#### 3.3.8.1 Maritime Safety Information / Notice to Mariners Service

An approach to MSI-handling and promulgation has previously been tested in the EfficienSea project with promising results. As part of the ACCSEAS project it was decided to develop and test this concept further [33], and based on analysis and user feedback, to include other important maritime information, specifically temporary and preliminary Notices to Mariners (NM T&P), within an integrated service for authoring, storing and promulgating maritime information.

There are many similarities and few differences between MSI messages and NM T&P. They largely serve the same purpose, with the main differences being down to the speed and methods of promulgation.
The MSI-NM interchange format has been detailed in an S-100 product specification designated S-124.

The most important information for vessels is safety-related information, including Maritime Safety Information, Notices to Mariners and chart corrections. These three information types, along with nautical charts and position updates, form the basis for safe navigation at sea. **Maritime Safety Information (MSI)** is navigational and meteorological warnings, meteorological forecasts and other urgent safety-related messages.

**Notices to Mariners (NMs)** are promulgated in order to keep paper nautical charts and publications, as far as possible, up to date. Temporary and Preliminary NMs (T) and (P) advise mariners of important matters affecting navigational safety, including new hydrographic information (in advance of new editions or chart updates), changes to routing measures and aids to navigation, and other important categories of data. Not all ENCs include T&P information currently.

**Chart corrections** are corrections to paper and digital nautical charts which makes it possible for the Mariner to keep the vessel’s charts up to date.

Chart corrections and the way they are promulgated have evolved over time and are in many ways very different from traditional MSI and NM T&P today. Chart corrections are georeferenced and portrayable by nature. MSI and NM T&P are often georeferenced but not necessarily portrayable with text and symbols.

The main differences between MSI and NM today are the way of promulgation and speed of handling and thereby quality assurance. The content of the two message types are on the other hand more or less the same and they solve the same user need.

MSI is today promulgated in text or voice via SafetyNET, NAVTEX, coastal radio stations and is in some countries accessible on the Internet. NM T&P’s are promulgated on paper weekly, fortnightly or monthly and are often accessible on the internet in pdf format. In addition Hydrographic Offices are encouraged to include as many NM T&P’s in their ENC updates as possible. There are obvious benefits in this but also disadvantages and pitfalls.

As part of the ACCSEAS project, a combined model for MSI and NM T&P has been devised and a web application has been developed in order to effectively test the combined model, the portrayal and promulgation of the messages. The MSI-NM System include features such as:

- An editor for MSI and NM T&P messages;
- Multi-language message support and features such as rich-text descriptions, attachments, etc;
- Management of message life cycles and base data such as categories, areas, charts, etc;
- Promulgation via web services, mailing lists, Maritime Connectivity Platform Messaging Service (MMS), NAVTEX, Twitter, etc;
• Web interface and API’s for searching and filtering MSI-NM T&P messages;
• Map-based portrayal of MSI-NM T&P messages.

Furthermore, a navigational display test application, the e-Navigation Prototype Display (EPD), has been updated to integrate with the MSI-NM System.

The map-based portrayal of the MSI and NM messages is based on the portrayal devised in the earlier EfficienSea project, where integration of MSI in navigational charts was explored and input made to the International Electrotechnical Commission (IEC).

The magenta MSI symbol has been supplemented with an analogous NM symbol. Also, a cluster symbol has been chosen to represent a cluster of MSI and NM messages and may be used in order to avoid clutter in maps:

![Symbology used to portray MSI, NM and clusters of information on ECDIS.](image)

When the message location is given by a polygon, a polyline or a circle, the actual geographical shape will be used for portraying the message as shown in Figure 31.

![Area message or polygon.](image)

Figure 32 shows the symbol above displayed on a prototype of an electronic chart system, developed for ACCSEAS, that is capable of interfacing to e-Navigation services and display the results. The Korean SMART navigation has further developed this MSI service to include full integration into an ECDIS provided by Kongsberg.
3.3.8.2 Tactical Route Suggestion

Route exchange plays a central role in the effort of the maritime community to integrate e-Navigation tools in an all-embracing system that will contribute to enhanced navigational safety and reduce the burden on the navigator.

The Tactical Route Suggestion Service [34], developed and tested in the ACCSEAS project, is intended as a tool for VTS operators to effectively communicate route suggestions to vessels as a response to developing traffic situations or as navigation assistance (hence the term “tactical”, as opposed to planning-based strategic route service). Also, the service may be used by pilots, communicating their pilot plan to the vessel before boarding, and in Search and Rescue Operations.

The service is a supplement to traditional VHF voice communication, which is prone to misunderstandings due to language problems, lacking situation awareness, wrong interpretation of surroundings and human error.

The Tactical Route Suggestion Service has been implemented using the e-Navigation Prototype Display (EPD), and field tests involving ships and shore-side VTS centres have been conducted with promising results.

Other route exchange concepts, such as intended route broadcasting and dedicated search and rescue tools, have also been investigated in the ACCSEAS project. A strategic route
suggestion service, which focuses on the planning of routes, has been explored in the MONALISA-2 project.

**A Use Case**
The scenario for this type of service might look like this:

1. The VTS centre monitors the ships passing through its area. In addition to positional information provided by radar and AIS, this may include the intended routes for the ships (see Tactical Exchange of Intended Route, another ACCSEAS project service).

2. If a ship is seen to be heading towards shallow waters, the VTS operator selects a standard route from her list, and sends it to the ship along with an explanatory text.

3. The suggested route pops up on the ECDIS of the targeted ship. The OOW gets a choice of either accepting or rejecting the new route. He accepts the route and makes it his active, monitored route.

4. At the VTS centre, the navigational display shows that the suggested route has been accepted and adopted as the ships intended route.

As a real-life example, such a service could find use in the River Humber along the approaches to the port of Hull and Immingham. The river is under continual bathymetric survey and dredging due to the continuous shifting of the seabed. Approaching vessels are often directed by the VTS to avoid passage along a particular side of the approach channel in order to avoid dredgers and survey vessels or recently discovered hazards.

### 3.3.8.3 Vessel Operational Coordination Service for search and rescue operations

When a serious accident occurs at sea, human lives will be at risk. This might be an aircraft performing an emergency landing at sea, a vessel taking on water, a man overboard or a small boat lost during a storm.

In such incidents, a Search and Rescue (SAR) operation is initialized by the government with jurisdiction over the specific areas in which the accident has occurred. This operation helps to locate people and vessels at risk and to resolve the situation.

An SAR operation requires key coordination of a myriad of vessels and personnel ranging from fishing boats to dedicated Search and Rescue vessels, aircraft and naval vessels.

To rescue someone at sea, access to all possible information, regarding wind, sea currents, ships available for the search and the movements of the ocean are all vital. The VOCT [35] seeks to solve these issues by allowing automatic distribution of SAR relevant data to all relevant participants in a SAR situation. The VOCT allows for seamless and automatic sharing of relevant data. The VOCT follows the organizational structure of the current standards, allowing an On Scene Coordinator (OSC) or the SAR Mission Coordinator (SMC) the tools to distribute and coordinate any participating Search Rescue Units. Once an operation is underway the OSC can monitor the progress for participating vessels and electronically update
the search areas via the Maritime Connectivity Platform. The VOCT allows the OSC to calculate SAR data using the built-in SAR calculator or import the SAR data from commonly used commercial drift calculation systems.

When an incident occurs the first steps in a SAR operation is to calculate the likely place that the search object is located. This is done by applying wind and current information to the drifting object to establish a likely search area. The VOCT applies the theory outlined in the International Aeronautical and Maritime Search and Rescue Manual (IAMSAR) and presents the user with an intuitive interface. Once the user enters the necessary data, the software performs the calculations. The SAR area is then displayed directly on the electronic chart (for vessels it’s displayed on the ECDIS).

![Figure 33 – A SAR area calculated and distributed by the VOCT service.](image-url)
Once the SAR area has been designed it can then be sent out to numerous vessels in the vicinity and displayed on the ECDIS or other e-Navigation display. Vessels are able to accept the search pattern and begin searching. The OCS can then monitor the progress of each vessel along its search pattern until the pattern is complete.

3.3.8.4 Summary

This section has highlighted only three e-Navigation services that have been demonstrated, there are many more such possible services as shown in Annex C.

None of the advantages of increased safety, security, efficiency and protection of the marine environment brought about by e-Navigation would be possible WITHOUT the provision of high integrity data communications and resilient PNT information.

3.4 Autonomous Vessels

According to Allianz Global Corporate and Speciality (AGCS) [36], between 75% and 96% of maritime accidents are a result of human error, often a result of fatigue. It is said that remotely controlled and autonomous ships would reduce the risk of such mistakes and along with it the risk of injury and even death to crew members, and dangers to the ship itself [37].

In addition, according to the MUNIN project [38], between 2005 and 2014 it was found that 50% of all total losses were due to collision or foundering; autonomous vessels are expected to reduce the risk of such events to around 5%.
Autonomous ships are expected to be cheaper to run since there would be no need to provide accommodation and support systems for crew. In addition, crew shortages are expected in the future, with the sea-faring profession falling out of favour. Autonomous vessels are also expected to be able to take more efficient routes during bad weather, instead of diverting around a weather system to ensure the comfort of the crew. In addition, autonomous ships and their operations could be built in such a way to be more resilient to piracy.

From a technology point of view the building blocks to allow the construction of autonomous vessels are already available [20]. More challenging issues are concerned with the regulatory changes required to allow such ships to operate. They will need to be at least as safe as existing manned vessels if they are to secure regulatory approval.

An autonomous ship will require the ability to sense and communicate what is going on around it, to at least the standards currently required by the Safety of Life at Sea Convention (SOLAS) and the Collision Regulations (COLREGs) so that it can navigate to its destination, avoid collisions along the way, and perform complex manoeuvres such as docking. Rolls Royce [39] are working on situational-awareness systems that integrate optical imagery from high-definition visible and infra-red light combined with LIDAR and radar measurements – thus providing a picture of the vessel’s immediate surroundings. This information could be sent back to the remote operations centre, or employed by onboard Artificial Intelligence (AI) systems for analysis and action.

3.4.1 Regulatory Work

In 2017/18, IMO initiated a regulatory scoping exercise for the review of relevant technical and legal instruments pertinent to Maritime Autonomous Surface Ships (MASS). The IMO review will place provisions into 4 categories:

1. applying to MASS and precluding autonomous operations;
2. applying to MASS, not precluding autonomous operations but requiring no action;
3. applying to MASS, not precluding autonomous operations but possibly needing to be amended;
4. having no application to MASS operations.

Initial review comments started to be collated in May 2019 for completion by the end of July 2019, with results planned to be presented at an Intersessional Working Group on MASS from 2nd to 6th September 2019. The UK and Ireland are not directly conducting or supporting the review of instruments; in particular the review in regard to SOLAS Chapter V (Safety of Navigation) is led by China with Denmark, Japan and Singapore in support.

IMO Maritime Safety Committee (MSC) 100 established provisional principles for the development of interim guidelines for MASS trials, and invited proposals to MSC 101 for the trial and testing of MASS functionality. Finland, Norway, the Republic of Korea and the UK have already established dedicated test-bed areas to operate MASS. In the UK in October 2018, the UK’s Department of Business Energy and Industrial Strategy (BEIS) granted £1M
funding for the creation of a Maritime Autonomy Regulation Lab, where the Maritime Coastguard Agency (MCA) and the National Oceanography Centre (NOC) collaborate with academia and support industry to promote on-water testing and flagship projects.

UK testing is focused in the Solent with small MASS under 24 metres in length. The trade body, Maritime UK, supported by the Maritime Autonomous Ship Regulatory Working Group (MASRWG) affiliated with BEIS, published version 2 of ‘Maritime Autonomous Surface Ships UK Code of Practice’ in November 2018. The code’s scope is restricted to small MASS, also under 24 metres in length. This is a voluntary code for industry, based on equivalence principles aligned to the functions and operations of manned vessels, for which navigation safety relies on comprehensive risk assessments with evidence provided by adherence to design standards backed up with practical trials and testing.

Development and future operations of larger MASS are initially limited to national waters, focused in Scandinavia and the Far East. The ‘Yara Birkeland’ is expected to commence fully unmanned operations in 2020, restricted to Norwegian coastal waters. Kongsberg also plans to establish a number of land-based control centres to support autonomous shipping internationally. China has established what will be the world’s biggest test site for unmanned vessels in Guangdong. The Maritime Port Authority of Singapore plans to introduce autonomous harbour ships in future for a number of operations, such as berthing, mooring and towing. In Europe, there are plans to introduce autonomous electric container barges operating from the ports of Antwerp, Amsterdam and Rotterdam.

The technology enabling autonomous ships is becoming well-established [38] [40] but there are regulatory, legal, safety and social issues that still need to be overcome. These include cybersecurity; safety, related to the lack of crew on board and the use of artificial intelligence; impacts on seafarer jobs and shipping; and liabilities including whether insurance cover would be offered by underwriters, insurers and protection and indemnity insurance clubs for commercial autonomous ships.

Regulatory issues are driven by the (lack of) roles of the Master and crew, who are currently required on-board and shore-based staff supervising operations. There is also an open question concerning the partitioning of liability in the case of an accident between the vessel manufacturer, software or data provider, or the onshore monitoring stations.

Autonomous vessels are not likely to be deployed on international voyages for some considerable time. However, as in Norway, it is likely that autonomous vessels will be deployed in coastal waters around the UK. The UK will need to understand how this will impact the level of risk and the mix of aids to navigation that need to be deployed. The UK should continue to monitor the development of autonomous vessels to understand how these might impact the needs for aids to navigation.

3.4.1.1 SARUMS (Safety and Regulations for European Unmanned Maritime Systems)

SARUMS is a working group of the European Defence Agency, which is tasked with exploring safe design and operations for European unmanned maritime systems.
Several aspects are being investigated:

- Legislation, assurance and liability;
- Systems, procedures, experience to achieve safe operations;
- Safety related to design including systems, products and technology.

### 3.4.1.2 Maritime Autonomous Systems Regulatory Working Group (MASRWG) - UK

MASRWG was formed to identify the issues related to the safe operation of Maritime Autonomous Systems, and to formulate a regulatory framework that could be adopted by the UK and other States as well as the international bodies charged with the responsibility to regulate the marine and maritime world. The work of MASRWG informs the UK Department for Transport and Business, Innovation and Skills (BIS).

Despite the regulatory and legal hurdles to be overcome, some organisations, for example Rolls Royce [39], believe that unmanned ocean going autonomous ships are expected to be common place by 2030 (Figure 35).

![Figure 35 – Timeline of autonomous vessel development. Source: [39].](image)

### 3.4.2 Example Project - MUNIN

The Maritime Unmanned Navigation through Intelligence in Networks (MUNIN) project [38], [41] was a collaborative research project co-funded by the European Commission under its Seventh Framework Programme. MUNIN aimed to develop and verify a concept for an autonomous ship, which is rather contradictorily defined by MUNIN as a vessel primarily guided by automated on-board decision systems but controlled by a remote operator in a shore side control station. The project concluded in August 2016.

The use case for MUNIN was that of a dry bulk carrier operating in intercontinental tramp trades. MUNIN only envisaged autonomous operation of an unmanned vessel during deep-sea voyage and NOT in congested or restricted waters; according to MUNIN tasks associated with the earlier and later voyage phases in congested waters will still be executed by an on-board crew, although they note that the ratio of the deep-sea period to total voyage length is an important economic factor for operational efficiency. Among the elements surrounding the concept of autonomous vessel operations, the project proposed:
• An Advanced Sensor Module, which takes care of the lookout duties on board the vessel by continuously fusing sensor data from existing navigational systems, such as radar and AIS, combined with daylight and infrared camera imagery.

• A Deep Sea (Autonomous) Navigation System, which follows a predefined voyage plan within certain degrees of freedom to adjust the route in accordance with legislation and good seamanship autonomously, e.g. due to arising encounter situations or significant changes in weather.

The aim of the Advanced Sensor Module is to replace the Officer of the Watch (OOW) on the ship’s bridge. It would be responsible for object detection, classification and environmental perception. It uses input data from infrared and visual spectrum cameras as well as radar and AIS data to detect objects and determine if they are a danger to the ship or if they need to be investigated further, for example to identify life rafts, flotsam or other dangers to navigation. It maintains a proper lookout for ship traffic, obstacles and monitors the environmental conditions in the vicinity of the ship.

The task of the Autonomous Navigation System is to navigate the vessel safely from boarding point to boarding point using existing functionalities of Integrated Bridge Systems. The Autonomous Navigation System ensures that the ship follows the planned route within the allowable deviations given by the present operational envelope; such deviations include those caused by developing severe weather conditions or to avoid complex traffic situations. The Deep Sea Navigation system developed and introduced by MUNIN includes functions to:

• Determine COLREG-obligations [42] towards other ships and manoeuvres the autonomous ship accordingly to the rules;
• Optimises trans-oceanic voyage plans based on meteorological forecasts;
• Operates the ship safely in immediate and harsh weather conditions in accordance with the IMO weather guidance criteria.

According to MUNIN the Deep Sea Navigation System will operate fully autonomously but also allows the Shore Control Centre operator to interact and thus remotely control the ship.

According to the Final Report of the project concerning the Autonomous Bridge [41], the ANS collision avoidance function will rely partly on information about neighbouring vessels from AIS, itself reliant entirely on GNSS.

For the purposes of technical discussion later on in this report, and provide a single point of reference, we will refer to the architectural structures and concepts developed by the MUNIN project.

3.5 The IMO’s Multi-system Receiver

Recognising the essential need for resilient PNT in e-Navigation, the recent IMO performance standard for vessels’ multi-system, multi-constellation radionavigation receivers (MSR) [25] supports the use of European GNSS (e.g. Galileo and EGNOS) alongside other GNSS
components of the World-Wide Radio Navigation System (WWRNS). The IMO MSR guidelines [43] propose this as the way to achieving the resilience and integrity of PNT required by ships’ systems. As shown in Figure 36, the basic principle of the MSR is to use all available signals, not only GNSS but also augmentations and terrestrial transmissions.

Figure 36 – The IMO’s proposed Multi-system Radionavigation Receiver architecture.

Figure 37 – The proposed architecture of Position Navigation and Timing Data Processing (PNT-DP) integrated as software into the Integrated navigation System, ECDIS or RADAR aboard ship.
The MSR concept consists of a sensor layer and a processing layer, the output of which contains Position Velocity and Time information, AND integrity and status data. This data output can also be integrated as part of the ensemble of other ships’ sensor systems (gyrocompass, speed logs etc.) within PNT Data Processing software running on the ECDIS, RADAR or Integrated Navigation System (INS) (Figure 37).

The concept of the MSR platform will form the basis of our considerations for the integration of the ship-borne components of the Resilient PNT systems explored within MarRINav.

In the timeframe of 2030 we assume that the core, or primary, PNT system aboard ship will be multi-constellation, multi-frequency GNSS; as discussed in Section 3.1. In Europe it is assumed that this will comprise GPS, GALILEO and EGNOS (the European Space based Augmentation System).

However, a very important point to note is that best performance is achieved using all available signals and at least three GNSS are needed to identify a whole-constellation fault in parts of the world where SBAS/GBAS signals are not receivable.

3.6 Integrity Threats and Mitigations

Within the MSR integrity should be assessed against a particular model of potential threats, which may impact the solution. For the maritime user of a radionavigation system, be it space based or terrestrial, we have numerous environmental hazards, which must be considered. Sub-sets of these example hazards are more applicable to some systems than others:

- Multipath
- Signal-obscuration
- Signal re-radiation
- Non-line of sight (NLOS) reception (obscuration)
- Local noise and interference
- Atmospheric delays and ionospheric scintillation due to Solar weather
- Jamming

In some cases we can apply a priori knowledge to help us mitigate hazards. For example line-of-sight multipath will induce time-varying pseudorange errors which will be limited in their maximum extent. It may be possible to design an error-model based on a Normal (Gaussian) Distribution that describes the magnitude and likelihood of multipath errors. For example, the use of SBAS (Space Based Augmentation System for GPS) in the aviation sector adopts just such a model [22]. This is possible because antenna-installation on an aircraft is highly regulated and the physical environment of the installation is well defined and relatively simple; radio signal reflecting surfaces are below the antenna ground-plane. No such assumption can be made for a marine antenna installation given the complexity of a vessel’s mast and above deck infrastructure.

NLOS is a more problematic issue since the magnitude of the error depends on the path-length difference of the reflected signal, and this can be very large. Receiver autonomous integrity
monitoring or fault-detection and exclusion (RAIM, FDE) algorithms [44] can help here, using redundant information in the position-solution to detect large measurement errors (the larger the error is, the easier it is to detect) and remove from solution the particular pseudorange(s) which is (are) affected by the error.

RAIM is good at spotting errors on individual GNSS pseudorange measurements, and of course is a form of resilience. While RAIM will be of some use against an elevated background noise, or jamming attack, it cannot exclude individual signals as they all will be affected, thus impacting all satellites in a position solution. A separate method of determining a clean radio-background may be needed – an interference detector for instance based on the monitoring of the signals’ Carrier to Noise Ratio (C/No). Interference-detection can be achieved by a variety of methods, such as using the reported satellites’ Carrier to Noise Ratio (C/No), the front-end gain-control or a multi-antenna setup. Again, the aviation world is able to very tightly control the local radio environment of an aircraft in flight; we are not so lucky in the maritime domain. The need for additional noise-monitoring is dependent on the likelihood of interference and jamming determined from extensive measurement campaigns or other operational evidence.

The use of detection thresholds has already been mentioned in 2.6 and for both RAIM, and interference-detection, alarm detection thresholds must be set. A probability of false-alarm will exist; at the same time a small residual integrity-risk, and a probability of missed-detection, will remain. An effective integrity monitor should strike a fine balance between the probability of false alarm ($P_{FA}$) and the probability of missed detection ($P_{MD}$). If an additional mitigation measure is needed, some of the continuity risk budget will have to be spent to accommodate it. Additional safety-checks cannot be included ad-infinitum without incurring cost to the continuity budget, because if they alarm, then continuity is lost – continuity and integrity, as we shall see, are intrinsically linked and they should not be considered separately.

Ionospheric delays are usually calibrated out of GNSS signal delays using an augmentation-system (DGPS or SBAS) to measure the state of the atmosphere and issue correction-data. In the time-frame that we are considering, the beginning of the era of e-Navigation [1] and the Multi-System Receiver (MSR) [3], from about the year 2025 onwards, most GNSS constellations will offer civilian-access signals on multiple frequencies. This evolution to multi-frequency operation allows the receiver to cancel ionospheric effects by itself without relying on an external augmentation system.

### 3.7 Sources of Resilience

Sources of resilience of PNT information include the following:

1. The provision of Receiver Autonomous Integrity Monitoring (RAIM) within PNT receivers, including Fault Detection and/or Exclusion (FDE), and Horizontal Protection Level (HPL) computation:
   a. Detecting a faulty GNSS satellite signal from a position solution preserves integrity, while,
b. Removing that faulty satellite signal from solution preserves continuity, and thus is a form of resilience.

2. Alternative PNT systems to which systems can fall back depending on the result of the computations of the built-in RAIM algorithms or the interference/jamming detector.

3. GNSS hardening techniques, for example beam-forming antennas and multi-antenna arrays.

4. The detection and reporting of sources of interference to ship or shore-side systems; this would include:
   a. Radio interference detection (from jamming, spoofing, natural sources);
   b. The detection, and prevention, of cyberattack on supporting data processing / communication systems.

3.8 Harmonisation

All this work on GNSS/PNT and RPNT and e-Navigation must be harmonised with the current IMO programme on the modernisation of the Global Maritime Distress and Safety System.
4  PNT Information in Use Aboard Ship and Ashore

The aim of this section is to attempt an understanding of how PNT information (derived primarily from GNSS) is employed by the various systems and service aboard ship, and ashore. The aim is to point out the dependence of such systems on GNSS as the primary source of PNT information, and thus understand the overarching need for Resilient PNT.

Section 1.5.1 presented a list of some of the systems, aboard and ashore, that use PNT information that is currently derived solely from GNSS; as a reminder on board systems include:

- ECDIS – Electronic Chart Display and Information System
- Global Maritime Distress and Safety System (GMDSS), including its components:
  - Automatic Identification System (AIS)
  - Long Range Information and Tracking (LRIT) system
  - Digital Selective Calling (DSC) on MF, HF and VHF communications
  - Electronic Position Indicating Radio Beacon (EPIRB) – Including as part of the Ships’ Security and Alert System
  - Search and Rescue Transponders (SART) - a GNSS receiver may or may not be included to speed up beacon location and thus Search and Rescue Response
  - Satellite Earth Stations (SES) aboard ship
- Voyage Data Recorder (VDR)
- Gyrocompass
- Radar
- Engine Management
- Satellite communications – VSAT, Inmarsat etc.
- Dynamic Positioning systems
- The upcoming VHF Data Exchange System (VDES)
- Hydrographic surveying
- Heli-deck monitoring
- Pilot’s Portable Pilot Unit (PPU)
- Oil Discharge Monitoring Equipment (ODME)
- Ballast Water Discharge Management System (BDM)
- Ship’s clocks
- Track Control System
- NAVTEX

**Shore-side** systems that depend on a vessel’s ability to provide electronic PNT information include:

- VTS
- Floating Aid to Navigation (AtoN) monitoring
- Mobile AtoN marking
- Port Collaborative Decision Making (PCDM), including just-in-time arrival logistics
- Consolidated European Reporting System (CERS)
• Vessel Traffic Monitoring supported by the European Vessel Traffic Monitoring Directive
• SafeSeaNet (SSN)
• Vessel Monitoring System (VMS)

4.1 Systems Aboard Ship that Use PNT Information

We first consider the systems used by the mariner, and likely to be employed by autonomous vessels aboard ship. We first of all consider the need for a GNSS receiver aboard ship from the point of view of regulations.

4.1.1 The Maritime GNSS Receiver and Regulatory Context

The UK is a contracting government to the IMO SOLAS Convention. SOLAS Chapter V concerns the Safety of Navigation and applies to “all ships on all voyages” (with some exemptions). Regulations V.19 and V.19-1 cover the carriage and use of navigation equipment and SOLAS Chapter XI-2 security equipment. Regulation V.19.2.1.6 requires that ships carry “a receiver for a global navigation satellite system or a terrestrial radionavigation system, or other means, suitable for use at all times throughout the intended voyage to establish and update the ship’s position by automatic means”. In the absence of “terrestrial radionavigation” or “other means”, GNSS becomes a requirement.

GNSS position and / or time is used in multiple ship systems, including navigation and reporting systems (as well as off-bridge systems). Their correct functioning is subject to verification during Port State Control Inspections, and some systems of a mandatory safety nature, if not functioning correctly, would (at worst) require the ship to be detained until the fault is rectified or at least to proceed to the next port where rectification can take place (not necessarily the planned destination port). If widespread GNSS disruption were to be experienced it would affect all ships in the area, including autonomous vessels, and flag and coast states’, and regional maritime safety organisations’ response to such an occurrence, has not been tested.

The GNSS receiver provides position, Speed Over Ground (SOG), Course Over Ground (COG), heading if fitted with two or more receive antennas, and other navigation data. These remarks apply to the three voyage phases considered under General Navigation requirements; Ocean, Coastal, and Port Approach phases.

4.1.2 ECDIS

An Electronic Chart Display and Information System (ECDIS) is a geographic information system used for nautical navigation that complies with International Maritime Organization (IMO) regulations, IHO and IEC standards as an alternative to paper nautical charts. IMO refers to similar systems not meeting the regulations as Electronic Chart Systems (ECS) [45] [46].

An ECDIS system displays the information from Electronic Navigational Charts (ENC) and integrates position information from position, heading and speed through water reference
systems and optionally other navigational sensors. Other sensors which could interface with an ECDIS are radar, Navtex, Automatic Identification Systems (AIS), and depth sounders.

It is envisaged that ECDIS will evolve to include the portrayal of the results of e-Navigation Services; however, in recent years concerns from the industry have been raised as to the system's security especially with regards to cyber-attacks and GPS spoofing attacks.

To be considered fully ECDIS compliant (see SOLAS Chapter V Regulation 19) the vessel needs to have at least one redundant ECDIS system (two independent ECDIS computers, databases, and screens.) If they meet this requirement, then they are not required to carry paper charts. They are only required to have valid and corrected ENC's for their planned voyage.

When a vessel is operating with greater proximity to shore and increased marine traffic density the mariner will likely place more emphasis on monitoring the ECDIS. With regard to monitoring the information provided by the ECDIS in relation to PNT information the International Chamber of Shipping’s Bridge Procedure Guide \[8\] provides the following points of note:

- The safety settings, particularly depth safety contours, should be set in compliance with the Ship Management System (SMS) and reflect the current operational status of the ship including the actual draught. Here GNSS is being used to ensure that the vessel does not run aground.

- Information from all sensors connected to ECDIS is available and correct. Particular attention should be paid to the availability of information from the GNSS receiver, gyro compass and speed log. The importance of electronic PNT input from GNSS is such that if GNSS is not available at the start of a voyage the vessel will not be allowed to leave port if the vessel is of a type and age where ECDIS is a mandatory carriage requirement, the ECDIS has been adopted as the Primary Means of Navigation (PMN) in the ship's safety certificate and its implementation of the International Safety Management Code for the safe operation of ships and pollution prevention (ISM), and where a Port State Control (PSC) Inspector visits the ship.

- The OOW should consider the potential for positioning or related errors. Every opportunity should be taken to confirm the validity of a GNSS position using traditional fixing techniques. These fixes should, wherever possible, be plotted using electronic lines of position (LOP).

