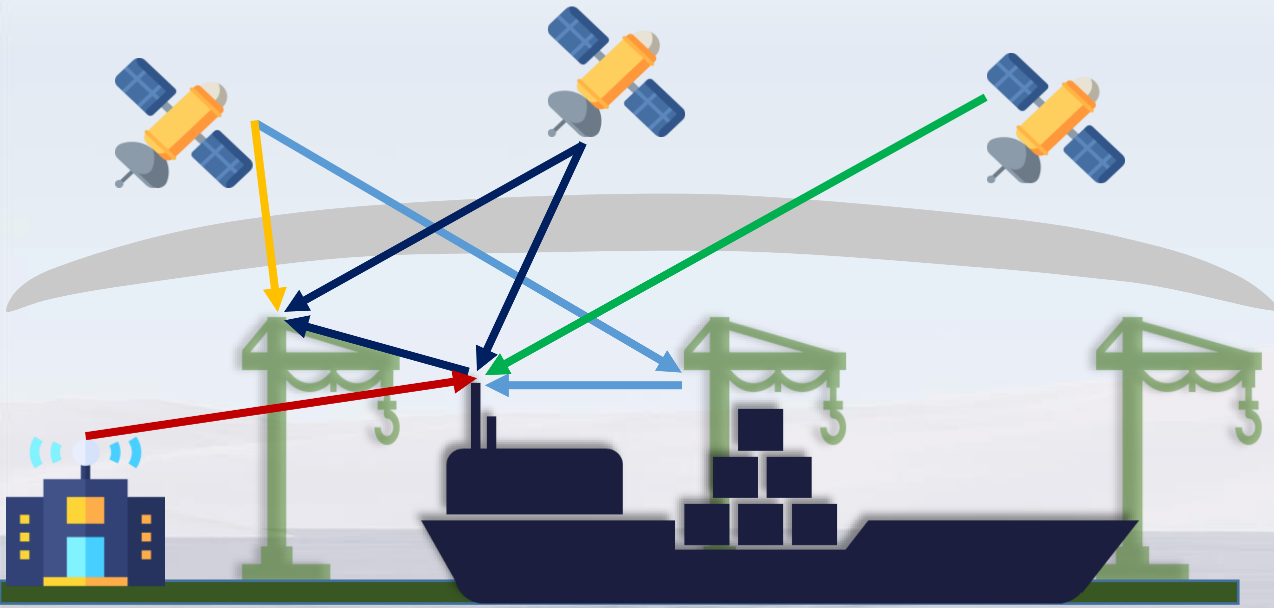
Integrated Navigation System-of-Systems PNT Integrity for Resilience

Final Presentation



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Integrated Navigation System-of-Systems PNT Integrity for Resilience

To explore and develop means of providing integrity for GNSS positioning information which can meet the navigational needs of current and future mariners

Lead Contractor & Systems Engineering
Jon Pring, Katie Lloyd, Kieran Bjergstrom

System-Level Integrity Monitor Development
Kiran Patel, Peter Niemann

User-Level Algorithm Development
Terri Richardson, Ginés Moreno López, Michael Pattinson

Signals of Opportunity
Washington Ochieng, Ma'mon Alghananim

Maritime Regulation & EGNOS Monitor Development
Alan Grant, Chris Hargreaves

Maritime User Engagement
Phil Buckley

Cost Benefit Analysis
Rasmus Flytkjaer, Tom Goulding

Stakeholder Engagement
Bob Cockshott, Mark Littlewood

NAVISP Funding, Technical Expertise & Guidance throughout
Jean-Christophe Denis, Dean Thomas

Agenda

- Context & Purpose
- Project's User Requirements
- Technical Solutions
  - User Level Algorithms & Prediction Tool
  - System Level Monitoring
  - Signals of Opportunity
- Cost Benefit Analysis
- Implementation & Exploitation
- Conclusions
- Q&A