The Guide notes that:

**Over reliance on ECDIS should be avoided particularly if detrimental to the keeping of a proper look-out.**

It also notes that the charted detail on some ENCs may not be as accurate as the GNSS position of the ship on the ECDIS; the OOW needs to ensure there is sufficient safety margin between charted hazards.
4.1.3  GMDSS

The Global Maritime Distress and Safety System is an international system that uses terrestrial and satellite technology, and ship-board radio systems to ensure, in the event of maritime distress, the rapid, automated alerting of shore-based communication and rescue authorities in addition to other ships in the immediate vicinity. GMDSS was adopted by means of amendments to the *International Convention for the Safety of Life at Sea (SOLAS), 1974*. From 1st February 1999 all applicable vessels have had to comply with the GMDSS requirements in SOLAS.

Implementation of the GMDSS requirements is the responsibility of Contracting Governments to SOLAS, and of the administrations of individual countries that have ratified the GMDSS requirements and incorporated them into their national law. Individual ship-owners are responsible for ensuring that their vessels meet GMDSS requirements, since they are required to obtain certificates from their respective flag States certifying conformity with all relevant international regulations.

Vessels fitted with GMDSS equipment are safer at sea and more likely to receive assistance in the event of distress, because the GMDSS provides for *automatic distress alerting and locating* in the event that the vessel’s crew do not have time to transmit a manual distress call.

Under GMDSS, all cargo vessels of 300 gross tonnes and above, and all passenger vessels engaged on international voyages, must be equipped with radio equipment that conforms to international standards set out in the system. Search and Rescue (SAR) authorities ashore, as well as shipping in the immediate vicinity of the vessel in distress, with be rapidly alerted through terrestrial and satellite communication techniques so that they can assist in a co-ordinated SAR operation with the minimum of delay.

4.1.3.1  GMDSS Sea-Areas

For GMDSS purposes, the world’s oceans are divided into four different categories of Sea Area, and equipment requirements for specific vessels are determined by the category of Sea Area within which they operate.

**Sea Area A1**
Within the radiotelephone coverage of at least one VHF coast station in which Digital Selective Calling (DSC) alerting is available; about 30 to 50 miles from the coast station.

**Sea Area A2**
The area, excluding Sea Area A1, within the radiotelephone coverage of at least one Medium Frequency (MF) coast station in which continuous DSC alerting is available. This area extends up to 150 to 200 miles offshore. MF DSC declared range information may be found in [3].
Sea Area A3
The area, excluding Sea Areas A1 and A2, within the coverage of an Inmarsat geostationary satellite in which continuous alerting is available. This area lies approximately between the parallels of 76°N and 76°S, but excludes A1 and/or A2 designated areas.3

Sea Area A4
Any area outside Sea Areas A1, A2 or A3. This is essentially the polar regions North and South of 76°.

4.1.3.2 Sea Areas and GMDSS Equipment
Coastal vessels are only required to carry minimal equipment if they do not operate beyond the range of shore-based VHF radio stations, but they may also carry satellite equipment. Some coasts, however, do not have shore based VHF radio facilities so that the area concerned may be classed as A2 or A3.

Vessels that operate beyond A1 are required to carry MF or satellite equipment as well as VHF.

Vessels that operate beyond MF range have to carry Inmarsat satellite equipment in addition to VHF and MF.

Vessels that operate in Sea Area A4 are required to carry HF (High Frequency), MF and VHF radio equipment.

4.1.3.3 Components
GMDSS comprises the following components:

Automatic Identification System (AIS)
The AIS is an autonomous and continuous broadcast system operating in the VHF marine mobile band. AIS operates on two dedicated VHF FM frequencies — AIS1 (Channel 87B – 161.975MHz) and AIS 2 (Channel 88B – 162.025MHz). AIS is used to identify ships and Aids to Navigation and display their PNT information on ECDIS or radar overlay, its primary function is to serve as a collision avoidance system, although this is unofficial and should not be relied upon as noted in Table 20 in section 7.2. However, it is also used to mark fixed and floating aids to navigation by:

1. Using of a physical AIS transponder aboard the AtoN, or
2. Virtual AtoN - where there is no physical AtoN present, or
3. Synthetic AtoN – where there is a physical AtoN, but no AIS transponder on board.

An evolving application of AIS is Mobile AtoN Marking.

3 Sea Area A3 will soon be redefined due to the inclusion of the Iridium satellite communication system within GMDSS.
**PNT information, including location, Speed Over Ground (SOG), Course Over Ground (COG), is derived from a GNSS receiver built into each ship-borne AIS transponder.**

For MarRINav, although part of GMDSS AIS will also be considered in its own right.

**Long Range Information and Tracking (LRIT) system**

LRIT [47] is a development of the AIS system which allows the monitoring of vessels at distances of up to 1000 miles offshore. LRIT was established by IMO Resolution MSC.202(81) in May 2006, amending SOLAS Chapter V Regulation 19-1. It binds all governments contracted to IMO. The SOLAS regulation establishes a multi-lateral agreement to share LRIT information among contracting governments for security and SAR purposes, in order to meet the maritime security needs and other concerns of such governments.

The regulations apply to all vessels on international voyages including all passenger vessels including high-speed craft, all cargo vessels over 300 gross tonnes, including high-speed craft, mobile offshore drilling units.

**Vessels are required to report their positions by LRIT at least every 6 hours. In order to comply with the regulations, vessels must be fitted with equipment capable of automatically transmitting their identity, location, and date and time of the position. GNSS is used as the source of PNT information.**

**Digital Selective Calling (DSC) on MF, HF and VHF communications**

Digital selective calling or DSC is a standard for transmitting pre-defined digital messages via the Medium Frequency (MF), High Frequency (HF) and Very High Frequency (VHF) maritime radio systems.

DSC was developed to replace a voice call in older procedures. A DSC signal has a slightly longer range than analogue signals with up to twenty-five percent longer range. DSC senders are programmed with the ship's Maritime Mobile Service Identity (MMSI) and are typically connected to the ship's GNSS receiver, which allows the apparatus to know who it is, what time it is and where it is. This allows a distress signal to be sent very quickly.

**Electronic Position Indicating Radio Beacon (EPIRB)**

An emergency position-indicating radiobeacon station is a distress radiobeacon, a tracking transmitter that is automatically triggered during an accident. Signals from an EPIRB are detected by satellites. The system is monitored by an international consortium of rescue services, COSPAS-SARSAT (Figure 38). The basic purpose of the system is to help rescuers find survivors within the so-called "golden day" (the first 24 hours following a traumatic event) during which the majority of survivors can usually be saved. The standard frequency of a modern EPIRB is 406 MHz.

There are several similar types of radiobeacon available, including:

- Emergency Locator Transmitters (ELT)
- SEPIRBs - Submarine EPIRBs
• SSASes – Ship Security Alert System
• PLBs – Personal Location Beacons

Distress alerts transmitted from ELTs, EPIRBs, SSASes, and PLBs, are received and processed by the International Cospas-Sarsat Programme, the international satellite system for search and rescue (SAR). These beacons transmit a 0.5 second burst of data every 50 seconds, varying over a span of 2.5 seconds to avoid multiple beacons always transmitting at the same time. The signals are monitored worldwide and the location of the distress is detected by non-geostationary satellites using the Doppler effect for trilateration, and in more recent EPIRBs also by GPS.

The location of a transmitting 406 MHz beacon can be determined within approximately three miles by the first satellite pass, and to within one mile after three satellite passes.

A GNSS receiver may or may not be included within an EPIRB in order to speed up beacon location and thus Search and Rescue Response

Search and Rescue Transponders (SART)
A search and rescue transponder (SART) is a self-contained, waterproof transponder intended for emergency use at sea. These devices may be either a radar-SART, or a GPS-based AIS-SART (Automatic Identification System SART).

The radar-SART is used to locate a survival craft or distressed vessel by creating a series of dots on a rescuing ship’s radar display. A SART will only respond to a 9 GHz X-band (3 cm wavelength) radar. The radar-SART may be triggered by any X-band radar within a range of approximately 8 nautical miles (15 kilometers).

GNSS receiver may be built into a SART to speed up beacon location and thus Search and Rescue Response.
GMDSS Satellite Earth Stations (SES) aboard ship

The “Inmarsat C” satellite communication system is used for maritime safety applications including ship to shore, ship to ship, shore to ship store and forward data and email messaging. The receiving equipment is based on the use of an omnidirectional receiver antenna, and so no position information is required to “point” the antenna in the direction of the satellites.

However, SOLAS now requires that Inmarsat-C equipment have an integral GNSS receiver, or be externally connected to a GNSS receiver. This connection ensures that accurate location information is sent to the rescue co-ordination centre if a distress alert is ever transmitted.

Inmarsat Fleet 77 (F77) is an updated version of the now redundant Inmarsat A and B, providing ship-to-shore, ship-to-ship and shore-to-ship telephone, telex and high-speed data services, including a distress priority telephone and telex service to and from rescue coordination centres. Fleet 77 fully supports the Global Maritime Distress and Safety System (GMDSS) and includes advanced features such as emergency call prioritisation. Fleet 77 has an end of life scheduled for 1st of December 2020.

A GNSS receiver is integrated into such antennas within the radome and provides accurate position information to allow the Mobile Earth Station to determine whether it is within coverage of a spot-beam and to orient the dish to the satellite to be used.

Rate sensors and inclinometers are typically employed for antenna stabilisation, so that the antenna remains pointed at the satellite during vessel manoeuvring or course changes.
In May 2018, the IMO’s Maritime Safety Committee (MSC) recognized Iridium as being able to offer maritime distress and safety communications within the GMDSS. This recognition ended a decades-long monopoly and allows for coverage where none existed before, including in Sea Area A4.

The Iridium network is designed to work in extreme conditions at sea. The system consists of 66 cross-linked satellites in Low-Earth Orbit (LEO) covering the entire globe, pole-to-pole. The Low Earth Orbit (LEO) service provides a stronger signal and better “look angles” than geostationary satellites, helping keep ships connected, even in adverse weather.

Iridium will be the first satellite provider to provide GMDSS globally, including over Sea Area A4, one of the most dangerous areas of the Earth, which is not currently served by the only satellite GMDSS solution.

Expected to launch in early 2020, Iridium will deliver new GMDSS voice and data solutions with improved Search & Rescue (SAR) functionalities in a single, small-form-factor maritime terminal.

4.1.4 Voyage Data Recorder (VDR)

A Voyage Data Recorder, or VDR, is a data recording system designed for all vessels required to comply with the IMO’s International Convention SOLAS Requirements (IMO Res.A.861(20)) in order to collect data from various sensors on board the vessel. It then digitizes, compresses and stores this information in an externally mounted protective storage unit. The protective storage unit is a tamper-proof unit designed to withstand the extreme shock, impact, pressure and heat, which could be associated with a marine incident (fire, explosion, collision, sinking, etc.).

Although the primary purpose of the VDR is for accident investigation after the fact, there can be other uses of recorded data for preventive maintenance, performance efficiency monitoring, heavy weather damage analysis, accident avoidance and training purposes to improve safety and reduce running costs.

Simplified voyage data recorder (S-VDR), as defined by the requirements of IMO Performance Standard MSC.163(78), is a lower cost simplified version VDR for small ships with only basic ship’s data recorded.

The information recorded in the unit(s), sometimes also called Black box for ship, may include the following information:

- **Position, date, time using GPS**
- Speed log – Speed through water or speed over ground
- Gyro compass – Heading
- Radar – As displayed, or AIS data if no off-the-shelf converter is available for the Radar video
• ECDIS – A screen capture every 15 seconds and a list of navigational charts in use every 10 minutes or when a chart change occurs
• Audio from the bridge, including bridge wings
• VHF radio communications
• Echo sounder – Depth under keel
• Main alarms – All IMO mandatory alarms
• Hull openings – Status of hull doors as indicated on the bridge
• Watertight and fire doors - status as indicated on the bridge
• Hull stress – Accelerations and hull stresses
• Rudder – Order and feedback response
• Engine/Propeller – Order and feedback response
• Thrusters – Status, direction, amount of thrust percentage or RPM
• Anemometer and weather vane – Wind speed and direction

4.1.5 Gyrocompass

A gyrocompass is a device used aboard ship, which when used together with the onboard speed log is used to provide a dead-reckoned position solution.

There are two different types of kinds of gyrocompass:

1. A North-finding spinning mass device
2. A “strapdown” gyrocompass

North-Finding Spinning Mass

This type of gyrocompass consists of a single large spinning mass gyro with its spin axis aligned along the north-south axis within the horizontal plane. The gyro assembly consists of a spinning disc with most of the mass around its edge, driven by a motor. The casing of the gyro assembly is either linked to the casing of the gyrocompass unit via a set of gimbals or floated in a bed of mercury. This isolates it from the motion of the host ship. The heading of the ship can thus be determined by reading off the angle between the gyro spin axis and the fore-aft axis of the ship.

The effect of the Earth’s rotation and motion of the ship results in the spin axis becoming misaligned with north. However, through action of gyroscopic precession, gravity and mechanical damping, with a typical time constant of 60 to 90 minutes, the gyro spin axis seeks north; the mechanical gyrocompass is thus self-aligning. Once the gyro-compass is aligned the Earth’s rotation will still act to precess the gyro out of alignment with a rate proportional to the sine of the geographical latitude. This can be corrected by applying a latitude-dependent torque to the rotor assembly. In addition, steaming errors resulting from the motion (speed) of the vessel can result in the vessel going out of alignment [44].

Thus all mechanical gyro-compasses incorporate a latitude and speed input, which is typically derived from GNSS.
The north seeking gyro compass element used in the NAVIGAT X MK 2 [48] system is the gyrosphere, a hermetically sealed unit with a funnel-shaped recess, reaching from the outer skin down to its centre.

Inside the gyrosphere, two mechanically linked gyroscopes are mounted with their spin axes horizontal in a carrying frame. The gyroscopes are allowed to turn around the vertical, but torsion bands effect a defined rest position, while a mechanical linkage ensures that the resultant spin vector of the gyro remains stationary relative to the gyrosphere. This twin gyro arrangement eliminates intercardinal roll error. Once the gyros have run up to speed, their resultant spin vector, and with it the sphere, settles in the direction of true North.

The term “strapdown gyrocompass” is a little misleading and is a colloquial name for an Inertial Measurement Unit (IMU) plus magnetometers, a more accurate name would be an Attitude and Heading Reference System (AHRS) [49]. If this was to be used aboard ship it would benefit from integration with GNSS for calibration. The device needs motion in order to be able to observe all the IMU errors. The ship may need to be turned (not particularly practical) or the sea-state motion may be enough.

4.1.6 Radar

In addition to the implied use of GNSS through provision of AIS overlay, GNSS is also used for radar ground stabilisation.

Within a marine radar there are two motion modes:

- Relative motion
- True motion

Relative means relative to own ship, while true means relative to an outside reference system. The outside reference is split into two stabilisation modes – ground stabilised and sea stabilised. In a sea-stabilised system the speed log is employed, which measures the vessel’s speed through water (STW). Ground stabilisation requires an external sensor signal that at least can determine the speed over ground (SOG) of the observing vessel. This is typically provided by GNSS. Before accurate positioning systems were available it was necessary to have independent measurements of the observing vessel’s course and speed through water, plus a measurement that estimated the rate (speed) and set (direction) of the tidal stream and current. This complexity of understanding is now not normally necessary as the radar display can effectively be considered to be referenced to a ground fixed coordinate system, such as WGS 84. However, it should be noted that the different presentation and stabilisation modes available should be selected depending on the intended use of the radar; for example position fixing may better be suited to a particular mode and collision avoidance another. A comparison of the presentation and stabilisation modes can be found in [50].
4.1.7 Engine Management

Engine management system technologies make use of satellite communications to transfer operational parameters from a vessel anywhere in the world to ship-owners/operators offices. These parameters are then presented to operations staff to view and act upon the information in near real time. It is also possible to feed this vessel information automatically into a preventative maintenance schedule.

On-board hardware connects to the engines and transmits the data in near real time to a web interface. This web interface then allows shore based operations staff clear visibility of vessels’ locations, derived from GNSS, but also its engine data.

4.1.8 Satellite communications – VSAT, Inmarsat etc.

As mentioned earlier, Inmarsat C now employs omni-directional antennas that do not require location input for “pointing” the antenna at the satellite. Other dish antenna systems such as Furuno’s FleetBroadband™ products incorporate a GNSS receiver within the antenna unit for dish pointing. Some communications satellites’ tracking systems incorporate an antenna steering system based on measurement of signal strength.

Furuno’s VSAT system incorporates an Antenna Control Unit (ACU) that can receive a GNSS based compass input, or a gyrocompass input; however, note that a gyrocompass is also calibrated using GNSS.

GNSS is also employed by Inmarsat operators to point spot beams from satellites to load demand based on the transmitted location of vessels.

4.1.9 Dynamic Positioning systems

For many offshore activities it is very important to keep a vessel at a fixed position and heading. Dynamic Positioning (DP) systems automatically control the position and heading of a vessel by using thrusters that are constantly active and balance the environmental forces of wind, waves, current etc.

![Dynamic positioning in action.](www.offshoreengineering.com)
There are five main components in a DP system:

- **Control System**: the DP control system calculates the offsets between the measured values of position and heading and the required values (setpoint values). Based on the calculated offsets, the control system calculates the forces that the thrusters must generate in order to reduce the errors to zero.
- **Power generation**
- **Thrusters and propulsion**
- **Environmental reference**
- **Position and Heading reference**

Dynamic positioning systems are typically used by offshore vessels for accurate maneuvering, for maintaining a fixed position or for track keeping (pipe/cable laying). We usually find DP systems on:

**Offshore drilling vessels**: (Drilling ships and Semi-submersibles). A Drilling vessel will use DP to remain in a fix location while drilling in deep water.

**Offshore support vessels**: Platform supply vessels (PSVs), Well intervention vessels, Diving Support Vessels. Support vessel use DP to stay at a safe distance from offshore platforms and drilling rigs.

**Pipe-laying and offshore construction vessels**: Pipe-laying vessels use DP for position keeping and track keeping.

**Dredging vessels**: Suction Hopper dredgers, Rock-dumping vessels, Trenching vessels.

**Shuttle Tankers**: Shuttle tankers during offloading of FPSOs.

In 1961, the drilling barge **CUSS 1** made scientific history when it was used to drill 601 feet into the sea floor to recover core samples of the Earth’s never-before-penetrated second layer, known as the Mohorovicic Discontinuity or “Moho”.

The **CUSS 1** (named for the Continental, Union, Superior, and Shell oil companies that developed it in 1956) was the first drillship in the modern sense of the word. It was equipped with four rotating thrusters, one at each corner, and was the first vessel to use dynamic positioning. Position monitoring was provided by way of submersible sonar buoys in a circular pattern around the vessel, from which it received signals in order to maintain a footprint of approximately 600 feet in diameter.

### 4.1.10 VHF Data Exchange System (VDES)

VDES is the evolution of AIS, aimed at providing additional VHF channels and higher data bandwidth. AIS has found further application, beyond collision avoidance, in Aids to navigation marking, Application Specific Messages (ASM), for example lock information in US inland waterways, Search And Rescue Transponders, Man-over-Board and EPIRB-AIS. The aim is for
the VDES to alleviate the channel overloading experienced on AIS in regions of significant maritime traffic, and thus avoid compromising the collision avoidance function of AIS.

### 4.1.11 Hydrographic Surveying Equipment

Hydrographic surveying equipment such as the Applanix POS MV™ system employs GNSS data with angular rate and acceleration data from an Inertial Measurement Unit (IMU) and heading from a GPS Azimuth Measurement System to provide a six-degrees of freedom position and orientation solution; such a mix of systems is required to compensate for ship’s motion and georeferencing.

Accurate and reliable positional information is critical for achieving the required accuracy of bathymetric surveys within the Statutory Harbour Authority area and approaches. Traditionally, tidal reductions to datum were achieved using local tide gauges, however to provide increased accuracies, Real-Time Kinematic (RTK) corrections are used to determine the tidal height/correction. With vessel draughts increasing and the significant costs associated with capital dredging to deepen the ports, having the ability to accurately determine the least depths within a channel or berth is essential when maintaining vessel under keel clearance values.

### 4.1.12 Heli-deck Stability Monitoring

A Helideck Monitoring System (HMS) is used to analyse helideck motion during helicopter landings to improve safety in hostile weather conditions. The HMS monitors helideck attitude and vertical velocity, wind speed and direction, air temperature and barometric pressure and presents this information to indicate landing conditions. The HMS is typically used offshore on floating production and storage vessels (FPSO) and seismic vessels. Standards for the performance of helideck monitor system equipment are described in [51]. The equipment provided within a helideck monitoring system suite varies with provider. The Vaisala offering [52] includes a GPS compass for helideck heading information, while the Kongsberg H200 system [53] does not provide a GNSS based device.

### 4.1.13 Pilot’s Portable Pilot Unit (PPU)

The pilot may be equipped with a Portable Pilot Unit (PPU) [54], but may not. If a PPU is brought aboard it is used together with the bridge’s other mandatory shipborne radiocommunications and navigational equipment. The PPU is the pilot’s tool that assists the local pilot in the safe navigation of the piloted vessel. It does this by incorporating a range of navigation sensors with an electronic chart and display. The sensors are typically GNSS (with or without augmentations), AIS Interfaces, and Heading - Rate of Turn Generators. Some PPUs do not contain their own GNSS sensor.

Other information can include tidal and depth information when this information is provided locally and any other information that is specific for a particular port. Typically, PPUs can be set up quickly on the Bridge with simple deployment of the navigation antennas and interfaces. Most connect using wireless technology to a personal computer (PC), laptop or tablet positioned where the Pilot normally navigates. Connection may also be made to the
ship’s AIS to allow display of other ships and navigational aids that have AIS capability. Some PPU’s include SBAS capability. Note that PPU’s are not regulated, even though they are used in the navigation of SOLAS class vessels.

According to the UK Maritime Pilots Association (UKMPA), without GNSS available there would be a requirement for two pilots to be boarded in order to consider all visual aids as efficiently as possible. Without GNSS more vessels would be required to take pilots aboard.

4.1.14 Oil Discharge Monitoring Equipment (ODME)

Oil discharge monitoring equipment (ODME) is based on the measurement of oil content in the ballast and slop water, to measure conformance with regulations. The apparatus is equipped with a GNSS receiver, data recording functionality, an oil content meter and a flow meter.

A sampling point on the discharge line allows for the analyser to determine the oil content of the ballast and slop water in Parts Per Million (PPM). The results of the analyser are sent to a computer, which determines whether the oil content values are classed as an overboard discharge or not. All oil tankers with a tonnage of larger than 150 gross tonnes must have efficient Oil Discharge Monitoring Equipment on board.

Based on regulations, the following values must be recorded by the system:

- Date and time of the discharge
- Location of the ship
- Oil content of the discharge in ppm
- Total quantity discharged
- Discharge rate

All records of Oil Detection Monitoring Equipment must be stored on board ships for no less than 3 years.

4.1.15 Ballast Water Discharge Management System (BDM)

Ballast water is sea-water that is pumped aboard ship and discharged in order to compensate for changes in cargo load, fuel usage, sea-state and weather in order to maintain stability and hull integrity of the vessel. IMO Resolution A.868 [55] contains guidelines for the management of ballast water in order to prevent the harmful transfer of animal, plant and bacteria to sites where their presence would be alien to the local ecology. Appendix 1 of [55] presents a form to be completed by the ship when reporting ballast water intake and discharge; entries include geographical location.

4.1.16 Ship’s Clocks and Other Uses of Time Aboard Ship

GNSS is a cheap source of UTC locked time. An alternative is the use of a Caesium standard costing multiples of tens of thousands of pounds. GNSS can be used to synchronise ship’s clocks, and time-stamp events logged in the Voyage Data Recorder. Master clocks are typically
synchronised to GPS time, which can then be distributed to other clocks aboard ship; for example the company “Wempe” manufactures several Master Clocks that are able to interpret GPS NMEA data, and also provides a 1 Pulse Per Second (PPS) input. These Master Clocks distribute precise time by serial port to secondary clocks or network (LAN) connection serving as network time servers for ship’s systems [56].

4.1.17 Track Control System

It is impractical for the helm of a vessel in deep ocean to be permanently manned for the duration of a voyage. The track control system is similar to the autopilot found in aviation. By knowledge of the degree of drift of the vessel from the intended track, the helm is adjusted accordingly. According to SOLAS Chapter V, Track Control systems have to be interfaced with an electronic position fixing system [57].

Track Control Systems use position, course and speed information to keep a ship on a planned track over the ground automatically. The ship will steer to maintain Course Over Ground (COG) which keeps the ship on track and moving towards the next waypoint. GNSS is used for general track keeping; and the track is maintained within limits given by the shipping company or the Master. Many variations of cross track deviation are permitted and the latitude given to OOW to manoeuvre the ship also varies. Track control systems can be used to navigate between a series of waypoints with the OOW alerted before alterations to course are made. Use of a track control system does not relieve the OOW of the duty to ensure that the ship is safely on track or navigating within an authorised cross track distance (XTD). The ability of the autopilot to follow a planned track closely will depend upon the accuracy of the cross track error (XTE) information sent to the autopilot form the navigation system.

This is where low level jamming or spoofing of GNSS could steer the vessel off course, increasing risk of inefficiency, security and safety. However, as part of the steering control system, there is an off-course alarm to warn the OOW when the ship deviates from its heading.

Rules for calling the master vary, but loss of GNSS signal would definitely require them to be informed by the OOW. The OOW will also face the “mass alarm” situation where almost every bridge (and many other ship systems) will display a fault condition and they will be faced with difficult prioritisation task.

4.1.18 NAVTEX

NAVTEX is the system for the broadcast and automatic reception of Maritime Safety Information by means of narrow-band direct-printing telegraphy. The international NAVTEX service uses a single-frequency 518 kHz transmission in English. National NAVTEX services may be established by maritime authorities to meet particular national requirements. These broadcasts may be on 490 kHz, 4209.5 kHz or a nationally allocated frequency and may be in either English or the appropriate national language. Further details can be found in [16] and [58].
NAVTEX uses GNSS latitude and longitude filtering to provide services to ships and GNSS disruption might make that ineffective. Thus navigation, meteorological and Search and Rescue warnings may not be received correctly.

4.1.19 The Use of Timing Information

During Work Package 6 Workshop 1 on 15th May 2019, it emerged that there was a lack of common understanding amongst participants of the needs and requirements for precise timing in maritime navigation (and security) equipment, and for the timing needs for their interfacing and/or integration into Integrated Navigation Systems (INS) or Integrated Bridge Systems (IBS), either mandatory or optional. Views varied from:

“time only needs to be accurate to one (or so) second(s) to time-stamp the transaction”

to

“nano-second accuracy is required to synchronise communications and data signal protocols that link and integrate maritime navigation and security systems”.

4.1.19.1 What does Blackett say?

While not explicit, the Blackett report implies that the consequences of detriment to GNSS as used as a source of timing would contribute not just to an equipment or system issue, but to a “system-of-systems” problem. The report notes that an atomic clock costing upwards of £50,000 (in any equipment) overshadows a GNSS multi-constellation receiver costing “a few pounds”. It also concludes that “our awareness of GNSS it out of step with our dependence on it.” The report does not address the specific timing requirements of maritime systems, except in so far as their integration might be included in the section on general telecommunications.

Table 3.1 in the Blackett report notes that “time” (assuming this means precise time), is not essential for transport applications. However, the report does note that “chaos on the bridge” ensued when a very low power jammer was introduced into a merchant ship – the work of the Blackett report does not distinguish between time and position, although they are inter-dependent.

4.1.19.2 Request to Industry

In order to elicit information and views from industry experts the authors approached two leading manufacturers and installers of maritime navigation and security equipment and systems, and a company that specialises in maritime equipment time synchronisation.

The questions posed were:

1. To what extent is individual ship equipment dependent on precise timing? By precise we mean <1 second.
2. Is UTC a common standard across this equipment?
3. In the event of a 5 day GNSS outage how would this equipment cope individually, and are their internal/ship time server clocks able to continue functioning effectively?
4. Which of this critical/compliance equipment, noting their dependence on GNSS, and their requirement/ability to interface with each other, will suffer most quickly, and most detrimentally?

Note that the phrase “compliance equipment” — refers to the risk that the ship will be detained by Port State Control for lack of serviceable equipment, or at least diverted to the next port where the repair can be completed.

4.1.19.3 Response from Industry

Industry was unable to answer these questions in detail from existing resources. The reasons given include the following:

“there is a major piece of work here to review the specifications of each of these products and establish a dialogue with suppliers. In some cases there will be multiple suppliers and multiple generations of product. Some may have mitigation technology already built in, some not.”

It was estimated that there is one year’s worth of academic required to answer these questions, with additional time required for trials of equipment.

From desk research it is also clear that multiple standards apply. These normally include the IMO Performance Specification, the IEC design, manufacture and test specification(s), (used by Test Houses to ensure that maritime equipment meets the relevant standards and that Maritime Administration can “Type Approve” equipment for use at sea), ITU Technical Characteristics standards, and in some cases IHO or IALA standards, and RCTM Guidance. Even if all these standards are clear and unequivocal, manufacturers are often left some latitude to distinguish their products from others by using innovation, and this may lead to interpretations of the standards which, as industry replied, would need investigation for each equipment and version of equipment.

The most recent (and classic example) of such variance is the introduction of ECDIS where interpreting the applicable standards led to 16 (or more) major anomalies being experienced by operators, and international action to alert mariners and to get manufacturers to rectify the anomalies. That work also raised the question that ECDIS was not determined to be a “safety critical” equipment, despite that fact that on most ships its carriage and its use as of 2018 is mandatory.

Precise timing has also not been determined to be a “safety critical” component of maritime equipment performance standards, although the EGNSS Timing Services Final Report does describe “navigating ships through narrow channels” as “safety critical”.

In addition, the increasing integration of ship and shore systems through broadband satellite connections leads to improved ability to access data transfer and multiple time references, but also raises the risks of failures in cyber security.
This scope of work is clearly not within the timeframe of MarRINav Phase 1 so detailed work has not been commissioned at this stage.