The Maritime World is becoming more and more complex

- Increasing maritime traffic
  - Total size of the world merchant fleet has increased from 83,000 to 108,000 vessels since 2011 – *UNCTAD Statistics*
- Increasing global shipping volume and value
  - Over the last decade, world container port throughput increas
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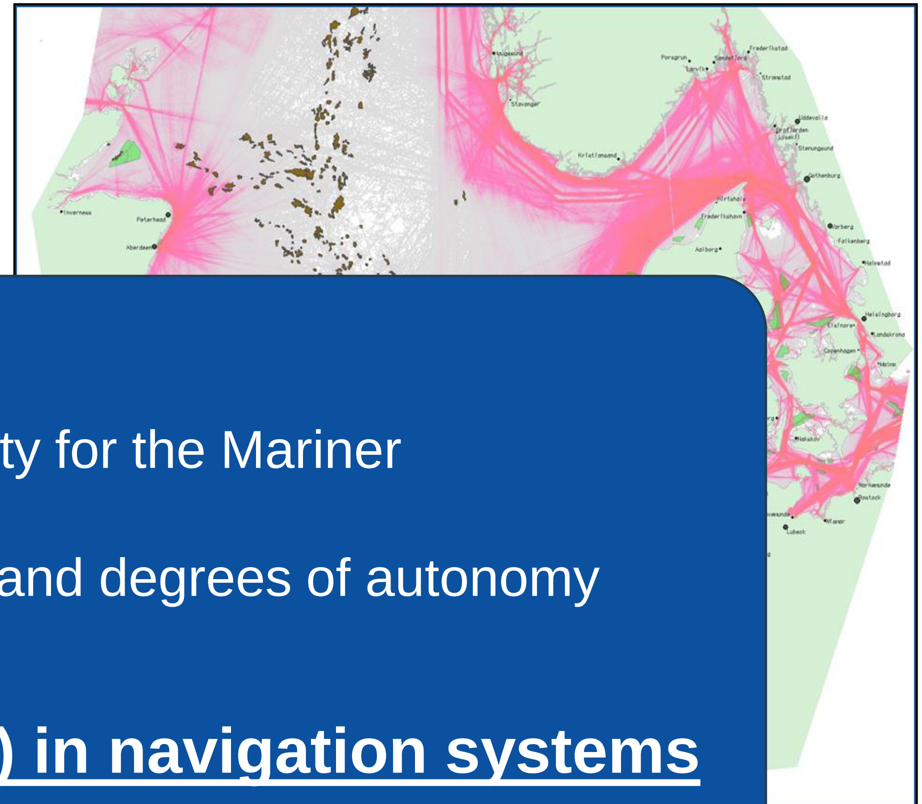
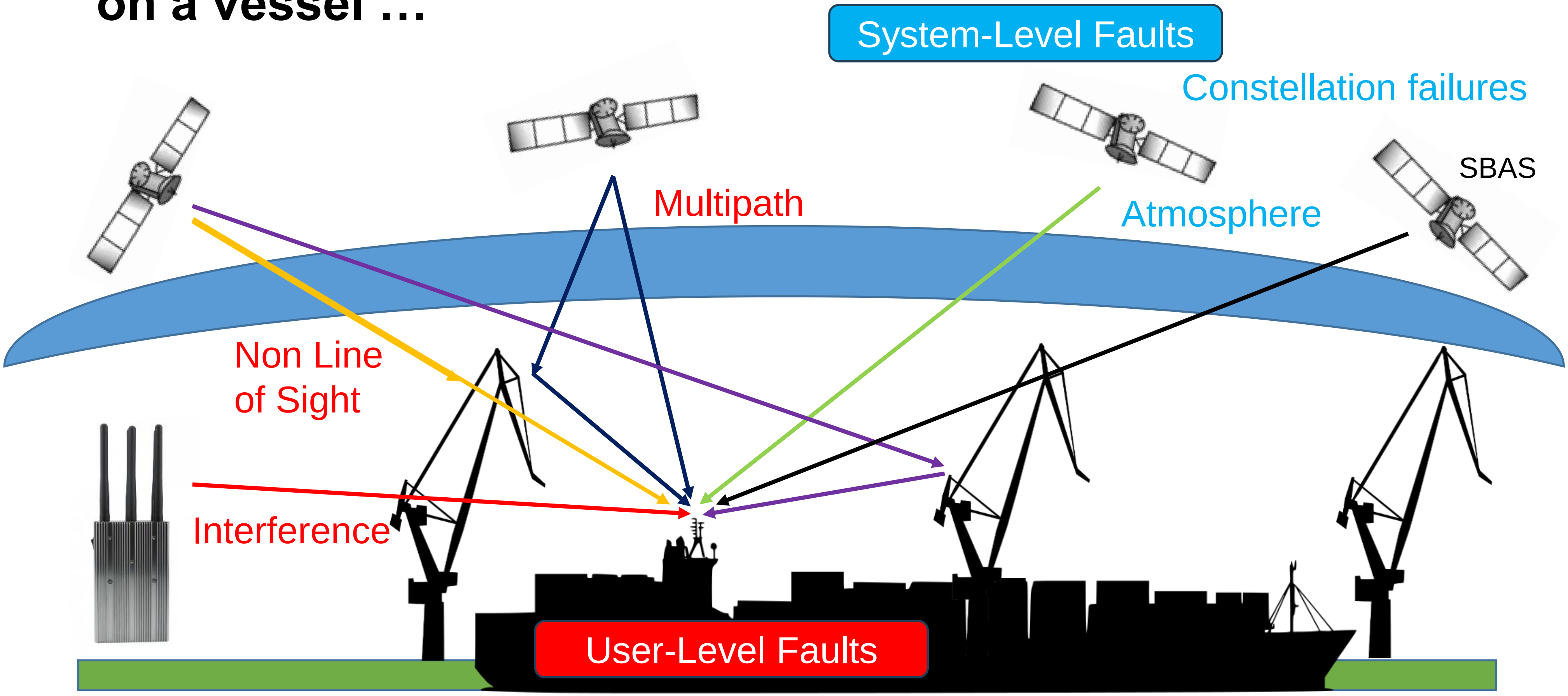