4.1.19.4 The ESA aviation ITT

While such implied complexity and uncertainty might seem surprising, ESA recently (April 2019) released a tender (NAVISP-EL1-037) for a “Proof of concept of promising PNT Techniques and Technologies” for the aviation industry, entitled “PNT Timing and Synchronisation for Aviation Systems and Networks”. The tender notes that:

“usage of time information from multiple GNSS is subject of research and is not yet standardised”

This aviation tender and the statement above seem to support the industry response to our MarRINav question concerning use of timing information in maritime equipment.

4.1.19.5 Conclusions

Timing accuracy is improving all the time, and (internal) time sources are producing accurate and available (near-UTC) time for longer periods bringing greater resilience to GNSS outages. What is less clear is the dependence of maritime equipment on precise time, and their requirements (in terms of precise time) for interoperability and integration one to another and (several) within a navigation system. Timing accuracy from GNSS sources is subject to the same vulnerabilities as position information – leap seconds, week number rollovers, withdrawal of service (space debris, war, electromagnetic pulse), space weather, intentional interference, cyber-attack, satellite system faults, and GNSS receiver faults, as well as multipath and NLOS urban canyon effects.

4.2 Systems and Services Ashore that Use PNT Information

We next consider shore side systems and services that require PNT information to be received from the vessel at sea.

4.2.1 AIS Service

Should GNSS fail, or become degraded over a wide area, GNSS based UTC time synchronisation (called UTC Direct) for AIS transmission would fall back to alternative methods, in the following order [59]:

- UTC Indirect
- Base-station – assumed operated by a competent authority
- Base-indirect – synchronisation to a mobile station that sits between own vessel and a base-station
- Mobile Station – to – Mobile Station, also referred to as “semaphore”
Each successive fall-back would result in lower quality time synchronisation than the previous, increasing the jitter of the time of transmission of the data frames; this would be detrimental to the AIS VHF channel data loading, and message throughput would reduce affecting the reliability of the AIS transmissions.

4.2.2 Vessel Traffic Services (VTS)

The IMO defines a Vessel Traffic Service (VTS) as a service implemented by a competent authority, designed to improve safety and efficiency of vessel traffic and to protect the marine environment. The service should have the capability to interact with traffic and respond to traffic situations developing within the VTS area.

VTS’s were established in many principal ports and their approaches, both to reduce the risk of collisions and to expedite the turn-around of vessels. VTS is established in areas where the volume of traffic and risk to navigation and the environment is high, and in approaches to ports and other areas of confined water. There are regional VTS providing services to transiting vessels, and so there may also be local VTS within more extensive VTS.

VTS monitors ship compliance with local regulations and optimises traffic management.

VTS reporting requirements are frequently marked on charts, with further details being provided in sailing directions and in lists of radio signals. The passage plan should include references to the specific radio frequencies to be monitored by the ship in order to communicate with VTS. Masters should expect VTS to be able to provide:

- An information service (IS) which may include reports on the position, identity and intentions of other traffic, waterway conditions, weather, hazards or any other factors that may influence the ship’s passage;

- A navigational assistance service (NAS) in difficult navigational or weather conditions or when a ship is suffering defects or deficiencies. The Master may request this service from the VTS;

- A traffic organisation service (TOS) to establish and manage priority of vessel movements, allocation of space, mandatory movement reporting, route information and speed limits or other appropriate measures.

IALA and IMO is supporting the provision of VTS digital e-Navigation services (through IALA’s ENAV and VTS committees) to cover these three services (see MS1, MS2 and MS3 in Appendix C).

For traffic information VTS centres rely on AIS, with its dependence on GNSS, and radar.

PNT information will be required to be provided automatically and seamlessly in the event of a GNSS outage or degradation.
4.2.3 Ship Reporting Systems

Ship reporting systems allow coastal states to monitor ships navigating through their waters and are intended to contribute to the safety of life at sea, the efficiency of navigation and the protection of the marine environment.

Routinely, ship reporting systems require information on the position, course, speed, persons on board, cargo and the destination of ships. In certain areas, information on defects affecting ship navigation equipment, propulsion or steering may be requested by coastal authorities.

The ship may have set up automatic reporting based on position, e.g. WETREP PSSA or EU CERS 72 hour arrival messages - these reports may not be successfully transmitted, or transmitted with false information, if GNSS is disrupted. This may lead to increased monitoring from shore. If the mariner is aware that these reports are not being made, or being made incorrectly, the mariner will have to provide the reports manually, increasing workload and thus incurring distraction from navigation and other onboard duties.

Where a ship reporting system has been adopted by the IMO, the Master should comply with requirements of the reporting system. Reporting may be required on entry and exit from an area covered by a reporting system or when there has been a material change in the condition of the ship. Masters may expect IMO adopted reporting systems to be able to provide information to assist the ship, if requested.

Ship reporting requirements will be referred to on charts with a note of any relevant provisions as to their use, including details of their mandatory/recommended status. Further details will be found in lists of radio signals.

Currently, the Automatic Identification System (AIS) provides traffic reporting systems with the ability to monitor ships in real time. This has reduced the need for reports from vessels in certain areas but Masters should continue to make reports as required by individual reporting systems. Masters should ensure that the static, passage and dynamic data programmed into AIS equipment is accurate, in order to avoid the transmission of false data to reporting systems and other ships.

AIS is a vulnerable system on two main fronts; positioning information is provided solely by GNSS, and the data signal is provided un-authenticated, meaning that the information is easily spoofed; VDES (the VHF Data Exchange System) is expected to provide data authentication.

Part of the rationale for e-Navigation is the provision of automatic ship reporting through the application of suitable e-Navigation digital services and a regional Single Window. With the single window method the ship would report to a single online location and the information would be shared with all relevant parties (stakeholders) along the vessel’s voyage; for example port community systems, Vessel Traffic Services (VTS), customs and excise, border force, and others, negating the need to complete separate forms and make individual contact with each stakeholder [60].

LRIT, part of GMDSS, is required to report automatically to shore once every 6 hours.
**PNT information is therefore expected to be provided automatically, and yet solely relies on GNSS.**

### 4.2.4 Port Collaborative Decision Making (PCDM)

Port Collaborative Decision Making (Port CDM) services will increase the efficiency of port calls for all stakeholders through improved information sharing (Figure 40), situational awareness, optimised processes, and collaborative decision making during port calls [19], thus providing just-in-time arrival logistics. For efficient port operations and just in time arrival planning PCDM will be provided with regular updates of the vessel’s estimated Time of Arrival (ETA) and the vessel’s location.

![Figure 40 – Data sharing with PCDM.](image)
Figure 41 – The co-ordination of port actors within the timeline of a port call. Note the requirement for knowledge of ETA (Estimated Time of Arrival), ETD (Estimated Time of Departure), and Actuals at various stages to ensure co-ordination. Source: [61].

Figure 41 shows the co-ordination of port actors within the timeframe of a vessel’s port call. In the realm of Business Development Management (BDM) the provision of automatic positioning that is taken for granted enables efficient business logistics.

*Time of arrival and departure information is employed extensively within PortCDM in order to maintain efficiency of the operations involved, implying a heavy reliance on PNT information that is invariably derived from GNSS.*

4.2.5 Vessel Monitoring System (VMS)

Vessel Monitoring Systems (VMS) is a general term used to describe systems that are used in commercial fishing to allow environmental and fisheries regulatory organizations to track and monitor the activities of fishing vessels. These systems are used to improve the management and sustainability of the marine environment, through ensuring proper fishing practices and the prevention of illegal fishing, and thus protect and enhance the livelihoods of fishermen.

*Vessel location input may be derived from AIS and therefore GNSS, however off the shelf, self-contained units are available, such as the ITRAC™ VMS from metOcean telematics (www.metocean.com), and this contains its own GNSS receiver.*

4.2.6 Consolidated European Reporting System (CERS)

The UK Consolidated European Reporting System (CERS) is an information management system which has been developed by the Maritime Coastguard Agency to meet, amongst
other things, the UK reporting obligations under the provisions and dates indicated in the European parliament and Council Directive 2002/59/EC. It includes the provision of information on ship arrival and departure notifications (including additional requirements for ships carrying dangerous or polluting goods), and reporting requirements in the event of an accident or incident [62].

The obligations under CERS primarily stem from the European Vessel Traffic Monitoring Directive (VTMD), which places a requirement to send vessel traffic information, as reported by vessels entering UK ports, onward to SafeSeaNet (SSN), the central European data system run by the European maritime Safety Agency (EMSA).

Basic information is required about the vessel and voyage including, vessel details, port of arrival, ETA, ETD, ATA, ATD, with additional information about previous port, next port and persons onboard.

**Accurate estimates of ETA require accurate and reliable PNT information to be available.**

### 4.2.7 SafeSeaNet (SSN)

According to the website of the European Maritime Safety Agency (EMSA) [63], SafeSeaNet is a vessel traffic monitoring and information system, established in order to enhance:

- Maritime safety
- Port and maritime security
- Marine environment protection
- Efficiency of maritime traffic and maritime transport

It has been set up as a network for maritime data exchange, linking together maritime authorities from across Europe. It enables European Union Member States, Norway, and Iceland, to provide and receive information on ships, ship movements, and hazardous cargoes.

The main information elements that are contained in the system and made available to users are as follows:

- Automatic Identification System (AIS) based near-real-time ship positions (i.e. one every 6 minutes)
- Archived historical ship positions (over several years)
- Additional information from AIS-based ship reports (e.g. identification name/numbers, flag, dimensions, course, speed, dimensions, destination and ship type)
- Estimated/actual times of arrival/departure
- Details of hazardous goods carried on board
- Information on safety-related incidents affecting ships
- Information on pollution-related incidents affecting ships
- Details of waste carried on board / to be offloaded (from June 2015)
- Ship security-related information (from June 2015)
- Information on the location of single hulled tankers
• Information on the location of ships that have been banned from EU ports
• Digital map layers (containing information on depths, navigation aids, traffic separation schemes, anchorages, AIS station locations, etc.)

This information is used for many different purposes.

SafeSeaNet relies heavily on AIS for vessel location information, and AIS is dependent solely on GNSS for PNT information.

4.2.8 Mobile AtoN Marking

IALA recommendation R1016 [64] defines a MAtoN as a non-fixed or un-moored AtoN; but does not include a fixed or moored buoy that is adrift from station, temporary or otherwise. MAtoN would not generally be used for unmanned vehicle applications. There are two types of Mobile AtoN; physical and virtual.

The use of MAtoN should be strictly controlled, authorised by a competent authority and only used when risk assessment has determined the requirement and benefit. Typical uses of MAtoN may include:

• Mobile Ocean Data Acquisition System (ODAS) (e.g. currents, weather)
• Drifting wrecks (e.g. containers, debris)
• Water quality & pollution monitoring, containment and retrieval
• Mobile guard zones & convoys
• Underwater operations
• Enhance navigational safety during military operations (e.g. no sail zones during minesweeping, target exercises)
• Identifying end of drifting lines (e.g. seismic survey lines)
• Towed and deployed applications (e.g. cable laying)
• Search & Rescue applications
• Special maritime events (e.g. Swimming events and fluvial processions)

IALA members and authorities should use Mobile AtoN (MAtoN) in accordance with the appropriated risk assessment, when the occurrence/event to be marked/identified is drifting or in movement at sea, and that IALA members and relevant authorities liaise and cooperate with VTS Authorities before a MAtoN is deployed in a VTS area.

In regard to monitoring and reporting of MAtoN IALA states that:

“Authorities need to take special care with position monitoring and integrity, as it pertains to drifting hazards and obstructions.

The broadcast of Maritime Safety Information is essential in the use and reporting of MAtoN. An Authority or owner losing the ability to monitor the MAtoN that it has deployed, nonetheless retains responsibility until either it is retrieved, sinks or the responsibility is assumed by another Authority.”
**No mention is made in the recommendation regarding the positioning system employed, however the links to VTS suggests AIS.**

4.2.9 Floating Aid to Navigation (AtoN) Monitoring

Some of the more important floating Aids to Navigation contain telemetry systems that report status information to the monitoring system hosted by AtoN provider authorities. In addition to general onboard battery energy level and equipment fault status, the position of the AtoN is monitored and compared to a guard ring radius based on the length of anchoring chain. Should the AtoN anchor fail, it is important for AtoN authorities to be able to be notified of this automatically, alert the mariner through Maritime Safety Information broadcasts, and subsequently track the AtoN for recovery.

*Currently PNT information is provided solely by GNSS.*
5 Systems and Equipment Aboard Ship that are currently Perceived as a Backup

Some systems and methods aboard ship provide a minimal (and often manual) backup to GNSS should it become degraded. Such methods are invariably less accurate than GNSS, with errors building over time until calibrated with a more accurate source. They also involve increased human interaction than the automatically provided navigation solution afforded by GNSS, distracting the mariner from other bridge related duties. Equally these methods are not very likely to be as integrated within other ships’ systems as GNSS.

Currently, methods alternative to GNSS for determining positioning and navigation information aboard ship include:

- Visual Techniques
- Radar – note the radar also depends on GNSS input for certain functions
- The gyro-compass – note that many devices also depend on GNSS for calibration of errors
- Magnetic Compass
- Speed log
- Inertial Navigation Systems
- Sextant

We now expand briefly on each of these systems, highlighting the use of PNT information.

5.1 Visual Techniques

For General Navigation purposes visual techniques [65] [66] may be employed providing that atmospheric visibility is good enough. Such techniques include:

- Taking azimuth bearings of charted objects to fix the position of the ship;
- Heading transits, which can provide a leading line along which a ship can safely steer;
- Beam transits, which can provide an additional check for use when altering course;
- Clearing bearings, which can be used to check that a ship remains within a safe area.

The above visual methods would not be able to be employed during fog and would be difficult under conditions of heavy precipitation. In addition, it is yet to be tested whether future increased traffic density will affect the timeliness of the position fixing afforded by the above visual techniques.
5.2 Radar

When radar conspicuous charted features are visible on the display, effective use can be made of radar. The following techniques should be used when monitoring the passage in coastal waters, particularly in conditions of restricted visibility or at night.

- Parallel indexing [50], which is recommended to ensure the ship’s track is maintained
- Radar bearings
- Radar ranges

Where ECIDS is integrated with radar and a Radar Image Overlay (RIO) feature is available the alignment of the radar picture with charted features can be used to further verify the ship’s position. The radar stabilisation mode employed is now more important.

Ground stabilization

- In ground stabilization mode true motion display of radar is used and the course and speed is fed from GNSS, hence the fixed objects on the radar display remain stationary.
- The movement of all moving objects is their movement over ground (COG and SOG).
- It is used for collision avoidance with fixed objects.

Sea stabilization

- In sea stabilization mode relative motion display of radar is used and the course is determined from gyro course and speed is from log speed. Hence the fixed objects on the radar display appear to have a course & speed equal to the reverse course & speed of own vessel.
- The movement of own vessel, fixed object and moving object is their movement through the water.
- This is ideal for collision avoidance action.

GNSS is used within radar for ground stabilisation. Should GNSS fail, or become degraded, the stabilisation mode will need to be changed from ground to sea, unless there is an accurate dead-reckoning solution available with accurate tidal stream information. The loss of ground stabilisation will increase the apparent clutter on the radar screen because normally apparently fixed objects will now appear to move across the radar image and leave trails.

Radar will be operated with ARPA – Automatic Radar Plotting Aid. AIS is used for situational awareness overlay, but if GNSS is unavailable then AIS cannot be trusted.

5.2.1 Radar Parallel Indexing

Marine radar may be employed in a technique known as parallel indexing. According to [67] parallel Index techniques provide the means of continuously monitoring a vessel’s position in relation to a pre-determined passage plan.
Parallel indexing enables the mariner to monitor the vessel’s progress moment by moment and by providing enough data to allow corrective manoeuvres to be made in a timescale which is similar to that of visual conning, about 2 to 3 minutes [50].

### 5.3 The Gyrocompass

Notwithstanding the fact that many gyrocompasses also depend on GNSS for calibration of errors, these devices are typically used for heading determination independently of magnetic compasses and GNSS compasses. See also Section 4.1.5.

### 5.4 Magnetic Compass

The onboard magnetic compass can be employed for computation of a dead reckoned solution. Magnetic variation will need to be accounted for, and is published in maritime almanacs. The ship owner should ensure that magnetic deviation (the effect of ferro-magnetic materials around the compass) is accounted for through calibration.

### 5.5 Speed log

An electromagnetic speed log can be used in order to provide Speed Through Water (STW), however this requires accurate tidal stream data (rate and set) to translate to Speed Over Ground.

Depending on the depth of water, a Doppler speed log can be used in order to provide speed over ground (SOG), rather than Speed Through Water (STW) derived from the electromagnetic log.

### 5.6 Inertial Navigation Systems

According to [68], using an aviation-grade INS (the best available at reasonable cost to the ship-owner) a position drift of about 100m (95%) over 10 minutes or 1500m (95%) over an hour can be achieved using traditional inertial navigation with vertical motion constraints. INS systems an order of magnitude better than the above are available for submarine and space applications. However, they cost approximately £1 million each and there may be restrictions on non-military uses.

Calibration of the sensor biases using GNSS can potentially reduce this. However turns are required to fully separate the accelerometer biases and attitude errors and calibrations can become out of date. The surge, sway and heave motion of ships can potentially assist with this calibration process. Further research is needed to assess the level of calibration that may be realistically achieved in a marine environment.

Other than over intervals of a few minutes, inertial navigation performance is significantly poorer than that achievable using traditional dead reckoning (see above) with ground velocity
measurements. However, it is not clear how inertial navigation compares to dead reckoning using water velocity or water speed measurements; further investigation is needed.

Due to its high short-term accuracy, inertial navigation can be used to improve the accuracy obtained using other positioning technologies.

5.7 Sextant and Other Celestial Systems

A sextant is used to determine the latitude of a celestial body (the Sun during day time, or a known star at night). Together with the longitude value, computed by taking the difference between local ship’s time and UTC, it is possible to compute a position solution to within 1 NM of accuracy. The time taken to produce the fix is not particularly suitable to sea areas close to coastline or in restricted waters, and the technique is better suited to mid-ocean position fixing.
6 Requirements Capture

This section discusses requirements capture and analysis for the project.

6.1 Introduction

Requirements may be divided into several categories:

1. User needs – the overarching need for resilient PNT as evidenced in the previous sections of this document.
2. Stakeholder requirements – including users e.g. the OOW (see Section 1.3), equipment manufacturers, service providers and others.
3. System requirements (derived from the stakeholder requirements), to begin to understand how to solve the stakeholders’ problem and which can be decomposed into:
   a. Functional requirements
   b. Non-functional requirements.

It is usual engineering practice, when determining system requirements, to ensure traceability to the original user requirements, thus validating that the system being created actually meets stakeholder needs.

One of MarRINav’s aims is to reaffirm (or not) stakeholder requirements and discover requirements that are emerging in the maritime domain due to the introduction of new applications as maritime technology and navigation systems evolve, including through the development of autonomous ships and e-Navigation. These requirements will mainly be determined through stakeholder liaison within Work Package 6. It is the goal of Work Package 1 to set the context and the framework for the requirements gathering and analysis processes and focusses, in the first instance, on user requirements.

6.2 Requirements Gathering Process

Requirements will be gathered in consultation with stakeholders and with reference to requirements setting technical and regulatory organisations outlined in Section 6.4. Each requirement may be assigned a status value, which indicates the maturity of the requirement.

Permissible values are:

- New - the requirement has been captured from an external source
- Ready - the requirement has been cleaned of any ambiguous statements and characterised
- Checked - the requirement has been checked by the project team
- Review - the requirement is being reviewed by stakeholders
- Agreed - the requirement has been accepted by stakeholders
- Rejected - the requirement has been rejected by stakeholders and is to be reworked
• Deleted - the requirement is no longer needed

The process of identifying stakeholders, gathering/adjusting requirements and assessing status is iterative, as indicated in Figure 42, not just through the primary requirements capture phase, but throughout the lifetime of the development project.

The intention of the first edition of this WP1 document is that it be a first iteration of the requirements capture process.

As such this document, and the supporting documents to be introduced later, will be a working document to be referenced throughout the life of the project, which will be updated when new information becomes available.

![Figure 42 - The stakeholder requirements process.](image)

6.2.1 Requirements Software Tools

A number of useful software tools have been identified to aid capture, storage and maintenance of requirements.

It is proposed that MarRINav employ a requirements management tool to capture text based requirements; Cradle™ [69], a systems engineering software tool, has been identified as being suitable for this purpose.

ArcGIS™ [70] will be used to demonstrate geographically based requirements, such as vessel traffic flows and their associated degree of risk of collision and grounding, and the locations of maritime applications found in the Blue Economy. GLA owned Resilient PNT coverage prediction software has been modified to be able to output GIS shapefiles (actually Google Earth™ KML files) that can be overlaid onto the GIS map, thus allowing the comparison and subsequent modification of the infrastructure layout to provide the best coverage performance in the regions that need it the most; this is one mechanism by which costs and benefits can be weighed off against each other.

In addition, Modelio™ [71] can be employed to produce UML (Unified Markup Language) based system engineering diagrams, including Use Case diagrams, data flow diagrams etc. However, this is a relatively sophisticated approach, and not all consortium members are familiar with the technique; it is therefore proposed that such diagrams are kept simple.
6.3 Stakeholders

As part of Work Package 6, an initial list of the types of stakeholders that would have an interest in MarRINav was developed.

It is convenient to use a systems engineering model for partitioning stakeholders into their part of the service provision chain (see Figure 43). Systems engineering includes phases of user requirements gathering, architecture specification, design, implementation, test and validation and operation and maintenance. Using this model, stakeholders who have requirements can be divided into users, designers, implementers, testers and operators. A more complete list of stakeholders is being compiled under Work Package 6, however some examples of each category of stakeholder are given below:

**Users**
Mariners, Network Rail, Road Freight, Port Authorities, VTS, Container Terminal operators, Container Port, BMT, Intertanko, Chamber of Shipping, BIMCO, MCA, UKHO

**Designers**
Equipment manufacturers; Roke Manor, Arquiva, uBlox, Cambridge Consulting, LOCATA, Ursanav, Orolia, Tideland, Pharos Marine, UrsaNav, Reelelektronika, Sperry marine, Furuno, software companies, system integrators, port and terminal equipment providers, e.g. Kalmar, Cargotec

**Implementers**
Arquiva, Terrafix, UrsaNav, Port/terminal planning software providers e.g. Navis, Cosmos, Tideworks

**Test and Validation**
Test houses, IEC

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**Figure 43 – Example of systems engineering V-diagram.**
Operators
Port Authorities, GLAs, VTS, IALA, Aquiva, Babcock International, container terminal operators, e.g. DP World, APM terminals, Peel Ports, Forth Ports, Hutchinson Ports

Regulatory Bodies
- International Maritime Organisation (IMO)
- International Telecommunications Union (ITU)
- International Association of Aids to navigation and Lighthouse Authorities (IALA)
- Department for Transport (DfT)
- Radio Technical Commission for Maritime Services (RTCM)
- International Electrotechnical Commission (IEC)
- International Hydrographic Organisation (IHO)
- UK Department for Environment Food and Rural Affairs (DEFRA)
- Marine Management Organisation (MMO)
- Marine Scotland
- UK Department for Business, Energy and Industrial Strategy (BEIS)
- European Union Directorate General Maritime Affairs and Fisheries (EU DG MARE)
- European Maritime Safety Agency

Phase 1 of MarRINav, the current phase, will for the most part concentrate on User Requirements, those requirements that are driven by the needs of the users of PNT systems and related data when performing their applications and operations to provide safety, environmental protection and economic efficiency. Users are the operators of machinery and processes that depend on GNSS, and supporting data, and ultimately Resilient-PNT.

6.4 Sources of Requirements
In addition to direct stakeholder consultation, there are a number of sources of navigation system stakeholder requirements. In the maritime domain the overarching mandating authority is the International Maritime Organisation (IMO). The International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) is also a major maritime stakeholder of requirements from a maritime safety perspective. The European Radionavigation Plan cites several sources for user requirements, in addition to expressing the overall user need for resilience. In addition, the GLA and the DfT have published maritime strategy documents that will likely have an impact on the outcomes of MarRINav.

6.4.1 International Maritime Organisation (IMO)
Maritime requirements, expressed in terms of the four Required Navigation Performance parameters outlined in Section 2, are presented in IMO Resolution A.915(22) [21]. In addition, resolution A.1046 (27) [72] talks of the worldwide radionavigation system, and presents system-level requirements for the ocean, coastal and harbour entrance voyage phases.

IMO A.1046(27) ‘Worldwide Radionavigation System’ was adopted on 30 November 2011; note that this is now 8 years old. The assembly resolution adopts as policy for the recognition
and acceptance of suitable radionavigation systems intended for international use the “Revised Report on the Study of a Worldwide Radionavigation System”. The latter being set out in the Annex to the resolution. This resolution invites governments to keep the IMO informed of the operational development of any suitable radionavigation systems conforming to the policy, which might be considered by the IMO for use by ships worldwide. It requests the Maritime Safety Committee (MSC) to recognise systems conforming with the operational requirements set out in the Annex to the resolution, and to publish information on such systems. The operational requirements stated in A.1046 concentrate only on navigation in ocean waters and harbour entrances, harbour approaches and coastal water.

IMO A.915(22) ‘Revised Maritime Policy and Requirements for Future Global Navigation Satellite System (GNSS)’ was adopted on 29 November 2001; it is now over 17 years old, but it is the best information we have regarding numerical requirements for the four RNP parameters for a wide range of maritime applications, from coastal voyage phase to underwater cable laying. Consultation with stakeholders could start by validating these requirements, however sensible decisions regarding the requirements need stakeholder’s understanding of the definitions of the RNP parameters described in Section 2, MarRINav can provide that guidance.

While MarRINav’s main aim is to determine the architecture and design of a resilient PNT system for the UK and its waters independently of any international administration, it is important to bear in mind IMO policy with regard to any system’s international recognition.

A recent GSA report states [73] that:

“The IMO resolution A.915(22) provides a list [of] most maritime applications, regulated or not, requiring the knowledge of the craft position or velocity for general navigation or any other purpose. This list shall be kept “as is” because the IMO resolution A.915 or its future updated version is indeed the internationally agreed reference document summarising the needs of the maritime users.”

The GSA report goes on to map the requirements listed in A.915 to a smaller number of categories corresponding to 10 m, 1 m, and 0.1 m horizontal accuracy. This grouping of similar requirements is aimed at “facilitating the exploitation” of the information.

The IMO is the sponsor, custodian and editor of international maritime conventions, including, importantly for this work, SOLAS and COLREGS. While IMO issues advice and guidance from time to time, legal changes to these conventions, involving 197 nations, often take years to complete.

Indeed, within MarRINav, this consolidation of maritime requirements will assist in the identification of potential Resilient PNT systems that are most suitable to support each application.
6.4.2 IALA

IALA produced Recommendation R-129 [74] on ‘GNSS Vulnerability and Mitigation Measures’ in December 2008; and is now 11 years old.

The document shows that IALA recognises the increasing dependence of all classes of maritime users on GNSS services, and the vulnerability of such services to both intentional and accidental interference. The initial focus of the IALA document is that of the call for resilience in IMO’s e-Navigation strategy.

IALA state that ‘in addressing the issue of position fixing, it can be defined as accurate and reliable electronic position, navigation and timing signals, with ‘fail-safe’ performance (probably provided through multiple redundancy, e.g. GNSS, differential transmitters, eLoran and defaulting receivers or onboard inertial navigation devices’, and that

‘National Members and other appropriate Authorities maintain and develop backup and contingency aids to navigation, which may include radio aids to navigation and conventional aids to navigation, appropriate to the identified level of risk.’

The IALA document considers GNSS vulnerability within the maritime field and the mitigation measures that may be used to overcome them, stating:

“The effect on marine navigation of interruptions to GNSS will be significant.”

However, it should be noted that outages to GNSS service are not necessarily the most dangerous aspect of GNSS vulnerability. GNSS can be disrupted such that, while the system is still providing a service, that service’s performance can be affected without total loss. This disruption could affect the performance of the system to dangerous levels without the knowledge of the mariner, who will continue using the system unaware of any danger. IALA, strongly supported by the Bridge Procedures Guide [8], also states that:

“It is accepted as good practice that all available sources of positioning information should normally be used.”

IALA defines alternative navigation systems as being able to provide PNT support at various levels:

- A **redundant** system provides the same functionality as the primary system, allowing a seamless transition with no change in procedures;

- A **backup** system ensures continuation of the navigation application, but not necessarily with the full functionality of the primary system and may necessitate some change in procedures by the user;

- A **contingency** system allows safe completion of a manoeuvre, but may not be adequate for long-term use.
A redundant system should provide equivalent performance levels in terms of positioning and timing accuracy, integrity, availability and continuity. It is tempting to say that other GNSS can provide redundancy, however all GNSS tend to have common failure modes; they are all space based, with low signal strength at the surface of the earth, with numerous cross system signals occupying the same part of the radio frequency spectrum. However, counter measures against jamming and interference of GNSS (so called GNSS hardening techniques) are being developed, for example beam-forming antennas, and these measures need to be considered within MarRINav.

A backup system may include terrestrial systems like eLoran, and radar combined with radar aids to navigation, or terrain matching algorithms. For the most part MarRINav will concentrate on analysing those systems able to provide a backup, and will base a UK RPNT architecture on such systems.

Contingency systems as defined by IALA are those that allow safe completion of a manoeuvre, and include such things as the IALA system of buoys and lights, inertial navigation systems, dead-reckoning and even depth sounders. Integrating an inertial navigation system with GNSS could provide up to a few minutes hold-over depending on the phase of voyage, the associated accuracy requirement and of course the quality (and financial cost) of the Inertial Measurement Unit (IMU). Dead-reckoning systems rely on the use of speed-log and gyro compass, accuracy depends on the last fix and decreases with time at a rate depending on the accuracy of the equipment, the sea-state and weather conditions; however, when integrated with radar based absolute positioning presented by Work Package 3, dead-reckoning could provide a self-contained backup navigation system independent of any external infrastructure. Indeed MarRINav is free to explore the combination of contingency systems in order to create a backup, and it is a fundamental principle that multiple systems may be integrated within the IMO’s multi-system receiver concept.

MarRINav shall give careful consideration regarding whether a particular RPNT system should be considered to be redundant, backup or contingency and provide recommendations accordingly, however any resulting RPNT system will likely be a hybrid mix of systems.

6.4.3 European Radio Navigation Plan (ERNP)

The first edition of the EC’s European Radionavigation Plan was published in November 2018 [24], capturing the characteristics of Europe’s radionavigation landscape and providing an inventory of existing and emerging radionavigation systems and user requirements and listing key stakeholders. The executive summary of the plan lists the following as its aim:

- Allow for a coherent harmonisation of the suite of radio navigation systems available in Europe.
- Provide incentives to streamline investment in terrestrial Positioning, Navigation and Timing (PNT) infrastructure whilst improving the safety, robustness and security of the PNT landscape as a whole (for both space and terrestrial systems).
- Facilitate the eventual coordinated rationalisation of legacy navigation infrastructure across Europe.
• Support the definition of the optimal mix of radio navigation services matching the needs of key user segments (e.g. maritime, civil aviation, railways, autonomous vehicles. Intelligent Transport Systems), enabling cost effective solutions that meet high standards with respect to safety, robustness and security.
• Reduce European dependency on non-European PNT systems.
• Provide a forward-looking perspective on the evolving range of radionavigation systems and infrastructure in Europe.
• Facilitate the adoption of the EU GNSS services and help define its modernisation plans.
• Establish synergies between sectors and facilitate the adoption of measures in one sector that were previously adopted in another.
• Support the definition of coherent European long-term strategies in key policy areas (e.g. transport, security and space).
• Support breakthroughs in Research and Innovation.

Among the main findings of the work of the ERNP is the following:

‘In some specific cases, e.g. for critical applications requiring both continuous availability and fail safe operations, namely the critical phases of “safety of Life” navigation, GNSS cannot be the sole means of PNT information. Contingency plans must be devised for such cases, resorting to redundancy, fault tolerance, recovery procedures, and/or independent back-up PNT solutions. Importantly, the additional technical means required to deliver adequate redundancy are often sector specific, and not necessarily radio-based’

Also,

‘The maritime community embraces the concept of “integrated PNT System” consisting of an overlay of satellite based, shore-based and on-board components, to provide resilient PNT data during all phases of vessel navigation. In addition, studies are ongoing to test the feasibility of a back-up PNT system for GNSS using trilateration based on signals from existing IALA beacon stations, AIS (VDES) base stations (both for the maritime and inland community) and Loran-C transmitters, or a subset of these.’

A clear statement is made in the Conclusions section of the ERNP that:

‘There are, however, some challenges that will need to be addressed. At Earth’s surface, the power of GNSS signals is very low, which makes them vulnerable to natural and artificial interference. Especially significant is the vulnerability of GNSS signals to intentional attacks like jamming and spoofing. Because of this, it is generally recognised that, at least for critical applications, GNSS should not be the sole source of PNT information, not even within the new multi-constellation and multi-frequency reality. Alternative PNT systems, not necessarily using radio frequencies, should be put in place where the criticality of the application requires. Requirements for backup PNT systems in each user segment with the open challenge of anticipating future sectorial needs must be analysed.’
It can be demonstrated that MarRINav supports all of the above initiatives from the maritime domain with consideration of the cross-sector benefits.

Figure 44 shows a table extracted from the ERNP illustrating maritime PNT RNP requirements derived from:

- IMO Resolution A.1046 [72]
- Swedish RNP Section 3.3 Marine Requirements [75]
- The United States Federal Radionavigation Plan [76]
- Commission Regulation (EC) No 415/2007 [77]

Appendix B of this document presents, for reference, the tables of RNP parameters from A.915.

<table>
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<th>Phase or application</th>
<th>Accuracy</th>
<th>Availability</th>
<th>Continuity</th>
<th>Time to alert</th>
</tr>
</thead>
<tbody>
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<td>100 m (95%)</td>
<td>99.8%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coastal waters</td>
<td>10 m (95%)</td>
<td>99.8%</td>
<td>99.97% in any 15 min</td>
<td>10 s</td>
</tr>
<tr>
<td>Harbour approach and entrance</td>
<td>10 m (95%)</td>
<td>99.8%</td>
<td>99.97% in any 15 min</td>
<td>10 s</td>
</tr>
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<td>Inland waterways</td>
<td>2 to 10 m</td>
<td>99.9%</td>
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<td>Lock operation</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>River engineering and construction</td>
<td>0.1 to 5 m</td>
<td>99%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surveying</td>
<td>Horizontal: 0.5 to 5 m</td>
<td>Vertical: 0.05 m</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 44 – Table of maritime user requirements from page 111 of the ERNP.
6.4.4 GLA Marine Navigation Plan

The GLA Marine Navigation Plan [2] describes the GLA plan for the overall marine Aids to Navigation (AtoN) service provision mix; covering electronic and visual AtoN. The document presents the GLA plan in respect of lighthouses, beacons, major floating aids, buoys, day-marks and other forms of visual AtoN required for safe navigation in their areas of responsibility. The plan has been created in the context of the introduction of e-Navigation, which will change the way that operators (mariners and remotely-operated or autonomous vessels) react to information that is presented to them. The plan considers and supports the expansion and increasing take up of GNSS infrastructure and technology, including GPS, Galileo, GLONASS, and BeiDou.

6.4.5 DfT Strategy

The UK’s Department for Transport has published a strategy document ‘Maritime 2050’ [78] that set out a long term strategy and high-level vision for the future of the UK maritime sector though to 2050. It provides a framework that will inform government policy development and industry decision making as well as giving even greater confidence to potential investors in the UK economy. The document sets out a cross-government and industry set of objectives and priorities against which government and business can plan for the long term. The document includes strengths, opportunities and risks for the future of the sector.
7 User Requirements for (Resilient) PNT

As mentioned earlier, Phase 1 of MarRINav, the current phase, will for the most part concentrate on User Requirements, those requirements that are driven by the needs of the users of PNT systems and related data when performing their applications (Use Cases) to ensure safety, environmental protection and economic efficiency. Users are the operators of machinery and processes that depend on GNSS, supporting data, and ultimately Resilient-PNT.

7.1 The Organisation of User Requirements

In general, user requirements for applications that employ maritime PNT, and supporting data, may be organised into several categories:

1. **Required Navigation Performance (RNP) parameters** specified quantitatively as **accuracy, integrity, continuity and availability**. These are parameters that express the performance of the system as required by the user in order to support the user’s application. For example those published by the IMO for various maritime applications. Appendix B illustrates tables of RNP parameters extracted from IMO A.915, and Section 2 presents definitions.

2. **General Operational Requirements** of the system. These are generally text based requirements that make a statement about how the PNT system should operate and are overarching characteristics of any proposed RPNT system. For example, the need for a RPNT system to not be limited in the number of simultaneous users. Requirements capture software, for example Cradle™ can be used to capture and maintain these. Appendix A presents a set of example general operational requirements.

3. **Geographical Requirements** are requirements based on the location of the user(s) applications or perceived need. Where do we need to provide a RPNT system? What are the locations of the various applications (and other needs) relative to the (estimated) coverage area of the RPNT systems we are proposing to use? For examples, the locations of aquaculture sites or areas of special scientific interest; or those geographical locations that possess a high degree of risk of collision or grounding risk based on traffic density and offshore infrastructure density around the UK. The MarRINav Geographical Information System (GIS) will be used to capture these. The GIS will then later be employed to optimise the architecture and design of the RPNT architecture for the UK and Ireland. Among other sources, information will also be drawn from the European Atlas of the Seas, the Marine Management Organisation and Marine Scotland.

In summary then, for the MarRINav RPNT architecture, the project aims to concentrate RPNT infrastructure in those locations that result in the best geographical coverage in those areas and applications around the coast that demand the highest level of performance as expressed by the these systems’ ability to meet the applications’ required RNP parameter values, while supporting the general operational requirements for a RPNT system.
For less critical regions we may provide less infrastructure - this is how the Cost Benefit Analysis performed by London Economics will work. Thus the research questions are:

*Where do we put our RPNT infrastructure, how much will it benefit UK CNI and how much will it cost?*

7.2 User Applications (or Use Cases)

User Applications can be considered to be collections of *Use Cases* for PNT information. MarRINav specifically highlights the following application domains for requirements analysis:

- General Navigation
- e-Navigation
- Autonomous vessels
- Blue economy
- Port/pilot Operations – sea side of the land/sea interface
- Port Operations – land side of the land/sea interface

The aim is for these Use Cases to be served by a Resilient PNT system consisting of a core Multi-Constellation, Multi-Frequency GNSS, together with suitable complementary/backup PNT systems depending on the Use Cases’ demands for resilience and integrity.

There are numerous research questions that need to be asked (and answered) of each Use Case. We provide example questions and answers below for a vessel making-way in mid-Ocean operating in the Ocean Voyage Phase – part of General Navigation):

1. **How is GNSS (PNT) used?**
   Example for Ocean Phase Use Case: To answer this question we refer to Section 4 of this document and the lists of systems aboard and ashore that employs PNT information. Briefly, to maintain minimum cross track error along the planned Ocean transiting route. There is no risk of grounding (provided of course that surveys are accurate, charts are up to date, and the mariner checks the CATZOC and Source Data Diagram information carefully). Traffic density is low so there is low risk of collision, BUT cargo containers can fall from ships and float around and need to be avoided. It is used to calibrate the drift of the gyro-compass, provides position input to the DSC system as part of GMDSS, provides location information for e-Navigation services.

2. **What are the quantitative RNP requirements in terms of accuracy, availability, integrity and continuity?**
   Example for Ocean Phase Use Case: IMO says 100 m in one document, IALA says 1000 m for a backup in another.

3. **What backups for PNT are already in place?**
   Example for Ocean Phase Use Case: The Officer of the Watch (OOW) should maintain paper charted positions taken at regular times of the day. A celestial navigation solution
by sextant may be taken several times once per day. It is unclear whether the sextant and celestial navigation still included in Standards of Training, Certification and Watch keeping for Seafarers (or STCW). A north seeking mechanical gyro-compass could be sufficient, but this needs a ship’s speed input based on ship’s latitude for calibration.

Organisations such as the UK’s Maritime Coastguard Agency (MCA) [67] make reference to the use of other means for position fixing and clearly state that mariners should:

- Appreciate the need to cross check position fixing information using other means;
- Be aware of the dangers of over-reliance on the output from, and accuracy of a single navigational aid.

4. **What are the data communications requirements that support PNT for that application and what technical infrastructure is in place to provide this support?**
   
   Example for Ocean Phase Use Case: system integrity warnings for a radionavigation service, probably provided by satellite communications such as Inmarsat C or Iridium.

5. **What future technologies, in the timeframe of 2030, are expected to come into operation that require PNT information?**
   
   Example: autonomous vessels will likely be remotely monitored but will mostly operate autonomously during the trans-oceanic phase of its passage.

These questions need to be asked for all other applications and their Use Cases. We begin though with General Navigation.

7.2.1 **General Navigation**

MarRINav is investigating a proposed architecture for the provision of resilience and integrity in and around UK and Irish coastal waters. Specific applications that require RPNT take place at various distances from the UK coast. One aim of requirements analysis is to understand the coverage performance of various resilient PNT systems and their traceability to a set of user requirements that describes the geographical region of operation of the intended application, and highlights geographical locations where risk of collision or grounding of a vessel is particularly high.
Figure 45 – Image showing the extent of the UK and Irish maritime administrative boundaries; territorial waters and Exclusive Economic Zones. *Picture output form ArcGIS based on Irish and UK government sources.*

Figure 45 indicates the limits of the Exclusive Economic Zones (EEZ), and territorial waters of the UK and Ireland. MarRINav will explore options for the provision of RPNT systems to the extremes of the EEZs. The software Geographical Information System (GIS) ArcGIS™ will be used to collate and analyse the performance of each system with respect to these regions, and locations of various Blue Economy applications, including General Navigation.

In [21] the IMO presents RNP requirements for five phases of General Navigation; ocean, coastal, port approach and restricted waters, port, and inland waterways. In [72] IMO mentions only four phases; ocean, coastal, and harbour entrances, and approaches. The United States’ Federal Radionavigation Plan (USFRP) [76] defines four major phases; inland waterway, harbour entrance and approach, coastal and ocean navigation.

In the USFRP inland waterway requirements focus on non-seagoing ships and their requirements on long voyages in restricted waterways, typified by tows and barges. In the following sub-sections we refer to the definitions provided by the USFRP.

### 7.2.1.1 Ocean Navigation

Ocean navigation is that phase in which a ship is beyond the continental shelf (200 m in depth), and more than 50 NM from land, in waters where position fixing by visual reference to land or to fixed or floating aids to navigation is not practical. Ocean navigation is sufficiently far from land masses so that the hazards of shallow water and of collision are comparatively small.
#### 7.2.1.2 Coastal Navigation

Coastal navigation is that phase in which a ship is within 50 NM from shore or the limit of the continental shelf (200 m in depth), whichever is greater, where a safe path of water at least 1 nautical mile wide, if a one-way path, or two nautical miles wide, if a two-way path, is available. In this phase, a ship is in waters contiguous to major land masses or island groups where transoceanic traffic patterns tend to converge in approaching destination areas; where interparty traffic exists in patterns that are essentially parallel to coastlines; and within which ships of lesser range usually confine their operations. Traffic routing systems and scientific or industrial activity (Blue Economy) on the continental shelf are encountered frequently in this phase of navigation and the presence of marine protected areas in all their forms starts to increase.

The boundary between coastal and ocean navigation is defined by one of the following, which is farthest from land:

- 50 NM from land;
- The outer limit of offshore shoals, or other hazards on the continental shelf; or
- Other waters where traffic separation schemes (TSS) have been established, and where requirements for the accuracy of navigation are thereby made more rigid than the safety requirements for ocean navigation.

#### 7.2.1.3 Harbour Entrance and Approach (Port Approach)

Harbour entrance and approach navigation is conducted in waters inland from those of the coastal phase. Harbour approach phase generally begins with a transition zone between the relatively unrestricted waters where the navigation requirements of coastal navigation apply, and narrowly restricted waters near or within the entrance to a bay, river or harbour, where the navigator enters the harbour phase of navigation. Usually harbour entrance requires the use of a well-defined channel, which can vary in width between 120 m to 600 m, channels used by smaller craft can be as narrow as 30 m.

The nature of the waterway, the physical characteristic of the vessel, the need for frequent manoeuvring of the vessel to avoid collision, and the closer proximity to grounding danger, impose more stringent requirements for accuracy and for real-time guidance information than for the coastal phase. The fundamental problem is that of precise navigation of large seagoing vessels in narrow channels between the transition zone and the intended mooring. In certain approaches the services of a pilot are required, should the Master of the vessel not carry an exemption certificate.

#### 7.2.1.4 The Degree of Risk of General Navigation

The GLAs are tasked by the Governments of the United Kingdom and Ireland to provide marine aids to navigation of the correct type and number consistent with the volume of traffic and the degree of risk. They are also tasked to be able to maintain those aids to international standards, and to be able to respond to the navigational dangers that, from time to time, are presented by wrecks or other newly discovered obstructions [79].
The volume of traffic and degree of risk is periodically assessed by the GLAs by employing IALA’s IWRAP [80] software tool. Using IWRAP it is possible to estimate the frequency of collisions and groundings in a given waterway based on information about traffic volume/composition (typically obtained from historical AIS data), route geometry and bathymetry.

Using the results of such a statistical analysis, together with the proposed coverage estimates of the various resilient PNT solutions, it should be possible to determine the optimal design of resilient PNT systems by reference to the degree of collision risk at various locations, concentrating extra infrastructure, for example transmitters, to provide RPNT coverage where it is needed the most. The reduction of collision and grounding risk for General Navigation is a user need.

7.2.2 e-Navigation

e-Navigation has been considered in relative detail within Section 3.3, but a brief reminder of the overarching need to RPNT for e-Navigation is presented here.

The IMO’s strategy for e-Navigation contains a high-level user need for data and system integrity. IMO states that [81]:

‘e-Navigation systems should be resilient and take into account issues of data validity, plausibility and integrity for the system to be robust, reliable and dependable. Requirements for redundancy, particularly in relation to position fixing systems, should be considered.’

From a MarRINav perspective, e-Navigation’s function is to:

1. Provide a number of e-Navigation services that support data requirements for Resilient PNT systems;
2. Provide standardised data formats for the transfer of data via these services (IHO Common Maritime Data Structure – CMDS based on S-100);
3. Provide a method of identifying maritime actors interacting with each other;
4. Provide a method of authenticating sources of data;
5. Provide a method of ensuring data availability through seamless transition to alternative data communications systems depending on a vessel’s location.

In addition to e-Navigation supporting Resilient PNT, Resilient PNT will also support e-Navigation. e-Navigation relies on knowledge of a vessel’s position in order to ensure that only data pertinent to a particular vessel, or group of vessel, and its location is received by the same [82]. Some e-Navigation services will assume that a vessel has sufficiently accurate and available positioning to make use of the service, for example a Route Exchange service [83].

In fact positioning and navigation requirements will differ depending upon the e-Navigation service in question; for example, there is an obvious difference in positioning requirements
between a Maritime Safety Information service [33] providing information concerning a region at sea and providing information concerning a single dangerous obstruction.

In another example, a search and rescue service [35] intended to co-ordinate a search vessel’s search pattern relative to others. Navigation system RNP requirements then are dependent upon the context within which a vessel is employing e-Navigation services, and it is likely that those requirements will depend upon the relevant general navigation voyage phase, or the application being undertaken.

7.2.3 Autonomous/Unmanned Vessels

Autonomous vessels have been introduced in Section 3.4. It is anticipated that autonomous vessels will not rely solely on GNSS as stated by stakeholders during Stakeholder Workshop 1 of Work Package 6. Autonomous vessel RNP requirements have been collected by the European GNSS Supervisory Authority (GSA) through surveys and interviews with the key players on autonomous vessel navigation [73].

The GSA states that:

‘Autonomous vessel requirements need to be coherent with IMO A.1046, and therefore any value that is not in line with this IMO requirement has been discarded for the derivation of the RNP requirements.’

Table 2 summarises the navigation performance requirements identified for ocean and coastal phase during the survey based on the received responses.

<table>
<thead>
<tr>
<th>Performance Parameter</th>
<th>Oceanic deep Sea Navigation</th>
<th>Coastal Navigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal accuracy (95%)</td>
<td>&lt;15m</td>
<td>&lt;5m</td>
</tr>
<tr>
<td>Continuity (over 15 minutes)</td>
<td>1·1x10⁻⁵</td>
<td>1·1x10⁻⁶</td>
</tr>
<tr>
<td>HAL</td>
<td>&lt;28m</td>
<td>&lt;12·5m</td>
</tr>
<tr>
<td>TTA</td>
<td>&lt;8s</td>
<td>&lt;6s</td>
</tr>
<tr>
<td>Integrity Risk</td>
<td>1·1x10⁻⁴</td>
<td>1·1x10⁻⁷</td>
</tr>
<tr>
<td>Availability</td>
<td>99·8%</td>
<td>99·8%</td>
</tr>
</tbody>
</table>

Table 2 – European-GNSS performance requirements for autonomous vessels according to survey results [73].

7.2.4 The Blue Economy

The EU 2018 Annual Report [84] notes that varying (international) definitions and poor comparability of Member States’ data make it difficult to decide what is included in “The Blue Economy” [85]. Moreover, upstream and downstream values are present in many Blue Economy value chains and this facet is not captured by some definitions. A good example is
bio-fuels, where marine bio-mass can be used to produce bio-fuel, and using bio-fuel saves emissions, but the net environmental effect is less clear.

The UN Sustainable Development Goal No 14 [86] (“conserve and sustainably use the oceans, seas and marine resources for sustainable development”) is coherent with OECD and EC goals, (“realising the full potential of the ocean will therefore demand responsible, sustainable approaches to its economic development”, and “our responsibility today is to make sure that maritime economic development leads to a sustainable and competitive blue economy”, respectively) [87]. The World Bank, UNEP TEEB and UN Department of Economic and Social Affairs have various different foci on Blue Economy sectors, but those differences are not significant for the purposes of this part of MarRINav WP1.

Figure 46 illustrates the established industry sectors, the emerging sectors, and proposes some additional economic activities and “enablers” for consideration within the Blue Economy; this was adapted by the authors from The EU 2018 Annual Report.
The authors have added emerging sectors of Mining and Aggregates and Carbon Capture and Storage (CCS). They have also added Ship to Ship Transfers and Illegal and Unreported Fishing and migration because the activities exist, but are frequently unobserved. They have also added “emergency response” to core maritime activity. They have also considerably enhanced the “enablers” part of the diagram to show a wider range of the regulation, planning, marine and maritime operations, technology and data activities that support the
Blue Economy, and, significantly, this is where GNSS (and therefore PNT information) features. Figure 46 also includes the key ship systems that depend, or can depend, on GNSS for safe and efficient functioning; many of the GNSS connectivity requirements are required by regulation, with a vessel not even being allowed to leave port with failed or faulty GNSS information. So Blue Economy activities that involve ships and are underpinned by some (or even many) of the enablers, have a triple dependency on GNSS; for safety, efficiency, and environmental protection. Every incident that involves a vessel has the potential for injury or loss of life, economic loss to ships equipment and cargo, and environmental damage – some accidents involve all three.

Blue Economy turnover in the EU in 2016 was €566B and GVA (Gross Value Added) €174B. The EC cautions that there will be double counting across some complex and inter-dependent value chains⁴. Moreover, the individual contribution of economic activity components to each NACE⁵ code is sometime difficult, or even impossible, to extract, and the value ascribed will simply be what the enterprise reports as its biggest GVA. Some 3.5 million people were employed in the EU Blue Economy in 2016, a rise of 2% since 2009.

In terms of “risk” value, coastal states, (those responsible for supervision and compliance within their internal waters, territorial waters, EEZs, Renewable Energy Zones, etc), spend a lot of money on risk mitigation. Using, for example, the UK values of countering and cleaning up maritime pollution, the Cost of Averting a Fatality (CAF), and the economic value of ships equipment and cargo, some £248B of risk exists in UK waters (within AIS range) each 24 hour period. Now, that is certainly not to say that a simultaneous accident will happen to every ferry, cargo vessel, cruise ship and fishing vessel in UK waters in a 24 hour period. But the resources spent (by any coastal state) on regulation, surveillance, monitoring, reporting, inspection, incident readiness and response represent an “insurance premium” against a proportion of that risk value⁶.

7.2.4.1 Examining the Blue Economy activities and their dependence on GNSS

Using Figure 46, activities were taken in turn and assessed for reliance on GNSS, and for risk when GNSS is degraded, unreliable or not present. Several Blue Economy activities can function without GNSS, but that is not the way that marine and maritime affairs are conducted nowadays, nor are many participants trained specifically to operate without GNSS. Moreover, monitoring and reporting many Blue Economy activities, much of that for compliance reasons, also depends heavily on GNSS, so while the operation itself might be conducted (safety and more or less efficiently) with degraded GNSS, its permissioning and reporting regime would not work and the activity might then be considered illegal for lack of accurate and timely reports; sea fishing and the Vessel Monitoring System (VMS) is a classic example.

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⁴ Fisheries information is taken from the EU Data Collection Framework (EC 199/2008) under the Common Fisheries Policy, and data for all other sectors are based on the Structural Business Statistics by Eurostat.

⁵ Nomenclature statistique des activites economiques dans la Communauté Européenne (NACE Rev 2 2006)

⁶ The Cost of Averting a (single) Fatality (CAF) is some £1.5m (DfT 2018); it costs about £16,000 to clean up 1m³ of oil, and the value of ships, equipment and cargoes is taken from maritime insurance claims.
Each activity was considered and assessed using the most appropriate method and granularity of execution. That means that planning, permissioning, licensing, installation, operations, maintenance, emergencies and decommissioning were normally considered components of the activity; this varies by economic activity because of the different stages experienced during the activity. This was done by literature research, on-line search, conference attendance, project team corporate knowledge and expert judgment. Stakeholders were not directly approached at this stage, but MarRINav’s Work Package 6 will choose to socialize (some of) these results with appropriate groups and any outlying results will be modified or explained.

Each activity or stage was assessed against the criteria for GNSS accuracy, integrity, availability and continuity and the result tabulated in Table 3. These parameters are referred to, in plain English, in the Blackett Report [3], but do have much more rigorous definitions elsewhere in this WP 1 report. The authors’ interpretations of these criteria, and thereby the assessment of their importance, is contained within the table itself, but broadly is as follows:

- **Red** = Very important to safety, environmental protection and efficiency of the activity and GNSS degradation brings high risk
- **Amber** = Medium importance to safety, environmental protection and efficiency of the activity and GNSS degradation brings moderate risk
- **Green** = Low importance to safety, environmental protection and efficiency of activity and GNSS degradation brings low risk, or the activity can wait until GNSS/PNT is restored
- **Clear** = if no GNSS is available alternate means can be employed but with increased time and cost

Each activity stage was given a traffic light colour code in each criterion. For example, Aquaculture - Planning – “Accuracy” was coded Amber because licensing requirements and juxtaposition to adjacent installations must be defined in enough detail and with enough accuracy to ensure compliance and separation. Aquaculture – Planning – “Continuity” was given a Green traffic light because the planning operation could be stopped and started without detriment to safety or environmental protection, (but with added economic time and cost).

Along with those assessments, IMO Resolution A.915 [21] was used to establish the 95% horizontal accuracy requirements for each stage of each activity. Where A.915 criteria were found to be practicable, effective and current, they were used, even though these requirements are 17 years old. Where there was an obvious, necessary, compliant, or more modern and practicable accuracy criterion, it was stated in red to show that it differs from A.915. It should be noted that A.915 does not draw a distinction between normal and low-visibility operations, where higher GNSS accuracy is generally required for the end stages of each part of the activities (except where other means, e.g. radar, can be reliable). A.915 also
only notes a few vertical positioning accuracy criteria, notably for hydrographic survey and offshore oil and gas installations.

It should be noted that A.915 maritime activities nearly all fit within Blue Economy sectors except for Casualty Analysis and Law Enforcement, which this report shows as enablers in Figure 46. In addition, A.915 does not include the standards needed for many “reporting” (mostly ship-to-shore) activities, most of which have emerged or been modified, including increasing frequency and accuracy requirements, over the past 17 years. It is also noted that vessels engaged, for example in fishing, offshore oil, gas, ocean and wind energy activities, and other “at sea” activities, have to leave and enter their ports and undertake coastal navigation, so portions of their voyages will involve differing GNSS requirements with the A.915 table.

In the “Where” column an estimate of the broad geographic location of the activity is recorded. While this was benchmarked against known UK criteria, the categories assigned reflect EU general classifications. Notes were added in the “Remarks” column if it was considered that additional explanation would help the reader.
<table>
<thead>
<tr>
<th>ESTABLISHED SECTORS</th>
<th>Acc</th>
<th>Int</th>
<th>Aval</th>
<th>Cont</th>
<th>95% Acc</th>
<th>Where</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aquaculture</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ITZ CW TW</td>
<td>Often operated by people in smaller craft</td>
</tr>
<tr>
<td>Planning</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5m</td>
<td></td>
<td>Precise locations inshore and adjacent to other proposals and installations</td>
</tr>
<tr>
<td>Installation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5m</td>
<td></td>
<td>Ditto</td>
</tr>
<tr>
<td>Operations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10m</td>
<td></td>
<td>Frequent navigation to and from sites</td>
</tr>
<tr>
<td>Maintenance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5m</td>
<td></td>
<td>Maintain site in permitted location</td>
</tr>
<tr>
<td>Emergencies</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10m</td>
<td></td>
<td>A.915 SAR</td>
</tr>
<tr>
<td>Decommissioning</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5m</td>
<td></td>
<td>Remove installation from permitted location</td>
</tr>
<tr>
<td>Fish processing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>?</td>
<td>Land</td>
<td>Catch landing declarations – ICES zone needed from GNSS for logbook / report</td>
</tr>
<tr>
<td>Operations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10m</td>
<td>&lt;12 CW EEZ INTL</td>
<td>Fish processing ships</td>
</tr>
<tr>
<td>Fisheries</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Planning</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10m</td>
<td>CW TW &lt;12 EEZ</td>
<td></td>
</tr>
<tr>
<td>Operations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100m down to 10m</td>
<td></td>
<td>Amber because of VMS requirements and red font because this is the commonly accepted accuracy requirement of VMS which is not the same as A.915</td>
</tr>
<tr>
<td>Maintenance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10m</td>
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<td></td>
</tr>
<tr>
<td>Emergencies</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10m</td>
<td></td>
<td>Law A.915</td>
</tr>
<tr>
<td>Ports, warehousing and water projects</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ITZ CW &lt;12 EEZ</td>
<td>This description covers many divergent activities and is not easily amenable to collective assessment. It will be treated in more detail in WP 1.1.5, 1.1.6 and 1.2. Requirements for accuracy vary from 0.1 to 1.0 metres. The following assessments are made using the activity classification in A.915.</td>
</tr>
<tr>
<td>Wi-max</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1m</td>
<td>Port limits</td>
<td>GNSS required to operate Wi-max</td>
</tr>
<tr>
<td>Tugs and pushers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1m</td>
<td>Port limits</td>
<td>Relative accuracy</td>
</tr>
<tr>
<td>Automatic docking</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.1m</td>
<td>Ports</td>
<td></td>
</tr>
<tr>
<td>Dredging</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.1m</td>
<td>Port limits, CW</td>
<td>Horizontal and vertical</td>
</tr>
<tr>
<td>Construction works</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.1m</td>
<td>ITZ CW TW</td>
<td>Horizontal and vertical</td>
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<td>Container / cargo management</td>
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<td>Operations</td>
<td>Maintenance</td>
<td>Emergencies</td>
<td>Decommissioning</td>
<td>Remarks</td>
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<td><strong>Shipbuilding and repair</strong></td>
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<td>Usually by traditional survey methods</td>
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<tr>
<td>Operations</td>
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<td></td>
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<td>Drone surveys may require GNSS for flight</td>
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<td></td>
<td></td>
<td>50m</td>
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<td>Emergency services to locate incident on shore – many other systems available so no need for A.915 SAR criteria</td>
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<td></td>
<td>Main requirements for survey, mapping, charting and signage – other geographic methods available</td>
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<td>Operations</td>
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<td>Loss of GNSS might mean closure of facilities and loss of revenue</td>
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<td>Maintenance</td>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td>Loss of GNSS might mean closure of facilities and loss of revenue, or increased risk to tourists and workers – e.g. Whale watching</td>
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<tr>
<td>Emergencies</td>
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<td>Recreational and leisure boating</td>
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<td>Planning</td>
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<td></td>
<td>A.915 is 1m for exploration, but blocks within 10m permissible for licensing</td>
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<td></td>
<td></td>
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<td></td>
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<td></td>
<td>Vertical accuracy requirements are less than 0.1m (A.915)</td>
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<td></td>
<td></td>
<td></td>
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<td>Especially if maintenance required to environmental protection</td>
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<td>Emergencies</td>
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<td>10m</td>
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<td>Major risks for life and environment</td>
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<td></td>
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<td>Same as for planning</td>
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<td>0.1m</td>
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<td>The movement of cargo and passengers by vessel</td>
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<td>95% Acc</td>
<td>Where</td>
<td>Remarks</td>
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<td>Ocean</td>
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<td>10m</td>
<td>&lt;12 EEZ INTL</td>
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<tr>
<td>Coastal</td>
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<td>10m</td>
<td>CW TW</td>
<td></td>
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<td>Port approaches and restricted waters</td>
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<td>CW</td>
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<td>CW</td>
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</tr>
<tr>
<td>Inland waterways</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5m</td>
<td>A.915 10m is too lax</td>
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<tr>
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<td></td>
<td></td>
<td>10m</td>
<td>Anywhere</td>
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<tr>
<td>Automatic collision avoidance</td>
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<td></td>
<td>10m</td>
<td>CW TW &lt;12 INTL</td>
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<tr>
<td>Icebreakers</td>
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<td>1m</td>
<td>CW TW &lt;12 INTL</td>
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<tr>
<td>Track control</td>
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<td></td>
<td>10m</td>
<td>CW TW &lt;12 INTL</td>
<td></td>
</tr>
</tbody>
</table>

### RISK SECTORS

| Ship to ship transfers | | 0.5m | (UK) TW >12 INTL | Special permissions have to be obtained for these operations (UK). Red risk because of the very significant environmental risk and the difficulty of responding |
| Illegal activities | | | | |
| Fishing and immigration | | | 10m | |

### EMERGENCY RESPONSE

| Emergency response | SAR | | | | 10m | UK SAR |
| | Towage | | | | 10m | UK SAR |
| | Salvage | | | | 10m | EEZ |
| | Pollution response | | | | 10m | UK PCZ |

### EMERGING SECTORS

7 The UK Regulations cease to apply from 1 April 2019 – this means that STS will not be permitted inside TW and transfers may therefore migrate back to the “Southwold box”, increasing risk.

8 These requirements are for law enforcement to deter, detect and prosecute, not for the illegal activity itself.
<table>
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<tr>
<th>Activity</th>
<th>Acc</th>
<th>Int</th>
<th>Aval</th>
<th>Cont</th>
<th>95% Acc</th>
<th>Where</th>
<th>Remarks</th>
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<td>ITZ CW TW?</td>
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<tr>
<td>Planning</td>
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<td>100m</td>
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<td>Emergencies</td>
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<td>1m</td>
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<td>For water quality and worker safety</td>
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<td>10m</td>
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<td>Deep sea mining (eg ATLAS project) 10km licence blocks</td>
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<td>SAR iaw A.915</td>
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<td>10m</td>
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<td><strong>Carbon capture and storage</strong></td>
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<td>CW TW &lt;12 INTL</td>
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<td>Dynamic positioning</td>
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<td>0.1m</td>
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<td>5m</td>
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### Offshore wind

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<td></td>
<td></td>
<td>0.1m</td>
<td>ITZ CW TW &lt;12 INTL REZ</td>
<td>0.1m for construction. Green for coast only</td>
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<tr>
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<tr>
<td>Operations</td>
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<td>Normally green as other methods available</td>
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### Ocean energy

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<tr>
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### ENABLERS

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<td>Classifications from A.915</td>
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<td>Ship to ship co-ord</td>
<td>10m</td>
<td>AIS-dependent unless shore radar present</td>
</tr>
<tr>
<td>Ship to shore co-ord</td>
<td>10m</td>
<td>AIS-dependent unless shore radar present</td>
</tr>
<tr>
<td>Shore to ship management</td>
<td>10m</td>
<td>AIS-dependent unless shore radar present</td>
</tr>
<tr>
<td>Local VTS</td>
<td>1m</td>
<td>Important in low visibility</td>
</tr>
<tr>
<td>VTMRRR</td>
<td>100m</td>
<td>Within AIS coverage EU requirement</td>
</tr>
<tr>
<td>Traffic Separation Schemes</td>
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<td>EU requirement</td>
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### Nautical charts and publications

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<td>UK EEZ 0.1m vertical. Other EU Member States?</td>
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<td>Oceanography</td>
<td>10m</td>
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<td>Acc</td>
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<tr>
<td><strong>Cable laying</strong></td>
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<td>Cables and pipes</td>
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<td><strong>AtoNs</strong></td>
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<td>Ocean</td>
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<td>Coastal</td>
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<td>Ports</td>
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<tr>
<td><strong>Use of drones for ship and port survey</strong></td>
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</tr>
</tbody>
</table>

**Table 3 – Blue Economy applications of GNSS – importance and risk assessment**

Definitions of Accuracy, Integrity, Availability and Continuity taken from Blackett page 19, and 95% Accuracy Figures are all from IMO Resolution A.915(22) January 2002 (where stated) unless the figure is in Red in which case it is an expert assessment for this study because A.915 is outdated or the activity is not included in A.915.
Key

- Red = Very important to safety, environmental protection and efficiency of the activity and GNSS degradation brings high risk
- Amber = Medium importance to safety, environmental protection and efficiency of the activity and GNSS degradation brings moderate risk
- Green = Low importance to safety, environmental protection and efficiency of activity and GNSS degradation brings low risk, or the activity can wait until GNSS/RPNT restored
- Clear = if no GNSS is available alternate means can be employed at increased time and cost
- Risk – risk to any or all of life, economic loss (to ships, equipment, cargo, production etc) or environmental damage
- Where column – ITZ Inter tidal zone, CW Coastal Waters, TW Territorial Waters, <12 Within 12nm, EEZ Exclusive Economic Zone, INTL International Waters, UKSAR UK SAR Region, REZ UK Renewable Energy Zone, PCZ UK Pollution Control Zone
7.2.4.2 What’s the fuss? – Competent Navigators Can Work Without GNSS Right?

Many navigators argue that mariners can manage without GNSS for positioning. They argue that this is true because there are many other methods used to achieve positioning and collision avoidance, but it is not how shipping works or is regulated today. Shipping is a 24/7 activity, day or night, week-day or week-end, fair or foul, good or poor visibility, storm or calm, the flow of people, goods and fuel continues, especially with “just in time” commercial imperatives. There are also special requirements for dynamic positioning, to keep a vessel in an absolute or relative position, to achieve its tasks, and that cannot be done without GNSS or a very capable inertial navigation system.

Moreover, the number of regular reports required from ships means that many of the submissions are semi-automated and use positions and times from GNSS. Completing the reports manually would not be practicable and would divert attention from more safety critical human tasks on board. In addition, the seas, especially coastal waters, are busy with maritime traffic, and with restrictions on manoeuvring and sea room that complicate navigation to the point where GNSS becomes an essential tool to speed up decision making and maintain safety; see Figure 47.

Figure 47 – Plenty of sea space? Diagram courtesy NLAI Ltd.
The United Nations Inter-Governmental Conference on biodiversity in areas beyond national jurisdiction (BBNJ)\(^9\), and the EU Maritime Spatial Planning Directive\(^{10}\), in addition to the continuing efforts of OSPAR, are further evidence that international and regional bodies are seeking to apply an ecosystems based approach to spatial planning which, while notionally taking account of socio-economic activity, puts ecosystems protection at the top of the agenda. This implies that shipping and many other maritime activities may increasingly find they need to avoid larger areas, or that speed or anchoring or other restrictions apply. For the mariner this means that continuous accurate positioning is required for compliance and often GNSS is the most, and only, efficient way to do this.

The EU Horizon 2020 MUSES project\(^{11}\) has also investigated the multi-usage of the seas and developed a number of geographical case studies where nine “competing” maritime activities could be closely positioned. MUSES acknowledged the complex relationships with WFD, MSFD and MSPD.

\[\text{Figure 48 – EU MUSES project – ocean multi-use [88].}\]

It is equally true that many national and EU studies that support the ecosystem-based approach to maritime spatial planning themselves depend on GNSS for their own data gathering and analysis, and contact with some of these EU marine and maritime studies has revealed a low level of understanding of the accuracy, integrity, availability and continuity parameters that may affect GNSS, and consequently their effects on the studies.

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\(^{11}\) Retrieved 11 April 2019 from https://muses-project.com
7.2.4.3 Summary and Conclusions

This section has presented a number of applications found within the Blue Economy, their RNP parameters and the criticality of each of those parameters in terms of maritime risk.
8 The Scenario and Use Cases

As presented in previous sections of this report stakeholder requirements take a number of forms: from quantitative RNP requirements such as accuracy, integrity performance, etc, expressed in numbers, to more general operational requirements and geographical coverage requirements.

We have seen that there are numerous organisations that specify RNP requirements for various user applications, and it is the intention of MarRINav to take those into account. In addition, we understand that the UK coastline is festooned with offshore infrastructure: windfarms, cables, aquaculture, port approach channels, Traffic Separation Schemes, oil and gas fields, to name several examples. There is also the need to consider requirements brought about by vessel traffic density and the risk of collision and grounding. So there is a geographical requirement for the regions which we should expect our candidate RPNT and data communication infrastructure to cover. These wide-area, regional, or macro requirements, can be best represented in a Geographical Information System (GIS) as we have explained.

In this section of the report we drill down into the finer detail of the activities undertaken by human (and machine) operators in order to understand more clearly those processes that employ GNSS and data at the local level, activity by activity (use case by use case). For example where is GNSS employed in a port terminal? What equipment uses GNSS for positioning, and what systems are currently available to provide backup in situations where GNSS fails, or performance is degraded? In other Work Packages we will consider that if no adequate RPNT systems are already available, what RPNT systems can be put in place at the various points of use of PNT information?

We have already seen examples of user needs and requirements for RPNT. Another way of eliciting user requirements is through the use of scenarios [89]. Scenarios are the “stories” of what activities are undertaken within a user’s process from start to finish and we can consider each activity in the scenario as being a Use Case for how GNSS is employed. Figure 49 illustrates the relationship between users, scenarios and user requirements.
Scenarios involve the exercising of a user need. There are various actors within the scenario, but an actor is not actually a concrete individual or a system, but rather a role. As such, actors might include stakeholders, including VTS operators, pilots, navigators and ships’ masters, but also temperature sensors, GNSS receivers, vessels manned or otherwise, etc. Actors will take part in a number of activities within the scenario [91].

Scenarios can be described diagrammatically, illustrating the entire process chain, for example, for the transport of a cargo of containers. We could start with the ship making way in deep ocean, entering the coastal region, making way along a port approach and eventually berthing and unloading. The scenario can then continue with a single truck leaving port with a single container. At each point in the scenario we can explicitly identify the navigation requirements of the ship, the positioning requirements of the cargo, and include land-side equipment (straddle carriers, cranes, etc.) and the navigation of the truck.

Each of the data flow and PNT considerations can later be ascribed to a particular activity in the scenario. Use Cases for GNSS (and ultimately RPNT) will then come from each of the activities within which GNSS is employed.

The idea proposed for MarRINav is to break the scenario down into a number of discrete activities, and for each activity:

1. Identify any dependence upon PNT (GNSS in the first instance), including data flows required to support PNT;
2. Identify any source(s) of Resilient PNT already in place.
Eventually the process will lead to:

1. The identification of the functional and non-functional system requirements for a RPNT system to be put in place;
2. The identification of supporting resilient data flows for that Resilient PNT system.

Ideally, we would use a limited number of scenarios to cover as many Use Cases of GNSS as possible.

In the following subsections we present a single scenario and the methods of analysis of the Use Cases discovered. Reference is made to the maritime literature, in particular documentation pertaining to bridge procedures [8], and most importantly the development, execution and monitoring of a Passage Plan. These are human centric activities – it is after all the human being, the Officer of the Watch, aboard ship that is dependent on Resilience and Integrity of PNT in order to ensure the safe passage of the ship, it's operational efficiency and the protection of the marine environment.

We introduce passage planning next, for background information, so that the reader understands the complex operational environment within which a vessel and its human crew operates. Elements of this background will be referenced when discussing the scenario in order to identify PNT and supporting data communication requirements.

### 8.1 Passage Planning

Before the start of the voyage the Master of the vessel will have prepared a Passage Plan [92], the purpose of which is to develop a comprehensive navigation plan for the safe conduct of the ship from berth to berth. The plan should identify a route which:

- Recognises hazards, and assesses associated risks and decision points;
- Ensures that sufficient sea room and depth of water is available;
- Includes appropriate position fixing opportunities;
- Complies with relevant reporting requirements and routeing measures for ships;
- Takes into account anticipated traffic and weather conditions; and
- Complies with all applicable environmental protection measures.
There are four stages of passage planning as outlined in Figure 50.

8.1.1 Appraisal

The first stage of passage planning is the *appraisal* phase, which is the process of gathering all information relevant to the proposed passage, which will allow risks to be identified and assessed to ensure that the passage plan is safe.

Factors that need to be considered during the appraisal phase of passage planning include:

- Navigation
- General/Operational
- Environmental
- Contingency

Appraisal includes the process of ensuring up to date maritime publications are available aboard ship, including official charts and other electronic or paper publications.

It is the Master of the vessel’s responsibility to check and approve the passage plan before departure. However it is understood that it might be impractical to include all details, particularly some of those details relating to arrival at the destination port and in this case the plan should be finalised as soon as possible.
Part of the appraisal phase of passage planning considers **environmental** factors of the proposed route, including:

- Ballast water management
- Emission Control Areas (ECA)
- MARPOL Special Areas
- National or regional requirements
- Particularly Sensitive Sea Areas (PSSA)
- Port reception facilities

The appraisal also considers **navigation** factors, including:

- Advice in Sailing Directions
- Anchoring and contingency options
- Availability and adequacy of charts and reliability of navigation aids
- Availability and reliability of navigation aids
- Available sea room and traffic density
- Communications including Maritime Safety Information (MSI) and GMDSS (Global Maritime Distress and Safety System)
- Pilotage requirements
- Draught restrictions including air draught (height of ship above sea-level), under keel clearance (UKC) requirements and squat
- Position fixing requirements
- Reliability of propulsion and steering systems and defects affecting the control or navigation of the ship
- Route selection and waypoints
- Routeing and reporting measures
- Weather routing

The above list of points indicates information and systems required when making way in any phase of navigation.

**Any Resilient PNT system will need to provide sufficient resilience so that none of the above factors are compromised.**

### 8.1.1.1 A note on the Accuracy of Nautical Charts

When used for passage planning, charts, electronic or paper, should be up to date. Electronic charts can be either ENC (Vector based Electronic Navigation Charts) or RNC (Raster Navigation Charts). Vector charts (based on IHO S-57 and soon to be S-100) allow for the provision of layers of information that can be switched on or off depending on the needs of the mariner and the desire for reduced clutter. RNC charts are based on rows and columns of image pixel data at a particular resolution; thus zooming in on an RNC results in reduced

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12 Sailing Directions provide essential information on all aspects of navigation including hazards, buoyage, weather patterns, pilotage details, regulations, port facilities and guides on port entry.
resolution and a loss in clarity of the information content. Accuracy of ENC data is assessed through the use of the Category Zone of Confidence (CATZOC) [93].

ENC, RNC and paper charts are typically based on the same hydrographic survey data. This means that an ENC is not more accurate than an RNC or paper chart covering the same area. Paper charts show charted objects (including hazards) with a precision of approximately 0.3 mm (15 metres or more at scales of 1:50,000 or smaller). Due to screen resolution of ECDIS, the precision of charted objects on ECDIS may not be substantially different from that of paper charts.

In addition, some bathymetry data is quite old and although areas with shifting shoals are surveyed more regularly there will always be uncertainty in chart data that must be taken into account along with uncertainty in PNT data. Also, there are human factor issues related to ENCs, especially in regard to changing range scales when the resolution of surveyed data may not be sufficient for the chosen display scale or when some features may occult when switching range scales. Human factors are therefore very important in the interplay between PNT data, its portrayal and the ENC.

8.1.2 Planning

Following the appraisal of all charts, nautical publications and additional information, a detailed passage plan should be prepared. This covers the entire passage from berth to berth, including pilotage areas (port approach). Planning for any one section of a route should be undertaken using either all electronic or all paper charts, rather than a mixture of both types. It should be recalled that vessels are no longer required to carry paper charts provided that two redundant ECDIS systems are available on the bridge (Section 4.1.2 and SOLAS Chapter V Regulation 19).

Figure 51 illustrates the planning requirements versus the General Navigation phase of voyage under consideration. Reference will be made to these requirements within the scenario description contained in Section 8.2.
ECDIS (Electronic Chart Display and Information System) is a useful tool for increasing the efficiency of passage planning. In an era when certified vessels no longer need to carry paper charts, this may now be the only means aboard ship. Effective use of route planning tools, voyage notes and action points should be part of a comprehensive passage plan.

In the context of PNT information the following should be considered when using ECDIS for passage planning:

- A maximum acceptable cross track distance (XTD) should be applied to each leg of a route. This should comply with any requirements in the Ship’s Management System (SMS) and be appropriate for the area;
- Safety depths and safety contours should be calculated and setup in accordance with the Under Keel Clearance (UKC) requirements in the SMS;
• Estimated Time of Arrival (ETA) information should be set manually or using route planning tools. If this is set incorrectly it may affect tidal data and time dependent information associated with the route;  
• Current and tidal data, if integrated with ECDIS and up to date, should be applied to the route;  
• Information relating to the vessel’s characteristics should be checked and confirmed as correct. This includes information about draught (including any allowance for squat or additional safety margins), turn radius and vessel dimensions.

8.1.2.2 Maritime Safety Information

Weather information (including gale warnings), NAVAREA warnings and coastal navigational warnings are broadcast by radio-telephony from coast radio stations and by NAVTEX. Long range weather warnings are broadcast by satellite communications systems, such as SafetyNET, along with NAVAREA navigational warnings as part of the World-Wide Navigational Warning Service (WWNWS). Details of weather routeing services for ships and information for shipping are contained in lists of radio signals and in [94].

8.1.2.3 Ship’s Routeing

Routeing measures for ships are designed to:

• Reduce the risk of collision between ships in areas of high traffic density;  
• Reduce the risk of grounding;  
• Manage shipping in environmentally sensitive sea areas.

Ships’ routeing measures can be adopted internationally by the IMO. Such measures are recommended for use by, and may be mandatory for, all ships, or certain types of ship, or for ships carrying certain cargoes. Mandatory ship’s routeing measures should always be used unless the ship has compelling safety reasons for not following them. IMO routeing schemes will be shown in charts with a note of any pertinent provisions as to their use. Further details will be found in sailing directions.

8.1.2.4 Other Considerations

Other considerations of passage planning include Ship Reporting Systems and Vessel Traffic Services. These are both explained in Section 4.

8.1.3 Execution and Monitoring

Execution and monitoring of the passage plan shall be described under the relevant voyage phase of the scenario described in Section 8.2.

13 Increasingly ETA information is being used in the ongoing assessment of arrival time at a destination port as part of the provision of just-in-time port services, for example berth availability, container truck slot arrival time, pilot booking, etc.
8.2 The Scenario – Large Container Vessel Executing a Passage Plan

8.2.1 Introduction

We consider here the scenario of a single container aboard a large cargo container vessel. The scenario starts with the vessel in mid-ocean making way to its destination port by adhering to a passage plan and then discharging its cargo onto the wharf at the destination port. Having been unloaded onto the wharf, we then follow the container through the port and finally out of the port gate on the trailer of a truck. The scenario may be broken down into a number of activities for the entire process:

- Activity 1 – Vessel is making way in ocean phase
- Activity 2 – Vessel approaches UK coastline, and enters coastal voyage phase
- Activity 3 – Vessel arrives at an anchorage, or a pilot station if a pilot is required
- Activity 4 – Vessel departs from pilot station or anchorage with or without a pilot aboard and enters port approach voyage phase
- Activity 5 – Vessel enters port phase and manoeuvres, perhaps to turn around if required
- Activity 6 – Vessel arrives at berth, begins berthing manoeuvres and is eventually moored
- Activity 7 – Vessel’s cargo is cleared and unloaded by crane; our single cargo container is now on the wharf either waiting to be collected or is on a port transport truck
- Activity 8 – Container is collected from the wharf and transported to the stack, perhaps on a straddle carrier or truck
- Activity 9 – Cargo container is loaded onto truck for departure from port
- Activity 10 – Truck makes way through port and exits port gate

These activities can then be broken down into further detail to elicit the actors involved, the activities undertaken, the equipment employed and to identify the use of data and PNT information.

Figure 52 shows a simple UML (Unified Modelling Language) Activity Diagram that describes The Scenario. We now consider each of the activities (green shaded boxes with rounded corners) within The Scenario.

For each activity in the Scenario we consider the questions outlined in Section 7.2:

1. What are the quantitative RNP requirements?
   a. As specified by documentation

2. How is GNSS used?
   a. Shore-side
   b. Ship-side

3. What backups/alternatives for PNT are already in place?
4. What are the data communication requirements that support PNT for that application and what technical infrastructure is in place to provide this support?

5. What future technologies, in the timeframe of 2030, are expected to come into operation that require PNT information?

In addition we consider:

1. The use of automated/unmanned systems including Maritime Autonomous Surface Ships (MASS) and automated systems at ports, now and in the future timeframe of 2030.

8.2.2 Ocean Voyage Phase

We consider first the vessel and its cargo operating in the Ocean Voyage Phase as defined in Section 7.2.1, and making way to landfall in the UK.
From a human perspective, passage planning for Ocean phase includes the following preparations (refer to Figure 51):

- Anticipated waypoint arrival times
- Cross track distances (XTD)
- Identification of navigational hazards
- Leg distances
- Planned track with true\textsuperscript{14} course
- Safety depths and safety contours

When planning ocean passages, particular consideration should be given to:

- Ocean routing charts which provide information on ocean currents, winds, ice limits and load lines\textsuperscript{15};
- Load Line charts which provide information on zones and seasonal periods required to assist in compliance with the IMO International Convention on Load Lines;
- Weather routing services;
- The use of gnomonic projection charts for plotting great circle routes, as appropriate.

The following considerations may have an impact on the selection of an ocean route:

- Ocean currents and the impact on passage speed;
- Weather conditions including anticipated seasonal variations such as heavy weather, tropical storms, ice and reduced visibility; and
- Environmental protection measures and associated requirements that may extend into an ocean route.

Landfall targets need to be identified and the expected radar and visual ranges considered. With respect to lights, this will include rising and dipping ranges and the arc/colours of sector lights.

### 8.2.2.1 Ocean Voyage Phase: RNP Requirements for General Navigation

Referring to Table 4, which has been extracted from Appendix B, it can be seen that there are clear differences between the requirements from various sources (IMO, IALA and ERNP).

*MarRINav should seek stakeholder input regarding the parameter values that should be adopted for Resilient PNT, as these decisions will affect the nature of the proposed Resilient PNT architecture.*

MarRINav notes that the time period for continuity has now been changed to 15 minutes and there is a clear reason to adopt the same period for the integrity parameter based on the

\textsuperscript{14} Bearings taken with reference to true North, rather than magnetic North, in order to ensure compatibility with charted positions.

\textsuperscript{15} A Load Line is a special marking, positioned amidships, which depicts the draft of the vessel and the maximum permitted limit in distinct types of waters to which the ship can be loaded. The fundamental purpose of a Load Line is to allot a maximum legal limit up to which a ship can be loaded by cargo.
interdependence of integrity and continuity as outlined in Section 2; this will be further explored in Work Package 2.

<table>
<thead>
<tr>
<th>System Level Parameters</th>
<th>Service Level Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute Accuracy</td>
<td>Availability % per 30 days</td>
</tr>
<tr>
<td>Integrity</td>
<td>Continuity % over 15 minutes</td>
</tr>
<tr>
<td>Horizontal (metres)</td>
<td>Coverage</td>
</tr>
<tr>
<td>Alert Limit (metres)</td>
<td>Fix Interval (Seconds)</td>
</tr>
<tr>
<td>Time to Alarm (Seconds)</td>
<td>/</td>
</tr>
<tr>
<td>Integrity Risk (per 3 hours)</td>
<td>/</td>
</tr>
</tbody>
</table>

IMO A.915  
10 25 10 10.5 99.8 N/A Global 1

ERNP  
100 Not Specified Not Specified Not Specified 99.8 99.97 in 15 Minutes Not Specified Not Specified

IMO A.1046  
100 Not Specified Not Specified Not Specified 99.8 (Signal/System only) N/A Not Specified 2

IALA R-129 (Backup)  
1000 2500 60 10.4 99 N/A Global 60

Table 4 – RNP Requirements for Ocean Phase from four sources, IMO A.915, IMO A.1046, IALA R-129 and the ERNP.

8.2.2.2 Ocean Voyage Phase: How is GNSS (PNT) Used?

PNT information is used aboard ship and by shore-side services and systems.

8.2.2.2.1 Ocean Voyage Phase: Executing and Monitoring the Passage Plan

During the Ocean phase the Officer of the Watch (OOW) will follow the passage plan, monitor the progress of the vessel, and will be making use of Ocean Passage/Routeing Charts and Guides, providing information on established ocean routes.

Compliance with the passage plan should be closely and continuously monitored by the OOW, in the context of PNT information this includes:

- To check that the ship’s position is maintained within an authorised cross track error (XTD), including following alterations of course to avoid collision or following planned alteration of course;
- By fixing the position of the ship at a frequency dependent on prevailing conditions and the proximity of navigational hazards;
- By cross-checking the ship’s position by all appropriate means;
- By monitoring the integrity information displayed on navigational equipment.

Traffic density is low, and there is little risk of collision with vessels. However, there is risk of collision with floating cargo containers, and ice in Sea Area A4. Risk of jamming and spoofing is low, however risk levels of solar events are consistent with that of other voyage phases.
8.2.2.2 Ocean Voyage Phase: Shipboard equipment using PNT information:

Table 5 illustrates the systems aboard ship; reference is made to section 4 as appropriate.

<table>
<thead>
<tr>
<th>System</th>
<th>Notes (if required)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECDIS</td>
<td>Section 4.1.2 ECDIS is used to monitor XTE and alarm if out of tolerance.</td>
</tr>
<tr>
<td>GMDSS</td>
<td>Section 4.1.3 We assume Sea Area A3. Radio communications, including DSC, will be by HF (High Frequency) radio or satellite link. If the satellite antenna is of an older Inmarsat variation then GNSS may be employed to steer the antenna onto the satellite signal, augmenting a signal strength tracking technique.</td>
</tr>
<tr>
<td>AIS</td>
<td>Section 4.1.3 AIS may be employed to overlay vessel positions on radar, but the mariner should be aware that not all vessels carry AIS transponders.</td>
</tr>
<tr>
<td>VDR</td>
<td>Section 4.1.4</td>
</tr>
<tr>
<td>Gyrocompass</td>
<td>Section 4.1.5. May need to be calibrated by GNSS infrequently due to reduced manoeuvring in Ocean phase. Gyrocompass may also be considered to be a backup system for heading information.</td>
</tr>
<tr>
<td>Radar</td>
<td>Section 4.1.6. Radar will be used to track and identify shipping, icebergs, small sailing craft and other floating objects. When GNSS is available the radar may be operated in ground stabilised mode, however ground stabilisation is only useful when close to coastal features where the motion of fixed objects should be eliminated from tracking.</td>
</tr>
<tr>
<td>Engine Management</td>
<td>Section 4.1.7</td>
</tr>
<tr>
<td>Satellite Communications</td>
<td>Section 4.1.8</td>
</tr>
<tr>
<td>Dynamic Positioning Systems</td>
<td>Section 4.1.9 Relevant for certain applications only</td>
</tr>
<tr>
<td>VDES</td>
<td>Section 4.1.10 N/A</td>
</tr>
<tr>
<td>Hydrographic Survey Equipment</td>
<td>Section 4.1.11 N/A</td>
</tr>
<tr>
<td>Helideck Stability Monitoring</td>
<td>Section 4.1.12 For ship to ship transfer, rescue.</td>
</tr>
<tr>
<td>PPU</td>
<td>Section 4.1.13 N/A</td>
</tr>
<tr>
<td>ODME</td>
<td>Section 4.1.14</td>
</tr>
<tr>
<td>BDM</td>
<td>Section 4.1.15</td>
</tr>
<tr>
<td>Track Control</td>
<td>Section 4.1.17</td>
</tr>
<tr>
<td>NAVTEX</td>
<td>Section 4.1.18</td>
</tr>
</tbody>
</table>

Table 5 – Shipboard systems requiring PNT information aboard ship. Entries marked N/A are not relevant to this activity.

8.2.2.3 Ocean Voyage Phase: Shoreside services employing PNT information include:

Table 6 illustrates shoreside services; reference is made to section 4 as appropriate.

<table>
<thead>
<tr>
<th>System</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIS Service</td>
<td>Section 4.2.1 N/A</td>
</tr>
<tr>
<td>VTS</td>
<td>Section 4.2.2 N/A</td>
</tr>
<tr>
<td>Ship Reporting Systems</td>
<td>Section 4.2.3</td>
</tr>
<tr>
<td>PCDM</td>
<td>Section 4.2.4</td>
</tr>
<tr>
<td>VMS</td>
<td>Section 4.2.5 N/A – we assume fishing vessel operate in coastal phase</td>
</tr>
<tr>
<td>CERS</td>
<td>Section 4.2.6 The reception of the 72 hour arrival message will include the ship's position. If within range of a coastal station this will be cross-checked with AIS/SSN.</td>
</tr>
<tr>
<td>SafeSeaNet</td>
<td>Section 4.2.7 N/A</td>
</tr>
<tr>
<td>Mobile AtoN Marking</td>
<td>Section 4.2.8 N/A</td>
</tr>
<tr>
<td>Floating AtoN Monitoring</td>
<td>Section 4.2.9 N/A</td>
</tr>
</tbody>
</table>

Table 6 – Shore services requiring PNT information. Entries marked N/A are not relevant for this activity.
8.2.2.4 Ocean Voyage Phase: What backups/alternatives for GNSS derived PNT Information are already in place?

Table 7 illustrates shore-side ship; reference is made to section 5 as appropriate.

<table>
<thead>
<tr>
<th>System</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual Techniques</td>
<td>Section 5.1 N/A apart from general lookout keeping</td>
</tr>
<tr>
<td>Radar</td>
<td>Section 5.2</td>
</tr>
<tr>
<td>Gyrocompass</td>
<td>Section 5.3 Electronic cross checking of the ships’ position may be limited to a dead reckoned solution using ship’s magnetic or gyro compass (Section 4.5) and the speed log.</td>
</tr>
<tr>
<td>Speed Log</td>
<td>Section 5.5 Electronic cross checking of the ships’ position may be limited to a dead reckoned solution using ship’s magnetic or gyro compass (Section 4.5) and the speed log.</td>
</tr>
<tr>
<td>Inertial Navigation Systems</td>
<td>Section 5.6</td>
</tr>
<tr>
<td>Sextant and Other Celestial</td>
<td>Section 5.7</td>
</tr>
</tbody>
</table>

Table 7 – Currently available “backup” systems.

8.2.2.5 Ocean Voyage Phase: What future technologies, in the timeframe of 2030, are expected to come into operation that require PNT information?

Autonomous vessels, refer to Section 3.4. Autonomous Vessels

8.2.2.6 Ocean Voyage Phase: What are the data communication requirements that support PNT and what technical infrastructure is in place to provide this support?

- Satellite broadband
- GMDSS, including LRIT [47], with HF or satellite communication system

8.2.2.3 Ocean Voyage Phase: e-Navigation

e-Navigation services (Appendix C) that are relevant during Ocean Voyage phase include:

- MS5 – Maritime Safety Information Service (MSI)
- MS8 – Vessel Shore Reporting
- MS9 – Telemedical Assistance Service
- MS10 – Maritime Assistance Service (MAS)
- MS11 – Nautical Chart Service
- MS12 – Nautical Publications Service
- MS13 - Ice Navigation Service
- MS14 – Meteorological Information Service
- MS15 – Real-time Hydrographic and Environmental Information Service
- MS16 – Search and Rescue Service
- MS17 – Piracy Service (Proposed)

Most of these services will require the availability of reliable PNT information in order to maximise their benefits.

8.2.2.4 Ocean Voyage Phase: Maritime Autonomous Surface Ships (MASS)

Maritime Autonomous Surface Ships (MASS), or Unmanned Surface Vessels, are being considered by IMO MSC and correspondence groups. The working assumption will be that
MASS will have to comply with existing regulations rather than requiring their amendment. Thus, USVs will have no more or no less reliance on GNSS than manned ships, and will have to be capable of adopting measures to compensate for GNSS disruption. The human backup on board a manned ship will find equivalence in USVs by the human in the USV control room ashore (provided they have the relevant training, qualifications and experience). There is a view that identifying a USV at sea might lead other mariners to treat the ship differently from a manned ship when encountered; during Coastal phase this psychological effect is likely to be more of a concern than during Ocean phase where traffic density is lower.

8.2.3 Coastal Voyage Phase

Next, we consider the vessel and its cargo operating in the Coastal Voyage Phase as defined in Section 7.2.1, and making way to port approach.

In addition to those preparations made for Ocean phase, the preparations for Coastal phase include the following (refer to Figure 51):

- Clearing bearings/ranges based on charted features
- Conspicuous charted features for position fixing
- No-go areas
- Routeing and reporting requirements
- Safe water, allowing for height of tide, under keel clearance (UKC), air draught and squat
- Tidal height and stream information
- Decision points for critical manoeuvres
- Contingency plans, including anchorages

Margins of safety in coastal or restricted waters are likely to be less than for the Ocean phase due to the available depth of water, proximity of land, coastal infrastructure and increased traffic density. The following factors should be considered:

- The importance of passing charted and other features at a safe distance
- Advice in sailing directions
- Available depth of water and tidal information contained in tide tables and tidal stream atlases
- Availability of visual and radar fixing opportunities
- Ship’s routing and reporting measures, as well as the availability of Vessel Traffic Services (VTS)
- The reliability of the ship’s propulsion and steering systems
- Environmental protection measures and associated requirements, including fuel changeover procedures

8.2.3.1 Coastal Voyage Phase: RNP Requirements for General Navigation

MarRINav notes that the time period for continuity has now been changed to 15 minutes [72], and there is a clear reason to adopt the same period for the integrity parameter based on the interdependence of integrity and continuity.
### System Level Parameters | Service Level Parameters
<table>
<thead>
<tr>
<th>Absolute Accuracy</th>
<th>Integrity</th>
<th>Availability % per 30 days</th>
<th>Continuity % over 15 minutes</th>
<th>Coverage</th>
<th>Fix Interval (Seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal (metres)</td>
<td>Alert Limit (metres)</td>
<td>Time to Alarm (Seconds)</td>
<td>Integrity Risk (per 3 hours)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **IMO A.915**
  - 10
  - 25
  - 10
  - 10.5
  - 99.8
  - N/A
  - Global
  - 1

- **ERNP**
  - 10
  - Not Specified
  - Not Specified
  - Not Specified
  - 99.8
  - 99.97
  - Not Specified
  - Not Specified

- **IMO A.1046**
  - 10
  - Not Specified
  - Not Specified
  - Not Specified
  - 99.8 (Signal/System only)
  - 99.97
  - Not Specified
  - 2

- **IALA R-129 (Backup)**
  - 100
  - 250
  - 30
  - 10.4
  - 99
  - N/A
  - Regional
  - 15

Table 8 – RNP Requirements for Coastal Voyage Phase from four sources, IMO A.915, IMO A.1046, IALA R-129 and the ERNP.

#### 8.2.3.2 Coastal Voyage Phase: How is GNSS (PNT) Used?

PNT information is used aboard ship and by shore-side services and systems. With the increased risk during coastal voyage phase timeliness of PNT information becomes more important.

##### 8.2.3.2.1 Coastal Voyage Phase: Executing and Monitoring the Passage Plan

During the Coastal phase the Officer of the Watch (OOW) will follow the passage plan and monitor the progress of the vessel. Compliance with the passage plan should be closely and continuously monitored by the OOW:

- To check that the ship’s position is maintained within an authorised cross track error (XTD), including following alterations of course to avoid collision or following planned alteration of course;
- By fixing the position of the ship at a frequency dependent on prevailing conditions and the proximity of navigational hazards;
- By cross-checking of the ship’s position by all appropriate means including:
  - By visual and/or radar fixing techniques using ranges and bearing of charted objects;
  - By echo sounder to monitor depths and contours
- By monitoring the integrity of information displayed on navigational equipment.

It is to be understood that navigating in coastal, or restricted waters increases the dangers of navigation compared to those experienced during Ocean voyage phase. The need for good situational awareness is heightened. Procedures and Master’s orders should ensure that:
• Navigation is conducted on the most suitable large scale ENC or RNC, or paper chart if they are available;
• The position of the ship is fixed at frequent intervals by the most appropriate means;
• All relevant navigation marks are positively identified by the OOW;
• The OOW is aware of mandatory reporting requirements for routeing schemes – there is a drive to make this sort of reporting automatic;
• The OOW takes into account the ship’s draught and manoeuvring characteristics, which may affect navigation in restricted waters;
• The OOW is aware of the squat characteristics for individual loading conditions and the effect of ship speed on squat. In shallow water squat may have a critical effect on the manoeuvrability and the under keel clearance (UKC) of the ship.

In shallow water due diligence should be made for the increased draft and effects on steering caused by ship squat\textsuperscript{16}, which increases with increased ship speed.

Traffic density is higher and the need for look-out is greater due to the greater complexity of navigation compared to Ocean phase. Alarming bridge systems would be increasingly hazardous due to higher prioritisation load, as this could cause cognitive overload, at least temporarily.

Cases of jamming and accidental interference upon GNSS, while rare, have a higher probability the closer the vessel gets to “civilisation”.

More importance is given to relative than absolute position in Coastal phase navigation, although more confined waters and more navigation dangers would argue against that. More alternate means of establishing position are readily available. Radar, visual, optical, and echo sounder systems, and the presence of AtoNs (floating and fixed Aids to Navigation), all help to quickly establish approximate position in the event of GNSS disruption. It should be easier to spot GNSS degradation through rapid comparison with other means, although automated systems relying on GNSS derived PNT information would have to be updated manually.

\textsuperscript{16} The squat effect is the hydrodynamic phenomenon by which a vessel moving quickly through shallow water creates an area of lowered pressure that causes the ship to be closer to the seabed than would otherwise be expected. Squat effect is approximately proportional to the square of the speed of the ship.
8.2.3.2.2 Coastal Voyage Phase: Shipboard equipment using PNT information:

<table>
<thead>
<tr>
<th>System</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECDIS</td>
<td>Section 4.1.2 XTE tolerance will be reduced in line with the RNP requirements.</td>
</tr>
<tr>
<td>GMDSS</td>
<td>Section 4.1.3 We assume the vessel is operating between Sea Area A2 and A1. GMDSS communications will be by MF, VHF or satellite. Should there be an emergency AIS employs Digital Selective Calling (DSC) on VHF frequencies for automatic data transmission of vessel’s position.</td>
</tr>
<tr>
<td>AIS</td>
<td>Section 4.1.3 AIS may be employed to overlay vessel positions on radar, but the mariner should be aware that not all vessels carry AIS transponders. AIS provides more information about more vessels.</td>
</tr>
<tr>
<td>VDR</td>
<td>Section 4.1.4 Continuous recording throughout all phases.</td>
</tr>
<tr>
<td>Gyrocompass</td>
<td>Section 4.1.5 All the considerations as for Ocean Phase apply. Steaming errors are likely to accumulate more quickly because of the increased requirements on manoeuvring in areas of higher density traffic.</td>
</tr>
<tr>
<td>Radar</td>
<td>Section 4.1.6 As a vessel approaches the coastline traffic density can be expected to be increased compared to Ocean phase. In this context the radar is employed for situational awareness and collision avoidance. The radar’s ground stabilisation system uses GNSS. The radar heading reference may be the gyrocompass, which itself is calibrated using GNSS, but also the magnetic compass is used for this purpose. Manual techniques also exist for adjusting the heading reference.</td>
</tr>
<tr>
<td>Engine Management</td>
<td>Section 4.1.7 Assume continuous monitoring throughout all phases.</td>
</tr>
<tr>
<td>Satellite Communications</td>
<td>Section 4.1.8 Some data communications functions may be taken over by terrestrial systems.</td>
</tr>
<tr>
<td>Dynamic Positioning Systems</td>
<td>Section 4.1.9 Only relevant for certain applications</td>
</tr>
<tr>
<td>VDES</td>
<td>Section 4.1.10</td>
</tr>
<tr>
<td>Hydrographic Survey Equipment</td>
<td>Section 4.1.11</td>
</tr>
<tr>
<td>Heli deck Stability Monitoring</td>
<td>Section 4.1.12</td>
</tr>
<tr>
<td>PPU</td>
<td>Section 4.1.13 N/A</td>
</tr>
<tr>
<td>ODME</td>
<td>Section 4.1.14</td>
</tr>
<tr>
<td>BDM</td>
<td>Section 4.1.15</td>
</tr>
<tr>
<td>Ships Clocks and Timing</td>
<td>Section 4.1.16 The data communications frame structure of AIS is synchronised by time derived from GNSS (solely GPS as of 2019).</td>
</tr>
<tr>
<td>Track Control</td>
<td>Section 4.1.17 The same considerations for Ocean phase apply here, however the desired XTE is lower.</td>
</tr>
<tr>
<td>NAVTEX</td>
<td>Section 4.1.18</td>
</tr>
</tbody>
</table>

Table 9 - Shipboard systems requiring PNT information aboard ship.

8.2.3.2.3 Coastal Voyage Phase: Shoreside services employing PNT information

<table>
<thead>
<tr>
<th>System</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIS Service</td>
<td>Section 4.2.1</td>
</tr>
<tr>
<td>VTS</td>
<td>Section 4.2.2 N/A</td>
</tr>
<tr>
<td>Ship Reporting Systems</td>
<td>Section 4.2.3</td>
</tr>
<tr>
<td>PCDM</td>
<td>Section 4.2.4</td>
</tr>
<tr>
<td>VMS</td>
<td>Section 4.2.5</td>
</tr>
<tr>
<td>CERS</td>
<td>Section 4.2.6</td>
</tr>
<tr>
<td>SafeSeaNet</td>
<td>Section 4.2.7</td>
</tr>
<tr>
<td>Mobile AtoN Marking</td>
<td>Section 4.2.8</td>
</tr>
<tr>
<td>Floating AtoN Monitoring</td>
<td>Section 4.2.9</td>
</tr>
</tbody>
</table>

Table 10 - Shore services requiring PNT information.
8.2.3.3 Coastal Voyage Phase: What backups/alternatives for GNSS derived PNT Information are already in place?

<table>
<thead>
<tr>
<th>System</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual Techniques</td>
<td>Section 5.1</td>
</tr>
<tr>
<td>Radar</td>
<td>Section 5.2</td>
</tr>
<tr>
<td>Gyrocompass</td>
<td>Section 5.3; Steaming errors could build up more quickly due to increased amount of manoeuvring.</td>
</tr>
<tr>
<td>Speed Log</td>
<td>Section 5.5; In shallower water, the speed log can be Doppler/Sonar based, meaning that Speed Over Ground may be computed without reference to tidal set and drift</td>
</tr>
<tr>
<td>Inertial Navigation Systems</td>
<td>Section 5.6</td>
</tr>
<tr>
<td>Sextant and Other Celestial</td>
<td>Section 5.7; N/A – the timeliness of obtaining a sighting is probably not appropriate.</td>
</tr>
</tbody>
</table>

Table 11 - Currently available “backup” systems.

8.2.3.4 Coastal Voyage Phase: What future technologies, in the timeframe of 2030, are expected to come into operation that require PNT information?

Sea Traffic Management is likely to become more important. STM project services based on System Wide Information Management (SWIM) could extend the existing identified e-Navigation services and be particularly important for coastal phase and contribute to integrated logistics information services - possibly beyond just the vessel but relating to particular cargo, containers or assets onboard ship.

8.2.3.5 Coastal Voyage Phase: What are the data communication requirements that support PNT and what technical infrastructure is in place to provide this support?

- Satellite broadband
- GMDSS, including LRIT [47], with MF and VHF radio or satellite communication system
- Possibly 4G within 15 NM of the coast

8.2.3.6 Coastal Voyage Phase: e-Navigation

e-Navigation services (Appendix C) that are relevant during Coastal phase include:

- MS1 – VTS Information Service (IS)
- MS2 – Navigational Assistance Service (NAS)
- MS3 – Traffic Organisation Service (TOS)
- MS4 – Local Port Service (LPS)
- MS5 – Maritime Safety Information Service (MSI)
- MS6 – Pilotage Service
- MS7 – Tugs Service
- MS8 – Vessel Shore Reporting
- MS9 – Telemedical Assistance Service
- MS10 – Maritime Assistance Service (MAS)
- MS11 – Nautical Chart Service
- MS12 – Nautical Publications Service
- MS13 - Ice Navigation Service
• MS14 – Meteorological Information Service
• MS15 – Real-time Hydrographic and Environmental Information Service
• MS16 – Search and Rescue Service
• MS17 – Piracy Service (Proposed)

Most of these services will require the availability of reliable PNT information in order to maximise their benefits.

8.2.3.7 Coastal Voyage Phase: Maritime Autonomous Surface Ships (MASS)

The same considerations for Ocean phase also apply to Coastal phase. MUNIN is of the opinion that full autonomy will be limited to Ocean Voyage Phase projects [41].

8.2.4 Port Approach Voyage Phase

We consider now the vessel and its cargo operating in the Port Approach (Harbour Entrance and Approach) Voyage Phase as defined in Section 7.2.1.

In addition to those preparations made for Ocean phase and Coastal phase the following is included (refer to Figure 51):
- Turn radius for each course alteration;
- Wheel over positions for each course alteration.

In addition to those preparations made for Ocean and Coastal phase, the passage planning preparations for Port Approach phase (or pilotage waters), include the preparation of a pilotage plan [8]. A pilotage plan is required when:
- The vessel is navigating in a non-mandatory pilotage area and no pilot has been embarked;
- The vessel is in pilotage waters and a pilot is embarked; or
- The vessel is in pilotage waters and pilotage is being conducted by a ship’s officer holding an appropriate and valid Pilotage Exemption Certificate (PEC).

The pilotage plan contains additional details which reflect the closer proximity to navigational hazards and the need to comply with local requirements. The pilotage plan, as appropriate, should take into account:
- Recommended routes and channel information;
- Procedures for pilotage including pilot boarding points and means of embarkation;
- Local conditions, rules and restrictions on navigation;
- Reporting and communications procedures;
- Details of prospective berth and/or anchorages.

Deep water ports, designed for large cargo container vessels, provide deeply dredged navigation channels within which a vessel is expected to remain.
8.2.4.1 Port Approach Voyage Phase: RNP Requirements for General Navigation

Referring to 6.4 there are clear differences between the requirements from various sources. **MarRINav notes that the time period for continuity has now been changed to 15 minutes [72], and there is a clear reason to adopt the same period for the integrity parameter based on the interdependence of integrity and continuity.**

<table>
<thead>
<tr>
<th>System Level Parameters</th>
<th>Service Level Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute Accuracy</td>
<td>Integrity</td>
</tr>
<tr>
<td>Horizontal (metres)</td>
<td>Alert Limit (metres)</td>
</tr>
<tr>
<td>Time to Alarm (Seconds)</td>
<td>Integrity Risk (per 3 hours)</td>
</tr>
<tr>
<td></td>
<td>Availability % per 30 days</td>
</tr>
<tr>
<td></td>
<td>Continuity % over 15 minutes</td>
</tr>
<tr>
<td></td>
<td>Coverage</td>
</tr>
<tr>
<td></td>
<td>Fix Interval (Seconds)</td>
</tr>
<tr>
<td>IMO A.915</td>
<td>10</td>
</tr>
<tr>
<td>ERNP</td>
<td>10</td>
</tr>
<tr>
<td>IMO A.1046</td>
<td>10</td>
</tr>
<tr>
<td>IALA R-129 (Backup)</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 12 – RNP Requirements for Port Approach and Restricted Waters Phase from four sources, IMO A.915, IMO A.1046, IALA R-129 and the ERNP.

8.2.4.2 Port Approach Voyage Phase: How is GNSS (PNT) Used?

PNT information is used aboard ship and by shore-side services, particularly VTS and its systems as outlined in Section 4.2.

8.2.4.2.1 Port Approach Phase: Executing and Monitoring the Passage/Pilotage Plan

Course alterations become more frequent during this phase, there may or may not be a pilot aboard ship, but navigation procedures are the same in either case. Under pilotage the Master still has ultimate responsibility for the safety of the ship and prevention of pollution as can be seen in Figure 53.
Figure 53 – Working relationship between the pilot and the Bridge team. Source: [8].
8.2.4.2.2 Port Approach Phase: Shipboard equipment using PNT information:

The same equipment as employed for coastal phase will be employed with the possible addition of the pilot’s Portable Pilot Unit.

<table>
<thead>
<tr>
<th>System</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECDIS</td>
<td>Section 4.1.2 XTE tolerance will be reduced in line with the RNP requirements. However, visual techniques are expected to take an increased role in navigation, unless visibility is poor in which case radar will take an increasingly dominant role.</td>
</tr>
<tr>
<td>GMDSS</td>
<td>Section 4.1.3 Should there be an emergency AIS employs Digital Selective Calling (DSC) on VHF frequencies for automatic data transmission of vessel’s position.</td>
</tr>
<tr>
<td>AIS</td>
<td>Section 4.1.3 AIS may be employed to overlay vessel positions on radar, but the mariner should be aware that not all vessels carry AIS transponders. AIS provides more information about more vessels. AIS importance is greater, especially in poor visibility.</td>
</tr>
<tr>
<td>VDR</td>
<td>Section 4.1.4 Continuous recording throughout all phases.</td>
</tr>
<tr>
<td>Gyrocompass</td>
<td>Section 4.1.5 Steaming errors are likely to accumulate even more so than coastal phase.</td>
</tr>
<tr>
<td>Radar</td>
<td>Section 4.1.6 As a vessel approaches port traffic density can be expected to be increased compared to Coastal phase, and the density of fixed infrastructure will increase. In this context the radar is employed for situational awareness and collision avoidance. The radar’s ground stabilisation system uses GNSS. The radar heading reference may be the gyrocompass, which itself is calibrated using GNSS, but also the magnetic compass is used for this purpose. Manual techniques also exist for adjusting the heading reference.</td>
</tr>
<tr>
<td>Engine Management</td>
<td>Section 4.1.7 Assume continuous monitoring throughout all phases.</td>
</tr>
<tr>
<td>Satellite Communications</td>
<td>Section 4.1.8 Data communications functions are more likely to be taken on by terrestrial systems such as 4G, 5G, VDES.</td>
</tr>
<tr>
<td>Dynamic Positioning Systems</td>
<td>Section 4.1.9 Only relevant for certain applications, like dredging or surveying</td>
</tr>
<tr>
<td>VDES</td>
<td>Section 4.1.10</td>
</tr>
<tr>
<td>Hydrographic Survey Equipment</td>
<td>Section 4.1.11</td>
</tr>
<tr>
<td>Helideck Stability Monitoring</td>
<td>Section 4.1.12 Not expected, except perhaps in emergencies or moving some forms of cargo?</td>
</tr>
<tr>
<td>PPU</td>
<td>Section 4.1.13</td>
</tr>
<tr>
<td>ODME</td>
<td>Section 4.1.14</td>
</tr>
<tr>
<td>BDM</td>
<td>Section 4.1.15</td>
</tr>
<tr>
<td>Ships Clocks and Timing</td>
<td>Section 4.1.16 The data communications frame structure of AIS is synchronised by time derived from GNSS (solely GPS as of 2019).</td>
</tr>
<tr>
<td>Track Control</td>
<td>Section 4.1.17 The same considerations for Ocean phase apply here, however the desired XTE is lower.</td>
</tr>
</tbody>
</table>

Table 13 - Shipboard systems requiring PNT information aboard ship during Port Approach Phase.

8.2.4.2.3 Port Approach Phase: Shoreside services employing PNT information

<table>
<thead>
<tr>
<th>System</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIS Service</td>
<td>Section 4.2.1</td>
</tr>
<tr>
<td>VTS</td>
<td>Section 4.2.2 The local VTS will be employing AIS in order to monitor the traffic situation and provide guidance regarding port approach.</td>
</tr>
<tr>
<td>Ship Reporting Systems</td>
<td>Section 4.2.3</td>
</tr>
<tr>
<td>PCDM</td>
<td>Section 4.2.4</td>
</tr>
<tr>
<td>VMS</td>
<td>Section 4.2.5</td>
</tr>
<tr>
<td>CERS</td>
<td>Section 4.2.6</td>
</tr>
<tr>
<td>SafeSeaNet</td>
<td>Section 4.2.7</td>
</tr>
<tr>
<td>Mobile AtoN Marking</td>
<td>Section 4.2.8</td>
</tr>
<tr>
<td>Floating AtoN Monitoring</td>
<td>Section 4.2.9</td>
</tr>
</tbody>
</table>

Table 14 - Shore services requiring PNT information.
### 8.2.4.3 Port Approach Phase: What backups/alternatives for GNSS derived PNT Information are already in place?

According to stakeholder liaison under WP6, GNSS loss could be quickly replaced by radar and visual navigation, although in low visibility, and at night, AtoNs might fail, contributing to navigational uncertainties.

VTS would prefer AIS to be available to assist their tasks, and inaccurate AIS positions from ships would affect the efficiency of situational awareness. VTS with effective optical and radar systems *might* be able to continue offering a VTS NAS in the event of GNSS disruption.

<table>
<thead>
<tr>
<th>System</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual Techniques</td>
<td>Section 5.1</td>
</tr>
<tr>
<td>Radar</td>
<td>Section 5.2</td>
</tr>
<tr>
<td>Gyrocompass</td>
<td>Section 5.3; Steaming errors would build up more quickly due to increased amount of manouevring.</td>
</tr>
<tr>
<td>Speed Log</td>
<td>Section 5.5; In shallower water, the speed log can be Doppler/Sonar based, meaning that Speed Over Ground may be computed without reference to tidal set and drift</td>
</tr>
<tr>
<td>Inertial Navigation Systems</td>
<td>Section 5.6</td>
</tr>
<tr>
<td>Sextant and Other Celestial</td>
<td>Section 5.7; N/A – the timeliness of obtaining a siting is not appropriate</td>
</tr>
</tbody>
</table>

Table 15 - Currently available “backup” systems.

### 8.2.4.4 Port Approach Phase: What future technologies, in the timeframe of 2030, are expected to come into operation that require PNT information?

See Section 8.2.3.4.

### 8.2.4.5 Port Approach Phase: What are the data communication requirements that support PNT and what technical infrastructure is in place to provide this support?

- Satellite broadband
- AIS
- VDES is in development
- Possibly 4G within 15 NM of the coast or LTE-Maritime up to 100km

### 8.2.4.6 Port Approach Phase: e-Navigation

e-Navigation services (Appendix C) that are relevant during Port Approach Voyage phase include:

- MS1 – VTS Information Service (IS)
- MS2 – Navigational Assistance Service (NAS)
- MS3 – Traffic Organisation Service (TOS)
- MS4 – Local Port Service (LPS)
- MS5 – Maritime Safety Information Service (MSI)
- MS6 – Pilotage Service
- MS7 – Tugs Service
8.2.4.7 Port Approach Phase: Maritime Autonomous Surface Ships (MASS)

It is unclear at this stage whether a large autonomous cargo vessel will be allowed to dock itself.

8.2.5 Port Phase

We consider now the vessel and its cargo operating in the Port Phase as defined in Section 7.2.1.

Once the vessel is in port, it may need to manoeuvre to turn around perhaps having been assigned an alternative berth. However, for the larger cargo container vessels this is likely to be impractical.

8.2.5.1 Port Phase: RNP Requirements for General Navigation

<table>
<thead>
<tr>
<th>System Level Parameters</th>
<th>Service Level Parameters</th>
<th>Fix Interval (Seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute Accuracy</td>
<td>Integrity</td>
<td>Availability % per 30 days</td>
</tr>
<tr>
<td>Horizontal (metres)</td>
<td>Alert Limit (metres)</td>
<td>Time to Alarm (Seconds)</td>
</tr>
<tr>
<td>IMO A.915</td>
<td>2.5</td>
<td>10</td>
</tr>
<tr>
<td>ERNP 17</td>
<td>Not Specified</td>
<td>Not Specified</td>
</tr>
<tr>
<td>IMO A.1046</td>
<td>Not Specified</td>
<td>Not Specified</td>
</tr>
<tr>
<td>IALA R-129 (Backup)</td>
<td>1</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Table 16 – RNP Requirements for Port Phase from four sources, IMO A.915, IMO A.1046, IALA R-129 and the ERNP.

8.2.5.2 Port Phase: How is GNSS (PNT) Used?

PNT information is used aboard ship and by shore-side services, particularly VTS and its systems. During port voyage phase accuracy of positioning will depend to a greater extent on GNSS augmentation systems in order to provide the 1 m accuracy performance required. It is expected that the Russian GLONASS system will provide 1 m accuracy by 2030 [95].

Port manoeuvring is an application that demands high accuracy PNT information, with high integrity and continuity, while operating in a difficult physical environment due to multipath and NLOS. Research is underway into a Precise Point Positioning (PPP) service via SBAS [96].

17 There is no entry for Port in the ERNP, thus we assume “Inland waterways” figures!
[97] [98], however the overall user requirement for this is unclear. The technique has inherent challenges for integrity and continuity.

There is a wider question on whether GNSS information is really used for navigation in such confined areas as ports, or whether it is really used for situational awareness for those ashore and monitoring the vessel’s location.

However, relative positioning is at least as important as absolute positioning, if not more so. For this reason, radar is and would be expected to remain a principal navigation aid in ports. Relative GPS techniques over the short ranges in ports using differential corrections may be important within applications. At shorter ranges, such as for docking, systems such as LIDAR may become increasingly utilised. The development of short range relative positioning technologies for autonomous land vehicles - including existing and future parking and lane holding sensors, etc, - will likely have valuable spin-overs into maritime.

The vessel is likely to be brought alongside the quay with the assistance of tugs, in which case the RNP parameters for tug operations apply (See Appendix C).

8.2.5.2.1 Port Phase: Shipboard equipment using PNT information:

<table>
<thead>
<tr>
<th>System</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECDIS</td>
<td>Section 4.1.2&lt;br&gt;The ECDIS is likely to be eschewed in preference of visual techniques.</td>
</tr>
<tr>
<td>GMDSS</td>
<td>Section 4.1.3&lt;br&gt;Should there be an emergency AIS employs Digital Selective Calling (DSC) on VHF frequencies for automatic data transmission of vessel’s position. Or the master may dial 999!</td>
</tr>
<tr>
<td>AIS</td>
<td>Section 4.1.3&lt;br&gt;AIS may be employed to overlay vessel positions on radar, but the mariner should be aware that not all vessels carry AIS transponders. AIS provides more information about more vessels.</td>
</tr>
<tr>
<td>VDR</td>
<td>Section 4.1.4&lt;br&gt;Continuous recording throughout all phases.</td>
</tr>
<tr>
<td>Gyrocompass</td>
<td>Section 4.1.5&lt;br&gt;N/A</td>
</tr>
<tr>
<td>Radar</td>
<td>Section 4.1.6&lt;br&gt;Used for situational awareness and location of other vessels and shoreside infrastructure.</td>
</tr>
<tr>
<td>Engine Management</td>
<td>Section 4.1.7&lt;br&gt;Assume continuous monitoring throughout all phases.</td>
</tr>
<tr>
<td>Satellite Communications</td>
<td>Section 4.1.8&lt;br&gt;Data communication may now be entirely terrestrial.</td>
</tr>
<tr>
<td>Dynamic Positioning Systems</td>
<td>Section 4.1.9&lt;br&gt;Only relevant for certain applications</td>
</tr>
<tr>
<td>VDES</td>
<td>Section 4.1.10</td>
</tr>
<tr>
<td>Hydrographic Survey Equipment</td>
<td>Section 4.1.11</td>
</tr>
<tr>
<td>Helideck Stability Monitoring</td>
<td>Section 4.1.12</td>
</tr>
<tr>
<td>PPU</td>
<td>Section 4.1.13&lt;br&gt;N/A</td>
</tr>
<tr>
<td>ODME</td>
<td>Section 4.1.14</td>
</tr>
<tr>
<td>Ships Clocks and Timing</td>
<td>Section 4.1.15&lt;br&gt;The data communications frame structure of AIS is synchronised by time derived from GNSS (solely GPS as of 2019).</td>
</tr>
<tr>
<td>Track Control</td>
<td>Section 4.1.16&lt;br&gt;The same considerations for Ocean phase apply here, however the desired XTE is lower.</td>
</tr>
<tr>
<td>NAVTEX</td>
<td>Section 4.1.17</td>
</tr>
</tbody>
</table>

Table 17 - Shipboard systems requiring PNT information aboard ship.
8.2.5.2.2 Port Phase: Shoreside services employing PNT information

<table>
<thead>
<tr>
<th>System</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIS Service</td>
<td>Section 4.2.1</td>
</tr>
<tr>
<td>VTS</td>
<td>Section 4.2.2</td>
</tr>
<tr>
<td>Ship Reporting Systems</td>
<td>Section 4.2.3</td>
</tr>
<tr>
<td>PCDM</td>
<td>Section 4.2.4</td>
</tr>
<tr>
<td>VMS</td>
<td>Section 4.2.5</td>
</tr>
<tr>
<td>CERS</td>
<td>Section 4.2.6</td>
</tr>
<tr>
<td>SafeSeaNet</td>
<td>N/A – reporting is assumed to have been done</td>
</tr>
<tr>
<td>Mobile AtoN Marking</td>
<td>Section 4.2.8</td>
</tr>
<tr>
<td>Floating AtoN Monitoring</td>
<td>Section 4.2.9</td>
</tr>
</tbody>
</table>

Table 18 - Shore services requiring PNT information.

8.2.5.3 Port Phase: What backups/alternatives for GNSS-derived PNT information are already in place?

<table>
<thead>
<tr>
<th>System</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual Techniques</td>
<td>Section 4.3.1</td>
</tr>
<tr>
<td>Radar</td>
<td>Section 4.3.2, This is expected to be the primary means of maintaining situational awareness in port in times of good visibility only.</td>
</tr>
<tr>
<td>Gyrocompass</td>
<td>Section 4.3.3, During times of poor visibility the radar will have an increased role in situational awareness.</td>
</tr>
<tr>
<td>Speed Log</td>
<td>Section 4.3.5, N/A</td>
</tr>
<tr>
<td>Inertial Navigation Systems</td>
<td>Section 4.3.6, N/A</td>
</tr>
<tr>
<td>Sextant and Other Celestial</td>
<td>Section 4.3.7, N/A</td>
</tr>
</tbody>
</table>

Table 19 - Currently available “backup” systems.

8.2.5.4 Port Phase: What future technologies, in the timeframe of 2030, are expected to come into operation that require PNT information?

Remotely piloted, semi-autonomous airborne drones may be employed to assist docking and port manoeuvring [99].

A multitude of sensors could become more prominent in ports, for example LIDAR (Light Detection And Ranging, a technique analogous to radar), Forward Looking Infrared (FLIR), Wi-Fi ranging, Ultra Wide Band (UWB). It could be that the increasing autonomy of land based vehicles will drive an explosion in such sensors that can then be readily adapted for short range operations of ships manoeuvring in ports.
8.2.5.5 Port Phase: What are the data communication requirements that support PNT and what technical infrastructure is in place to provide this support?

- Satellite broadband
- AIS
- VDES is in development
- Possibly 4G within 15 NM of the coast or LTE-Maritime

8.2.5.6 Port Phase: e-Navigation

e-Navigation services (Appendix C) that are relevant during Port Approach Voyage phase include:

- MS1 – VTS Information Service (IS)
- MS2 – Navigational Assistance Service (NAS)
- MS3 – Traffic Organisation Service (TOS)
- MS4 – Local Port Service (LPS)
- MS5 – Maritime Safety Information Service (MSI)
- MS6 – Pilotage Service
- MS7 – Tugs Service

8.2.5.7 Port Phase: Maritime Autonomous Surface Ships (MASS)

It is unclear at this stage whether a large autonomous cargo vessel will be allowed to dock itself.

8.2.6 Example - Port and Pilot Operations Use Cases

For this part of the work BMT worked with a current Thames pilot to model a number of scenarios simulating mariner/pilot responses to a loss of GNSS and to test a number of mitigations. BMT’s industry recognised REMBRANDT™ simulator was utilised for this study. Two areas within the Thames estuary and river were used to provide representative case studies for understanding the consequences of the loss of GNSS derived PNT information for port and pilot operations.

8.2.6.1 Case Study – River Thames

Two areas in the estuary and river area of the River Thames were employed for this simulator based Case Study:

- Study Area 1 – Estuary to Oaze area
- Study Area 2 – Inland – Gravesend Reach and Northfleet Hope
**Study Area 1 – Estuary to Oaze Area**

![Screen shot of an Electronic Navigation Chart showing the area of Study Area 1.](image)

**Existing condition:** The area (shown in Figure 54) is the intersection of the access channels for the River Thames (Sea Reach), River Medway (Medway Approach), with the Barrow Deep and Oaze Deep routes from the Estuary feeding to it. The Oaze deep is the focal point for the Princes Channel (the main channel for ships entering from the South / North East Spit pilot boarding area) and the Black Deep / Knock John channels, which deep draught and vessels entering from the North via the Sunk boarding area will use. The Oaze pilot boarding position is used by small ships below defined length and draught criteria exempted from compulsory pilotage within the Estuary channels by regulation. A comprehensive mix of traffic in all directions, from small leisure craft and fishing vessels, through to Q-Max LNG (Liquid Natural Gas) ships for the Medway and ULCVs (Ultra Large Container Vessel) for the Thames, transits and crosses the area in all directions.
Study Area 2 – Inland – Gravesend Reach and Northfleet Hope

Figure 55 – Chart showing the area of Study Area 2.

Existing condition: The Tilburyness area is the most constricted and complex area within the commercial river section of the River Thames. The Gravesend passenger ferry crosses the river at the East of the area with the Cruise and Ro-Ro terminals adjacent on the North shore. Opposite on the South Shore is the PLA VTS (Port of London Authority Vessel Traffic Service) and pilot stations with a pilot change-over point (between the Sea and River pilot districts) in the river as indicated. On the south side of the river are a number of active berths for Bitumen, paper goods and quarried stone with a large cement berth on the south shore at the bend. On the north side of the channel near the western wind generator is a shoal area in the river, which forces deeper draft vessels into the middle of the channel when rounding the bend inward bound, thus significantly reducing their available navigable width. Tidal flows on the bend are complex with significant strong back eddies particularly on the flood tide but also on the ebb. The lock (Panamax size) entrance is challenging, being across the tidal flow with different approach protocols required for entering and departure depending on ship type, size and tidal conditions. Upstream of the lock before the Broadness bend on both sides of the river are deep-water berths handling container, grain and steel vessels. There is a marine civil engineering base on the south side of the river with an aggregate berth immediately upstream. This is followed when proceeding inwards by a number of barge moorings in constant use. Upstream of the Grain terminal on the North shore in the bight of the bend is the Thurrock yacht club – very active in the sailing season with numerous swinging yacht moorings.
8.2.6.2 Simulating the Loss of GNSS

A REMBRANDT simulation was performed within each of the River Thames Study Areas outlined above. REMBRANDT is a Windows based, time domain navigation and seakeeping simulation software application. It is fully scalable, designed to run on a laptop or single/multiple desktops, as shown in Figure 56.

![Figure 56 – BMT’s REMRANDT™ simulator in action.](image)

It also operates in full mission mode as a DNV Class A full mission-based simulator. It can be configured in single or multiple split screen modes with a variety of user controls. It is installed in users’ offices, training centres and onboard ships, most notably cruise and LNG ships. More recently, it has been adopted by UK autonomous vessel designers and builders, as part of a development plan aimed at implementing COLREGS-cognisant AI navigation algorithms and to test scenarios of interactions in congested waters.

A wide range of user configurable controls allow for a variety of environmental conditions. These include day/night, reduced visibility, wind shielding, multi-directional swells and complex current flows. The software supports IHO (International Hydrographic Organisation) S-57 standard Electronic Navigation Charts (ENC)s, other electronic charts may be supported. Visual topography, including bathymetric representation is automatically generated from the ENC chart. The system is AIS-enabled, allowing real-time displays of live traffic as part of a vessel simulation. The system includes a large database of fully calibrated (via sea trials and
pilot cards) six degree-of-freedom hydrodynamic ship models and linked engine modules. Physical phenomena such as squat, bank effects and ship-ship interaction are included.

The system is used by multiple maritime stakeholders. Users and licensees include a number of statutory accident investigation bodies; including the US NTSB and UK MAIB, ship operators, floating oil and gas developers (FSU, FSRU, FLNG,) pilots, law firms, expert witness firms and port developers. Apart from its advanced features, it is also a powerful platform for visualisation. REMBRANDT built-in algorithms recognise and accept a range of VDR and AIS data sources to facilitate automatic visual reconstruction. User friendly set up allows users to switch between visualisation and simulator modes when the user wishes to “take control” and explore “what if” scenarios.

As a serving current Thames pilot, Captain Don Cockrill MBE, attended the simulations and contributed to the study as an independent expert. He is a senior Port of London pilot covering the Thames estuary and lower river areas. He is Secretary General (and former Chairman) of the UK Maritime Pilots' Association. Captain Cockrill has extensive expert knowledge of pilotage matters.

### 8.2.6.3 Study Area 1: Oaze

Traffic was simulated according to the following:

1. **Inbound Traffic Thames**
   
   For the simulation a containership with 11,000 teu capacity was selected. Length of the containership is 347m and beam of the containership is 45.2m. At the start of the simulation the 11,000teu containership was on an inwards course in Oaze Deep and was approaching Argus buoy, see following figure.

2. **Inbound Traffic Medway**
   
   For the simulation, a coaster tanker was selected. Length of the coaster tanker is 74.5m and beam is 15m. At the start of the simulation was on an inwards course at Warp pilot position towards Medway buoy, see following figure.

3. **Outbound Traffic Thames**
   
   For the simulation a containership with a capacity of 2,000teu was selected. Length of the vessel is 200m and beam is 28.2m. At the start of the simulation, vessel was on an outwards course at Sea Reach No. 2 buoy towards Yantlet channel, see following figure.

4. **Outbound Traffic Medway**
   
   For the simulation, a coaster was selected. Vessel is a 91.3m long general cargo carrier with beam of 13.8m. At the start of the simulation, vessel was on and outwards course at Medway No5 buoy towards Barrow Deep, see following figure.

5. **Survey Vessel**
   
   For the simulation a depth survey vessel was selected as the vessel whose GNSS signal is lost on-board. Dimensions of the vessel are 16.7m X 5.9m. During simulation, survey vessel sailed on a course N-S lines across Sea Reach Buoy No.1 – West Oaze channel.
8.2.6.4 Study Area 2 – Gravesend Reach and Northfleet Hope

A typically common traffic situation is exampled:

1. **Outbound Traffic #1**
   For the simulation a Ro-Ro ship was selected. Ship is 199.8m long and beam is 26.5m. At the start of simulation, vessel was on an outbound course and was approaching Broadness, see following figure.

2. **Inbound Traffic**
   For the simulation, a bulk carrier ship was selected. Dimension for the bulk carrier is 175m X 26m. At the start of the simulation, bulk carrier was on an inbound course and was passing Tilbury power station at Gravesend Reach, see following figure.

3. **Outbound Traffic #2**
   For the simulation, a 110m long coaster ship was selected. Coaster is 11.4m width and is a dry bulk cargo carrier. At the start of the simulation, coaster was on outbound journey and was about leaving Tilbury Lock, see following figure.
4. **Passenger Ferry [Gravesend – Tilbury]**

For the simulation, a 27m long passenger ferry was selected as the candidate to have GNSS signal lost on-board. Beam of the vessel is 8.8m. Ferry operates between Gravesend and Tilbury, see following figure.

![Study Area-2
Gravesend Reach & Northfleet Hope](image)

**Figure 58 – Study Area 2 – Gravesend and Northfleet Hope.**

### 8.2.6.5 Results

**Effects aboard Ship**

Following the simulation of loss of GNSS onboard the candidate vessels, a discussion session was held with the pilot, with potential risks and mitigations identified in Table 20.
<table>
<thead>
<tr>
<th>Facility</th>
<th>Effect</th>
<th>Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECDIS</td>
<td>Loss of position determination</td>
<td>Resort to traditional and radar navigation techniques*</td>
</tr>
<tr>
<td>High Accuracy positioning systems (as used in “Heavy” Portable Pilot Units - PPUs)</td>
<td>RTK systems compromised.</td>
<td>Use of alternative visual and technical solutions for berthing large ships – e.g. Doppler radar or Lidar systems. Use of other non-GNSS high fidelity positioning systems.</td>
</tr>
<tr>
<td>AIS transmissions (total failure)</td>
<td>Identification of other vessels, predicted CPA &amp; TCP lost.</td>
<td>If required – utilise VHF for ID confirmation. AIS should not be used for anti-collision purposes. Use Radar.</td>
</tr>
<tr>
<td>LRIT system</td>
<td>Loss of GNSS positioning.</td>
<td>Fit a secondary positioning system</td>
</tr>
<tr>
<td>Radar</td>
<td>Little effect other than for target identification. However, GLA trials have demonstrated that the radar will alarm due to failed GNSS input, which would no doubt be of concern to the mariner.</td>
<td>ARPA facilities should always be used for anti-collision work, not AIS data.</td>
</tr>
<tr>
<td>Epirbs &amp; radio distress alarms etc.</td>
<td>406 MHz EPIRB failure. Distress signals could have been transmitted by radio with no location data. The Galileo “Return Link Service” would be lost with implications for the successful survival of distressed casualties.</td>
<td>None?</td>
</tr>
<tr>
<td>Oil - Water Discharge Monitor?</td>
<td>ODME potentially rendered out of order.</td>
<td>Potentially 100% Slop discharge permitted to shore only under MARPOL.</td>
</tr>
<tr>
<td>Ballast Discharge Monitor?</td>
<td>BDM equipment potentially ineffective. Accurate position data for record keeping lost.</td>
<td>Retention of ballast water on board / pump ashore?</td>
</tr>
<tr>
<td>PPU (Lite) systems</td>
<td>Utilise AIS data via AIS plug thus rendered inoperable.</td>
<td>“Heavy” systems may use high accuracy non GNSS locally based systems.</td>
</tr>
<tr>
<td>Satellite Communications system</td>
<td>GNSS signals used for aiming some satcom dishes?</td>
<td></td>
</tr>
<tr>
<td>On board computer networks</td>
<td>Potentially affecting non-navigational use of timing signals if used in on-board networks.</td>
<td></td>
</tr>
</tbody>
</table>

Table 20 – Example facilities affected by GNSS loss, effects and possible mitigations, according to BMT’s simulation study.

Note * Where the GNSS failure occurs in pilotage waters with a pilot on board then it is unlikely to have any marked navigational effect, as the pilot will simply continue to conduct the navigation using the available equipment, that is, radar, visual and his/her own comprehensive expert knowledge. However, there would be alarms sounding, the Pilots PPU
may be lost as it is dependent on GNSS, and the radar (and other systems) would need to be de-coupled from GNSS before they could be relied upon [10].

Outside of pilotage waters (which may be estuarial or near coastal) then the challenges to the navigating officer could be significant.

*The obligatory carriage and acceptance of fully ECDIS systems with no requirement for paper charts has led to an unintended dependency on automatic GNSS positioning on ENCs with little (generally no) independent checking of the vessel’s position or the accuracy of GNSS derived positions being plotted.*

There are a number of reasons for this related not only to the design of ECDIS systems themselves but also to the increased non-navigational duties which are delegated to navigating officers whilst on the bridge at sea. The result is that the traditional visual position fixing and monitoring skills historically maintained by bridge officers have markedly deteriorated; this can potentially include the use of position and track monitoring skills using radar, e.g. parallel indexing.

**Effects at a VTS Station**

The loss of GNSS aboard ship also affects the position and other dynamic data transmitted from ships.

The effect on a VTS system from the loss of GNSS, and thus AIS data, from vessels within the VTS area will depend on the type of VTS system installed. Where the system is a combination of AIS and Radar processes then following the loss of GNSS signals it is probable (depending on the sophistication of the system) that the VTS monitoring process will default to a radar only display with automatic tagging of the targets using data from an installed database – an example being the Signalis STYRIS system [100]. Alternatively, the VTS system may be a radar only based system where targets are (or are not) tagged manually once identified by VHF, or some other communication method. In this case, a loss of GNSS signal would have no real effect on the VTS system. Note that some VTS also have CCTV capabilities.

Where the system is purely AIS based (usually in small ports) as for example with the Transas TrAN Viewer [101] or AIS Monitor [102] systems, then the loss of GNSS signals will clearly have a catastrophic effect on the presented visual overview and traffic monitoring aspects of the system rendering it almost useless.

**8.3 Port Shore-side Container Operations**

There are different types of cargo and related terminal handling methods, for instance bulk cargo (tankers, grain or construction aggregate carriers, etc), roll-on-roll-off (Ro-Ro) cargo (ferry or cargo transporter etc.) and indeed containerized cargo. For the purposes of this project the focus is on container ports/terminals as this type of terminal tends to be highly optimised and GNSS is used within certain operations.
A container terminal is a facility where cargo containers are moved between different transportation modes for onward transportation [103]. The movement may be between ships and trains and trucks. In countries with large rivers (Holland, Germany, France, the UK), these complexes are located next to the river and are reached by large barges that transport the goods and containers from the large sea ports. The yards in the container terminals are organised into “holds” and “bays” where the containers are positioned according to their final destination and the type of load. Maritime container terminals usually also provide storage facilities for loaded, empty and refrigerated containers. Some container terminals are defined as “transhipment hubs” because they specialise in receiving large ships (mother vessels) operating on transoceanic routes, and redistribute their loads onto smaller craft called “feeders” bound for regional ports.

We consider now the cargo container being transported from the wharf to the gate exit. For convenience of discussion this activity encompasses the three final activities shown in the diagram of Figure 52: unload cargo, container on wharf, container on tug (or tractor) and/or straddle carrier, then finally the container on the truck carrying the unit out of the port. This process involves the co-ordination of the movement of the container from the ship into the terminal, either for temporary storage or direct to its related onward transport mode (road/rail/onward connecting vessel) and the need to monitor the location of the container in order to optimise the efficiency of this transfer. At the same time, cargo will be arriving at the port terminal gate by road, rail, or onward connecting vessel. This incoming cargo also needs to be moved and loaded onto an outbound vessel.

Port operators divide their operations into:

- **Water-side Operations** – loading or unloading cargo containers to or from the vessel and stacking the containers in the terminal area for eventual collection for forwarding

- **Land-side Operations** – the movement of the containers from the stacks and placing them onto truck or rail container carriers for onward travel

### 8.3.1 Container Handling Equipment

Container cranes are divided into two categories:

- Quay-side cranes such as Ship-to-Shore gantry cranes (STS) and Mobile Harbour Cranes (MHC) are used to transport containers between ships and the handling yard, or vice versa

- Yard cranes such as Rubber Tyred Gantry Cranes (RTG), Rail Mounted Gantry Cranes (RMG) and Straddle Carriers (SC) work within terminal yards, where they stack containers for storage and load or unload containers onto trucks or trains
8.3.1.1 Ship to Shore Gantry Cranes

STS Gantry cranes can traverse the length of a quay or yard, on rails. These cranes use a spreader to pick up the containers. The spreader is lowered down on top of the container and locks on to the container’s four corner points using a “twistlock” mechanism. Cranes normally transport a single container at once, however, some newer cranes have the capability to pick up two 20ft containers at once. A comprehensive mechanical and electrical system is used to monitor the status of the twistlock mechanism to ensure safe operation and to indicate when the container has “landed”.

![Ship to Shore Gantry Cranes](image)

**Figure 59 – Ship-to-Shore Gantry Cranes at Port of Felixstowe.**

8.3.1.2 Rubber Tyred Gantry (RTG) Cranes

Gantry cranes are a type of crane that can straddle multiple lanes of rail/road and/or container storage and lift objects using a hoist that is fixed to a rail mounted trolley that can travel along the horizontal gantry of the crane.

RTG cranes are mounted on rubber tyres as opposed to RMG (Rail Mounted Gantry) cranes that are mounted on rails. RTG cranes are used for stacking shipping containers within the storage areas of a container terminal. They are the most common yard handling system and are used in the world’s largest container terminals and container storage yards.
Figure 60 – An RTG at the Port of Felixstowe.

Figure 6 shows a photograph of an RTG at Port of Felixstowe. The standard span of an RTG is six containers plus one truck lane. In the photograph the white markings of the truck lane can just be seen. The lift height of such cranes is specified to allow a container to pass over a stack of containers; for example an RTG is described as ‘1 over 5’ if the crane is of sufficient height to be able to carry a single container over a stack of five.

8.3.1.3 Rail Mounted Gantry (RMG) Cranes

RMG cranes are yard container handling machines. This type of crane is specifically designed for intensive container stacking due to its automation and lower need for human handling. Compared to the RTG crane the RMG crane has the advantages of being driven by electrical power which eliminates the exhaust fumes from the diesel engine, increases lifting capacity, and increases the speed of the gantry when travelling with load. RMG cranes are particularly effective for rail/road trans-shipments of large quantities of containers and it is an excellent choice for intermodal terminals where containers are loaded from trucks to trains or vice versa. One of Port of Felixstowe’s RMGs is shown in Figure 61.
Figure 61 – A Rail Mounted Gantry (RMG) crane at Port of Felixstowe employing RTK GPS for positioning information feedback to the Terminal Operating System. The antenna can be seen on the top of the equipment in the green circle.
8.3.1.4 Straddle Carriers

An SC crane (Figure 63) is used within port terminal yards for stacking and moving standard containers from quay to yard or from yard to quay. They are used in large spaces where containers are stored in rows. The greatest limitation is the need for space on both sides of the container to enable the SC crane to transit. They generally have eight wheels, anti-slip and anti-blocking functions ensure best grip and safe driving control in any conditions. Some ports, including Port of Felixstowe employs tugs to transport containers to/from the stack RTGs to the quay (Figure 64).
Figure 63 – A Straddle Carrier in action. Source: www.container-mag.com.

Figure 64 – A tug in operation at Felixstowe.
8.3.2 Position Information in Ports

The location of the CME is key information employed for the optimisation of port efficiency. Much use is made of magnetically guided equipment and sophisticated local wire networks, in these cases cargo positioning systems within terminals do not rely solely on GNSS.

The Port of Felixstowe employs a local Real Time Kinematic GPS system for its STS, RTG and RMG cranes even though the port is not yet fully automated. The positioning information is used by the Port Operations Centre’s Vessel Co-ordinator (VC) personnel when monitoring and controlling the loading and unloading of container vessels; a time and efficiency critical process. Each VC may have responsibility for up to seven STS wharf-side cranes, and multiple RTGs, and there may be up to four such VCs operating at Felixstowe at any one time. All position information entering their monitoring system is derived from RTK GPS (see Figure 61 and Figure 62).

So, for terminals that are not fully automated, GNSS is often used as part of the tracking of assets, which feeds into the Terminal Operating System to aid efficiency of terminal operations. In the Port of Southampton, DP World’s straddle carriers, cranes and overheight frames are all trackable using GPS. GNSS helps the Container Handling Equipment (CHE) operator by reducing/removing the need to constantly enter data in order to keep the Terminal Operating System (TOS) up to date. It provides guidance to the CHE operator to help him efficiently perform the task of moving, storing and retrieving containers. For example, Peel Port Liverpool and DP World Southampton [104] both use Navis™ software [105]; where the asset is tracked using GNSS then the data will be used to update the terminal planning system each time equipment has completed a move.

When a container is delivered (export) or collected (import) by a straddle carrier, or tug, to/from the STS crane the unit number (an historic system based on a series of 4 letters and 7 numbers) is processed through an RDT (Radio Data Transmitter – effectively an Apple iPad™ built into the straddle carrier or tug). The operator confirms that they are collecting the correct container by touch screen function on the RDT. This allows DP World to GPS track the unit via the straddle carrier. Once it has dropped the container at the vessel there is no way to trace the container. The leading hand, who is onboard the vessel, confirms on a handheld device when the container has been loaded.

The elimination of data entry errors and the failure to manually update positions is a pre-requisite for the reduction and elimination of many common container terminal efficiency issues. Typically the operator of the equipment will have a manual override (a button on a screen or onboard device) in the event that GNSS is not working. This allows the Terminal Planning System to have a live accurate database, optimise equipment utilisation, and make optimal storage and retrieval decisions.

Numerous organisations produce GPS systems for CHE location monitoring and control, for example Gotting [106], and Control Techniques [103].
8.3.2.1 Container Port Automation

Broadly speaking, somewhere in the region of 10-15% of container terminals worldwide are already automated, with ports like Singapore, Hamburg and Baltimore leading the way [107]. Terminals employ sophisticated terminal planning software systems (the Terminal Operating System) and location tracking enabling devices installed on equipment.

According to the Port Equipment Manufacturers’ Association (PEMA) [108], the main technological challenge with all Automated Guided Vehicles (AGV) has been the development of reliable positioning, navigation and perception systems for unmanned vehicles and the need for wireless communication. The PEMA document lists the following existing and proposed new navigation systems:

- Transponders or magnets buried in the ground and antennas in the bottom of the vehicle
- GPS satellite positioning (Real-Time-Kinematic RTK-GPS delivering cm-grade accuracy)
- Local radio-positioning networks and RFID systems
- Laser-based positioning
- Camera-based positioning
- Millimetre-wave-radar positioning.

![Figure 65 – Typical DGPS guided crane automation system in use at ports. Source: Control Techniques [103.](image)]
Figure 65 shows a typical arrangement for a DGPS guided automated crane produced by the UK company Control Techniques [109] [103], a company that supplies port GPS applications for both RTG and RMG cranes.

The typical system consists of several components:

- A base station. This is a device with an antenna, located at a fixed position (in the open), suitable for receiving GNSS satellite signals. The base station uses a radio modem to transmit differential corrections to the receiver aboard the CHE.

- A mobile station. This is the GNSS device, and radio modem, installed on board the CHE. It processes the signals from its own GPS and the corrections from the base station and generates the necessary control input to the CHE’s automation system.

- The automation system. The mobile station’s GPS receiver is connected to an industrial computer that processes GPS data and outputs it to the CHE’s automation system. The computer processes this data and transmits the necessary control signals to the CHE’s Programmable Logic Controller (PLC). This GPS data is read at a frequency of about 1.5 times a second.

Since RTGs do not have any fixed reference points (for example the end of a rail track) they need guidance in order to follow pre-determined paths and perform their picking/placing operations accurately. The DGPS system for RTG provides two values; AP, the distance from a known point or origin and, D, the divergence (blue line in Figure 66) of the RTG from the ideal container picking/placing line (black line in Figure 66).

![Figure 66 – RMG trajectory following based on training.](image)

Referring to Figure 66 the training process of the RTG involves taking the RTG to its starting position (A) and the location entered into the control system. The RTG is then taken to location (B) and again the location is entered into the system. Once the learning process has been completed the GPS system starts supplying distance and deviation data for the RTG’s current position.

RMGs operate differently. Unlike RTG cranes, RMGs run along a fixed physical rail the path deviation from which should be zero. DGPS applications on RMGs allow for complete container warehouse management since the exact picking/placing position of each container in storage is always known with great precision. Referring to Figure 67, a training procedure for this type of system involves taking the RMG to its first useful working position (A) and
entering the location into the control system. The RMG is then taken to its last useful location (B), and again the location is entered into the control system. Once this training sequence has been performed the DGPS system starts supplying distance and deviation data for the RMG’s current position, as well as the RMG’s gantry position relative to rows and lines of the container stack. This position information can be made available to the port’s TOS for use by the Vessel Controller. With RTK GPS providing some 20 cm positioning accuracy.

![Figure 67 – Positioning an RMG crane.](image)

8.3.3 GNSS Outages at Ports and The Effects

In recent years, incidents of GPS interference, jamming and indeed spoofing have disrupted the flow of commerce within ports around the world by blocking the signals needed for crane operators to locate and move goods, in addition to creating confusion for vessel operating within the port area. The Israeli ports of Haifa and Ashdod experienced disruptions in the operation of cranes and the location of containers during June and July 2019, due to problems with GPS-based systems, according to a senior port official. Disruptions were experienced in the system installed within the port’s cranes, assisting in unloading ships resulting in workers having to shift to manual operation of the crane, with the result that delays were caused to the unloading process.

One official stated:

‘The problem is that when the cranes don’t know where they are, they can’t find containers to pick up, and don’t know where to put the ones they have. Reverting from automated to manual operation is so time consuming that a port is effectively shut down.’

During correspondence with magazine Dredging and Port Construction (DPC) [110] Prof. Todd Humphreys, of the University of Texas, commented:

‘This interference to the global positioning system (GPS) reception does not appear to be specifically directed at Israel’
His implication is that the issues experienced by Israel are a side-effect of Russian efforts to spoof GPS guided drones and other guided weapons.

Zohar Rom, spokesperson for Haifa port, told DPC that the problem has been overcome by the use of sensors that override the GPS system in the cranes and as a result, no further interferences has taken place.

The Port of Shanghai has also experienced AIS and GPS interference during July 2019. In an article on www.maritime-executive.com [107] Dana Goward, President of the Resilient Navigation and Timing Foundation, outlines one incident that was documented to the U.S. Coast Guard; the service’s Navigation Center [111] receives reports about GPS problems from maritime and other users around the world.

Posted to the Navigation Center’s website on July 17, the report states:

‘Upon arriving to dock in Shanghai, a U.S. flagged MV master checked ECDIS at the AIS to see if their berth was clear. Another ship on the berth appeared to be in the channel making 7 knots (kts) speed over ground (SOG), but then disappeared from AIS. A few minutes later she was back and at the dock, then underway again, 5 kts, 2 kts, 0 kts, in the channel, then back at the dock, then gone. This pattern repeated multiple times. It turned out the other ship was actually all fast the entire time. Later, while the MV was turning in the river off the same berth, both GPS units lost their signals, no position, no SOG, multiple alarms on various integrated equipment. The GPS signal would come back for a minute and then be lost again. This continued to the dock and has continued. The GMDSS GPS is experiencing the same thing. Master suspects GPS signal jamming is occurring at this berth. Vessel checked all antennae connections – all connections are secured and dry. There have been no other issues with these units.’

The article goes on to say:

This scenario fits a pattern of GPS jamming that is fairly well documented. This was first documented by the General Lighthouse Authorities of the United Kingdom and Ireland in 2009 and 2010 during maritime jamming trials. When jamming signals are first encountered, receivers often initially accept them as valid and generate hazardously misleading information. After some time, the receiver will be unable to calculate any sort of position and then fail to report position.

The incident reported appears to be part of an on-going problem at Shanghai. In addition to several anecdotal reports, analysts at the non-profit C4ADS have been observing the area and advise that the report received by the Coast Guard “does not appear to be an isolated incident.”

Detecting GPS disruption in commercial maritime sector is often much easier than in other areas because of the Automatic Identification System (AIS), which effectively broadcasts the problem to maritime users. GPS is the primary sensor for location information transmitted by AIS to other vessels and shore stations as explained earlier in this report. AIS transmissions are also detected by satellite and the information they provide is easily available. By studying
AIS transmissions in the Black Sea and other Russian waters, a C4ADS study earlier this year identified almost 10,000 deliberate maritime spoofing incidents and associated them with Russian VIP protection efforts.

It is because of events such as those reported above that MarRINav proposes that a nationwide GNSS interference detection network be established, with sensors at all major UK ports.

8.3.4 Summary

Although there is in many cases other sensors and systems aboard CHE to aid positioning and navigation, GNSS, specifically Real Time Kinematic GPS, is employed at ports in order to maintain the efficiency of cargo container handling within the facility whether the port is fully automated or otherwise. It is typically deployed aboard RMGs and RTGs to provide centimetre positioning accuracy for container picking and placement, and is seen as a convenient source of automatic positioning data provision into the Terminal Operating System.

Couple this use of GNSS on the port land-side with the use of GNSS aboard vessels within the port manoeuvring phase and there is the capacity for severe disruption to the efficiency of the cargo transfer process, in addition to the usual maritime safety concerns.
9 Summary and Conclusions

This document comprises deliverable D1 of the MarRINav project and was produced under Work Package 1 – Maritime Context and Requirements.

Current maritime PNT, based as it is on GNSS, does not fulfil Resilience and Integrity requirements. In consequence, there is a risk - not yet mitigated - to the safety of life, security, to the environment and to the economy, including maritime and other sector operations in the event of reduced PNT availability or when PNT delivers hazardously misleading information. The maritime sector employs GNSS as primary source of PNT information, including for navigating a vessel and for situational awareness ashore.

The aim of Work Package 1 is to provide as comprehensive a record as possible of the dependence of the maritime sector on PNT information, and in particular GNSS. Once we identify the points of use of GNSS we can then begin to think about how to mitigate the vulnerabilities of GNSS through the provision of Resilient PNT systems. In addition to technical aspects, the work also identifies the regulatory considerations of PNT provision, with reference to the IMO and the SOLAS convention, IALA, and other standards bodies.

Section 1 of the report presents a summary of the context within which MarRINav’s work will operate, taking into consideration Critical National Infrastructure, resource management and control, situational awareness, the need for robust communications. In this age of digital systems we still maintain focus on the “human in the loop”, the mariner on the bridge of a vessel, with their increased workload brought about by the operation of ships that are larger and with voyage plans more time critical than ever, working in a sea environment that is becoming increasingly cluttered with other traffic and offshore infrastructure. We consider the evolution of maritime technology in the light of increases in autonomy, including autonomous and unmanned ships, and the advent of e-Navigation services and supporting robust data communications infrastructure, and we outline why reliance on GNSS should not be taken for granted.

Section 2 presents some important definitions, including of the four Required Navigation Performance parameters and we attempt a definition of Resilience at least from the maritime perspective.

The technical rationale for the work is presented in Section 3, including introducing Space based Augmentation Systems and Ground Based Augmentation Systems and we describe more fully the concept of e-Navigation, introducing some example e-Navigation services that for the most part all require PNT information with high integrity and resilience. Key to the success of e-Navigation is the provision of robust communications and the VHF Data Exchange System is briefly outlined.

Section 4 discusses the current use of PNT information aboard ship and ashore within the major systems employed. Receivers are low cost and widely available and GNSS has become
so convenient and so taken for granted that it has become ubiquitous in its application in the maritime domain.

Section 5 presents some currently available systems that are perceived by some as sufficient backup. However, some of these systems, such as the gyrocompass and radar rely on GNSS for part of their functioning.

Section 6 explains the requirements capture process to be employed for MarRINav, firstly identifying stakeholders at all stages of service provision. During Phase 1, MarRINav concentrates on user requirements. Some requirements are provided by regulatory bodies, others may be derived from applications themselves and yet others are geographically oriented particularly when we consider the risks associated with high densities of marine traffic and associated collision risk. Collision risk becomes more relevant as traffic density increases due to the reduced room to manoeuvre brought about by the growth in offshore infrastructure such as wind farms, underwater mining and other Blue Economy applications.

User requirements capture will not stop with the publication of this report. Indeed requirements capture will be an iterative process requiring stakeholder liaison throughout the lifecycle of the project. For the most part, in later Work Packages of the project, in particular Work Package 4, performance of any proposed Resilient PNT system will be compared against the geographical requirements contained within the MarRINav Geographical Information System, which will be an ongoing development.

Section 7 illustrates user requirements and begins with General Navigation – the movement of a vessel through the various voyage phases, from Ocean to Port. The Blue Economy is expanded upon further and an attempt is made to elicit the RNP parameters for various Blue Economy applications.

Section 8 presents a key user scenario, that of a large cargo container vessel making way from mid-ocean to port. The scenario approach allows the requirements analyst to identify the key stages and Use Cases of PNT information, indicating, in a carefully considered way, those systems and services identified earlier in the report that require PNT information. In the scenario we also consider land-side port operations of Container Handling Equipment from the point at which a container is offloaded onto the wharf to its exit through the port gate on the trailer of a truck.

One key finding of the work is that it is difficult for some maritime service providers, such as port operators, to conclusively point to locations where GNSS is employed within their systems. Indeed this is the case with all organisations that provide critical national infrastructure, an issue that has been identified by the BRIG and PNTTG. There are some who conclude that GNSS is provided as a means of measuring the efficiency of port operations, for example how quickly can a container transport truck get through a port. For others GNSS (particularly RTK GPS) is vital to maintain the efficiency of port operations, particularly when loading and unloading a vessel. For this part of the work MarRINav has liaised with various port operators including Felixstowe and Southampton.
The main result of Work Package 1 is that the scene has been set in terms of the maritime context within which PNT information is used, the need for Resilient PNT has been identified in more detail than has ever been previously presented, and the user requirements capture process has been formulated and begun.
10 Reference Documents


[30] ‘http://s100.iho.int/S100/’.
[38] ‘MUNIN - Research in Maritime Autonomous Systems Project Results and technology Potentials’, European Commission, Grant Agreement Number: 314286, 2016.
D1 Maritime Context and Requirements v2.0 (Section 8 updated)

[88] ‘https://muses-project.com/’.
[95] ‘https://www.gpsworld.com/k2-will-drive-glonass-under-1m/’.
[104] ‘https://www.londongateway.com/’.
[105] ‘https://www.navis.com/’.

[71x790]MarRINav – 4000126063/18/NL/MP – 2019-08-16


[109]’www.controltechniques.com’.


### Appendix A – General Operational Requirements

This appendix outlines the general operational requirements of any navigation used as a component of a resilient-PNT system.

<table>
<thead>
<tr>
<th>Req. ID</th>
<th>Requirement</th>
<th>Source</th>
<th>Stakeholder</th>
</tr>
</thead>
<tbody>
<tr>
<td>MR001</td>
<td>To avoid the necessity of carrying more than one set of receiving equipment on a ship, the shipborne receiving equipment should [shall] be suitable for operating either with a worldwide radionavigation system, or with radonavigation systems, which cover the area in which the ship trades.</td>
<td>IMO A.915</td>
<td>User</td>
</tr>
<tr>
<td>MR002</td>
<td>Shipborne receiving equipment should [shall] conform to the relevant performance standards not inferior to those adopted by the IMO</td>
<td>IMO A.915</td>
<td>User, Designer</td>
</tr>
<tr>
<td>MR003</td>
<td>Radionavigation systems should [shall] make it possible for shipborne receiving equipment to automatically select the appropriate stations for determining the ship’s position with the required performance</td>
<td>IMO A.915</td>
<td>User, Designer</td>
</tr>
<tr>
<td>MR004</td>
<td>Shipborne receiving equipment should [shall] be provided with at least one output from which position information can be supplied in a standard form to other equipment</td>
<td>IMO A.915</td>
<td>User, Designer</td>
</tr>
<tr>
<td>MR005</td>
<td>The system shall be considered available when it provides the required integrity for the given accuracy level</td>
<td>IMO A.1046</td>
<td>User, Operator</td>
</tr>
<tr>
<td>MR006</td>
<td>The requirements may be met by individual radionavigation systems or by a combination of such systems</td>
<td>IMO A.1046</td>
<td>All</td>
</tr>
<tr>
<td>MR007</td>
<td>All systems should [shall] be capable of being used by an unlimited number of ships</td>
<td>IMO A.1046</td>
<td>User</td>
</tr>
<tr>
<td>MR008</td>
<td>All available sources of positioning information shall be used</td>
<td>IALA R.129</td>
<td>User</td>
</tr>
<tr>
<td>MR009</td>
<td>Data communications and information flows supporting RPNT provision shall be robust</td>
<td>IMO</td>
<td></td>
</tr>
<tr>
<td>MR010</td>
<td>The user of a PNT system shall be provided with a method of identifying when interference occurs to the PNT system</td>
<td>MarRINav</td>
<td>All</td>
</tr>
</tbody>
</table>
## Appendix B – Maritime Required Navigation Performance Requirements from IMO A.915

### General Navigation

<table>
<thead>
<tr>
<th>System Level Parameters</th>
<th>Service Level Parameters</th>
<th>Fix Interval (Seconds)</th>
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</thead>
<tbody>
<tr>
<td>Absolute Accuracy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integrity</td>
<td></td>
<td></td>
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<tr>
<td>Horizontal (metres)</td>
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<td></td>
</tr>
<tr>
<td>Alert Limit (metres)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time to Alarm (Seconds)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integrity Risk (per 3 hours)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Availability % per 30 days</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continuity % over 3 hours</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coverage</td>
<td></td>
<td></td>
</tr>
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<table>
<thead>
<tr>
<th>Area</th>
<th>Absolute Accuracy</th>
<th>Alert Limit (metres)</th>
<th>Time to Alarm (Seconds)</th>
<th>Integrity Risk (per 3 hours)</th>
<th>Availability %</th>
<th>Continuity %</th>
<th>Coverage</th>
<th>Fix Interval (Seconds)</th>
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</thead>
<tbody>
<tr>
<td>Ocean</td>
<td>10</td>
<td>25</td>
<td>10</td>
<td>10.5</td>
<td>99.8</td>
<td>N/A(^\text{19})</td>
<td>Global</td>
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<tr>
<td>Coastal</td>
<td>10</td>
<td>25</td>
<td>10</td>
<td>10.5</td>
<td>99.8</td>
<td>N/A(^\text{19})</td>
<td>Global</td>
<td>1</td>
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<tr>
<td>Port Approach and Restricted Waters</td>
<td>10</td>
<td>25</td>
<td>10</td>
<td>10.5</td>
<td>99.8</td>
<td>99.97</td>
<td>Regional</td>
<td>1</td>
</tr>
<tr>
<td>Port</td>
<td>1</td>
<td>2.5</td>
<td>10</td>
<td>10.5</td>
<td>99.8</td>
<td>99.97</td>
<td>Local</td>
<td>1</td>
</tr>
<tr>
<td>Inland Waterways</td>
<td>10</td>
<td>25</td>
<td>10</td>
<td>10.5</td>
<td>99.8</td>
<td>99.97</td>
<td>Regional</td>
<td>1</td>
</tr>
</tbody>
</table>

\(^\text{18}\) More stringent requirements may be necessary for ships operating above 30 knots.

\(^\text{19}\) Continuity is not relevant to ocean and coastal navigation.
## Positioning

<table>
<thead>
<tr>
<th></th>
<th>System Level Parameters</th>
<th>Service Level Parameters</th>
<th>Coverage</th>
<th>Fix Interval (Seconds)</th>
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<tbody>
<tr>
<td></td>
<td>Accuracy</td>
<td>Integrity</td>
<td>Availability % per 30 days</td>
<td>Continuity % over 3 hours</td>
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<tr>
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<td>Horizontal (metres)</td>
<td>Vertical (metres)</td>
<td>Alert Limit (metres)</td>
<td>Time to Alarm (Seconds)</td>
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<td><strong>Operations</strong></td>
<td>Relative Accuracy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Tugs and Pushers</strong></td>
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<td>2.5</td>
<td>10</td>
<td>10.5</td>
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<td><strong>Icebreakers</strong></td>
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<td>10</td>
<td>10.5</td>
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<td>10</td>
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<td><strong>Traffic Management</strong></td>
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<tr>
<td><strong>Ship-to-ship co-ordination</strong></td>
<td>10</td>
<td>25</td>
<td>10</td>
<td>10.5</td>
</tr>
<tr>
<td><strong>Ship-to-shore co-ordination</strong></td>
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<td><strong>Shore-to-ship Traffic Management</strong></td>
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20 More stringent requirements may be necessary for ships operating above 30 knots.
21 There may be a requirement for accuracy in the vertical plane for some port and restricted water operations.
22 Traffic management applications in some areas, e.g. the Baltic, may require higher accuracy.
## Positioning (continued)

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<tr>
<th>Position</th>
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<tr>
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### Positioning (continued)

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<th></th>
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<th>Service Level Parameters</th>
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<tr>
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<td>Accuracy</td>
<td>Integrity</td>
</tr>
<tr>
<td></td>
<td>Horizontal (metres)</td>
<td>Vertical (metres)</td>
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<td>Absolute Accuracy</td>
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## Positioning (continued)

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<td>Integrity</td>
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<td>Fisheries Monitoring</td>
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</table>

23 A vertical accuracy of a few cm (less than 10) is necessary to monitor platform subsidence.
24 A vertical accuracy of a few cm (less than 10) is necessary to monitor platform subsidence.
25 Positioning during fishing in local areas may have more stringent requirements.
Positioning (continued)

<table>
<thead>
<tr>
<th>Recreation and Leisure</th>
<th>Absolute Accuracy</th>
<th>System Level Parameters</th>
<th>Service Level Parameters</th>
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</thead>
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<tr>
<td></td>
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<td>Accuracy</td>
<td>Integrity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Horizontal (metres)</td>
<td>Vertical (metres)</td>
</tr>
<tr>
<td>Ocean</td>
<td>10</td>
<td>25</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>10</td>
<td>10.5</td>
</tr>
<tr>
<td></td>
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## Appendix C – IMO’s Maritime Services in the Context of e-Navigation

<table>
<thead>
<tr>
<th>No</th>
<th>Identified Services</th>
<th>Identified Service Provider</th>
<th>Short Description</th>
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</table>
| MS1| VTS Information Service (IS)        | VTS Authority               | The VTS Information Service (IS) is defined as “a service to ensure that essential information becomes available in time for onboard navigational decision making”. Relevant information is broadcasted at fixed times and intervals or provided when deemed necessary by the VTS or at the request of a vessel. A VTS IS involves maintaining a traffic image and allows interaction with traffic and response to developing traffic situations. An Information Service should provide essential and timely information to assist the onboard decision-making process, which may include but is not limited to:  
  • the position, identity, intention and destination of vessels;  
  • amendments and changes in promulgated information concerning the VTS area such as boundaries, procedures, radio frequencies, reporting points;  
  • the mandatory reporting of vessel traffic movements;  
  • meteorological and hydrological conditions, notices to mariners, status of aids to navigation;  
  • manoeuvrability limitations of vessels in the VTS area that may impose restrictions on the navigation of other vessels, or any other potential hindrances; or  
  • any information concerning the safe navigation of the vessel.  
The VTS IS is designed to improve the safety and efficiency of vessel traffic and to protect the environment. Among others, such services include: Routing, Channel info, Security level, Berthing, Anchorage, Time slot, Traffic monitoring and assessment, Waterway conditions, Weather, Navigational hazards, any other factors that may influence the vessel’s transit, Reports on the position, Identity and intentions of other traffic. |
| MS2| Navigational Assistance Service (NAS)| National Competent VTS Authority/Coastal or Port Authority | The NAS is defined as "a service to assist onboard navigational decision-making and to monitor its effects". NAS may be provided on request by a vessel in circumstances such as equipment failure or navigational unfamiliarity. Specific examples of developing situations where NAS may be provided by the VTS include:  
  • Risk of grounding; Vessel deviating from the recommended track or sailing plan; Vessel unsure of its position or unable to determine its position;  
  • Vessel unsure of the route to its destination; Assistance to a vessel to an anchoring position; Vessel navigational or manoeuvring equipment casualty; Inclement conditions (e.g., low visibility, high winds); Potential collision between vessels; Potential collision with a fixed object or hazard;  
  • Assistance to a vessel to support the unexpected incapacity of a key member of the bridge team, on the request of the master.  
The TOS is defined as "a service to prevent the development of dangerous maritime traffic situations and to provide for the safe and efficient movement of vessel traffic within the VTS area". The purpose of the TOS is to prevent hazardous situations from developing and to ensure safe and efficient navigation through the VTS area. 
The TOS should be provided when the VTS is authorized to provide services, such as when:  
  • Vessel movements need to be planned or prioritized to prevent congestion or dangerous situations;  
  • Special transports or vessels with hazardous or polluting cargo may affect the flow of other traffic and need to be organized. |
| MS3| Traffic Organization Service (TOS)  | National Competent VTS Authority/Coastal or Port Authority | The NAS is defined as "a service to assist onboard navigational decision-making and to monitor its effects". NAS may be provided on request by a vessel in circumstances such as equipment failure or navigational unfamiliarity. Specific examples of developing situations where NAS may be provided by the VTS include:  
  • Risk of grounding; Vessel deviating from the recommended track or sailing plan; Vessel unsure of its position or unable to determine its position;  
  • Vessel unsure of the route to its destination; Assistance to a vessel to an anchoring position; Vessel navigational or manoeuvring equipment casualty; Inclement conditions (e.g., low visibility, high winds); Potential collision between vessels; Potential collision with a fixed object or hazard;  
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<table>
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<th>MS4</th>
<th>Local Port Service (LPS)</th>
<th>Local Port/Harbour Operator</th>
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- an operating system of traffic clearances or sailing plans, or both, has been established;
- the allocation of space needs to be organized;
- mandatory reporting of movements in the VTS area has been established;
- special routes should be followed;
- speed limits should be observed;
- the VTS observes a developing situation and deems it necessary to interact and coordinate vessel traffic; and
- nautical activities (e.g. sailing regattas) or marine works in-progress (such as dredging or submarine cable-laying) may interfere with the flow of vessel movement.

LPS is applicable to those ports where it has been assessed that a VTS, as described above, is excessive or inappropriate. The main difference arising from the provision of LPS is that it does not interact with traffic, nor is it required to have the ability and/or the resources to respond to developing traffic situations and there is no requirement for a vessel traffic image to be maintained. Provision of LPS is designed to improve port safety and co-ordination of port services within the port community by dissemination of port information to vessels and berth or terminal operators. It is mainly concerned with the management of the port, by the supply of information on berth and port conditions. Provision of LPS can also act as a medium for liaison between vessels and allied services, as well as providing a basis for implementing port emergency plans. Examples of LPS may include:

- berthing information;
- availability of port services;
- shipping schedules; and
- meteorological and hydrological data.

A number of web-based LPS services are being developed. An example is AVANTI, an initiative of the International Harbour Masters Association (IHMA).

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<th>MS5</th>
<th>Maritime Safety Information Service (MSI)</th>
<th>National Competent Authority</th>
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The Global Maritime Distress and Safety System (GMDSS) as described in SOLAS chapter IV defines the seventh functional requirement as:

"Every ship, while at sea, shall be capable of transmitting and receiving maritime safety information".

The MSI service is an internationally coordinated network of broadcasts of Maritime Safety Information from official information providers, such as:

- National Hydrographic Offices, for navigational warnings and chart correction data;
- National Meteorological Offices, for weather warnings and forecasts;
- Rescue Co-ordination Centres (RCCs), for shore-to-ship distress alerts; and
- the International Ice Patrol, for Oceanic ice hazards.

Specific information on Aids to Navigation and restrictions on safe navigation are part of MSI services provided by National Authorities. This can include but is not limited to, the following type of information to be available to mariners:

- status of Aids to Navigation;
- status of GPS and DGPs;
- buoy tendering operation; and
- restriction on safe navigation such as bridge/hydro cable air gap, new hazards, construction or dredging operations.

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<th>MS6</th>
<th>Pilotage Service</th>
<th>Pilot Authority/ Pilot Organization</th>
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The aim of the pilotage service is to safeguard traffic at sea and protect the environment by ensuring that vessels operating in pilotage area have navigators with adequate qualifications for safe navigation. Each pilotage area needs highly specialized experience and local knowledge on the part of the pilot.
Efficient pilotage depends, among other things, upon the effectiveness of the communications and information exchanges between the pilot, the master and the bridge personnel and upon the mutual understanding each has for the functions and duties of the other. The Pilot’s Portable Unit (PPU) is a useful tool for safe navigation in clear and restricted visibility. Data accessible by the PPU should be made available in a structured, harmonized and reliable manner, and the interface for accessing such e-navigation information should be standardized.

Establishment of effective coordination between the pilot, the master and the bridge personnel, taking due account of the ship's systems and equipment available to the pilot, will aid a safe and expeditious passage (see resolution A.960(23)).

Efficient tug operations depend on, among other things, the effectiveness of the communications and information exchanges between relevant stakeholders. The aim of the tugs services is to safeguard traffic at sea and protect the environment by conducting operations such as:

- transportation (personnel and staff from port to anchorage) operations;
- ship assistance (ex: mooring) operations;
- salvage (grounded ships or structures) operations;
- shore operations;
- towage (harbour/ocean) operations;
- escort operations; and
- oil spill response operations.

The aim of vessel shore reporting is to safeguard traffic at sea, ensure personnel safety and security, ensure environmental protection and increase the efficiency of maritime operations. Single-Window is one of the most important solutions to reduce the Mariners workload (amount of time spent on preparing and submitting reports to shore-based authorities). To achieve this, reports should be automatically generated as much as possible from onboard systems. Some other important possibilities for vessel shore reporting system may include:

- single-entry of reportable information in single-window solution;
- automated collection of internal ship data for reporting;
- all national reporting requirements to apply standardized digital reporting formats based on IMO FAL forms; and
- automated or semi-automated digital distribution/communication of required reportable information.

TMAS centres should provide medical advice for seafarers 24 h/day, 365 days/year. TMAS should be permanently staffed by physicians qualified in conducting remote consultations and who are well versed in the particular nature of treatment on board ship. Within the maritime medicine the prevailing view has for a long time been that a standardization of the TMAS services is both necessary and wanted. This would firstly enhance the quality of the medical practice, and secondly, a standardization of reporting and registering of medical events will make a much better basis for advancement.

The primary mission of MAS is to handle communication between the coastal State, ship's officers requiring assistance and other players in maritime community. These can be fleet owners, salvage companies, port authorities, brokers, etc. The MAS is on 24-hour alert to deploy rapid assistance and professional support for ships in connection with combating pollution, fire and explosions on board, collision, grounding, maritime security, terror mitigation, etc.

The Ship Security Alert System enables a vessel to send a distress call if it is attacked by pirates, etc. On receiving such a call, the MAS is responsible for alerting the relevant authorities responsible for a response. The MAS is responsible only for receiving and transmitting communications and monitoring the situation. It serves as a point of contact between the master and the coastal State concerned if the ship’s situation requires exchanges of information between the ship and the coastal State.

Situations where the MAS apply are as follows:
• ship involved in an incident (loss of cargo, accidental discharge of oil, etc.) that does impair its seakeeping ability but nevertheless has to be reported;
• ship in need of assistance according to the master's assessment, but not in distress situation that requires the rescue of personnel on board; and
• ship in distress situation and those on board have already been rescued, with the possible exception of those who have remained aboard or have been placed on board to attempt to deal with the ship's situation.

The MAS entails the implementation of procedures and instructions enabling the forward of any given information to the competent organization and requiring the organizations concerned to go through the MAS in order to make contact with the ship.

The aim of the nautical chart service is to safeguard navigation at sea by providing information such as nature and form of the coast, water depth, tides table, obstructions and other dangers to navigation, location and type of aids to navigation.

The Nautical Chart service also ensure the distribution, update and licensing of electronic chart to vessels and other maritime parties.

The aim of the nautical publication service is to promote navigation awareness and safe navigation of ships. The nature of waterways described by any given nautical publication changes regularly, and a mariner navigating by use of an old or uncorrected publication is courting disaster. Nautical publications include:

- tidal currents, aids to navigation system, buoys and fog signals, radio aids to marine navigation, chart symbols, terms and abbreviations, sailing directions; and
- a Chart and Publication Correction Record Card system can be used to ensure that every publication is properly corrected prior use by mariners.

The ice navigation service is critical to safeguard the ship navigation in ice-infested waters, given how quickly the ice maps become outdated in the rapid changing conditions of the ice-covered navigational regions. Such services include:

- ice condition information and operational recommendations/advice;
- ice condition around a vessel;
- vessel routing;
- vessel escort and ice breaking;
- ice drift load and momentum; and
- ice patrol.

The meteorological service is essential to safeguard the traffic at sea by providing weather, climate digital forecasts and related information to mariners who will use these types of information to support their decision making. Such information includes:

- weather routing, solar radiation and precipitation;
- cold/hot durations and warnings;
- air temperature, wind speed and direction; and
- cloud cover and barometric pressure.

The real-time hydrographic and environmental information service is essential to safeguard navigation at sea and protect the environment. The services provided are such as:

- current speed and direction;
- wave height;
- marine habitat and bathymetry;
- sailing Directions (or pilots): detailed descriptions of areas of the sea, shipping routes, harbours, aids to navigation, regulations, etc.;
- lists of lights: descriptions of lighthouses and lightbouys;
<table>
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<th>MS16</th>
<th>Search and Rescue Service (SAR)</th>
<th>National Competent Authority Organization/Authorities</th>
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- tide surge prediction tables and tidal stream atlases;
- ephemerides and nautical almanacs for celestial navigation; and
- notice to mariners: periodical (often weekly) updates and corrections for nautical charts and publications.

The SAR service is responsible for assisting, coordinating search and rescue operations at sea. In maintaining a state of full readiness the MRCC may perform the following rescue functions:
- survivors of any aircraft (not in an act of war) crashes or forced landings at sea;
- the crew and passengers of vessels in distress; and
- survivors of maritime accidents or incidents.

The SAR services must also coordinate the evacuation of seriously injured or ill person from a vessel at sea when the person requires medical treatment sooner than the vessel would be able to get him or her to a suitable medical facility.

MRCCs may also be pro-actively involved in activities such as:
- information collection, distribution and coordination;
- monitoring towing operations;
- monitoring and evaluating levels of risk from Maritime Safety Information (MSI) broadcasts to ensure an immediate response in case of life threatening situations developing;
- monitoring vessels not under command; and
- pollution reports and vessels aground.

E-navigation can provide additional information such as number of persons on board, type of ship, port of destination etc. and enable provision of additional information such as available SAR resources on board ships etc. Information on other vessels in the area can be crucial for an effective rescue.

Communication solutions used for e-navigation will be able to exchange information about SAR areas and allocate search patterns and provide facilities for MRCCs to set up a common information sharing log or chatroom for MRCCs, on-scene coordinator and other resources to share and update information during a SAR incident.
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