Increasing complexity for the Mariner

Use of systems, technology and degrees of autonomy

A need for trust (integrity) in navigation systems

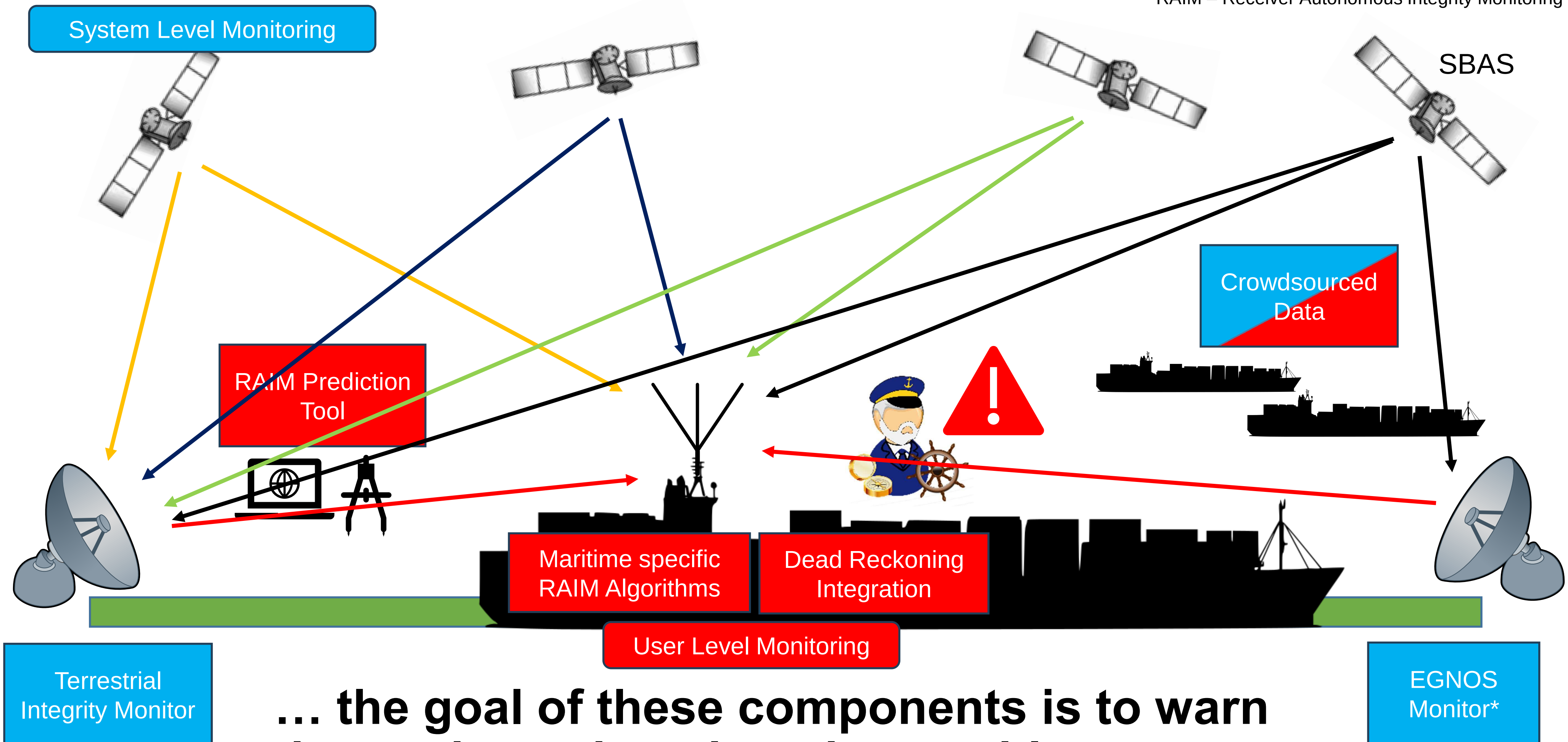
GNSS is often a primary source of navigation information on a vessel …



… but GNSS is vulnerable to threats and faults

INSPIRe has developed and tested components of an integrity monitoring architecture

SBAS – Space Based Augmentation System
EGNOS – European Geostationary Navigation Overlay Service
RAIM – Receiver Autonomous Integrity Monitoring



… the goal of these components is to warn the mariner when there is a problem

*Aims to provide assurance of EGNOS SoL for the UK

INSPIRe's solutions are part way along the journey to a future maritime

Today

Future (TBD)

Crewed vessel

Mariner guided by integrity information

Simple definition of integrity

INSPIRe

In INSPIRe, we:

- ✓ Consolidate user needs to develop a set of user requirements
- ✓ Investigate integrity monitoring technologies which meet maritime users' needs
- ✓ Communicate the costs and benefits of integrity
- ✓ Identify the next steps for development

Fully autonomous vessels

No mariner /or remote operator to interpret integrity information

Fully defined requirements and standards

User Requirements

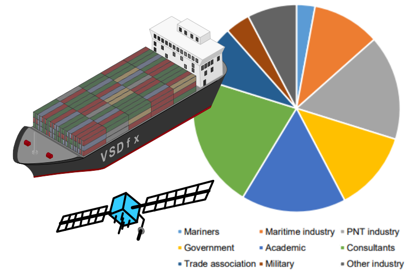
The project has developed solution agnostic requirements based on mariners' needs

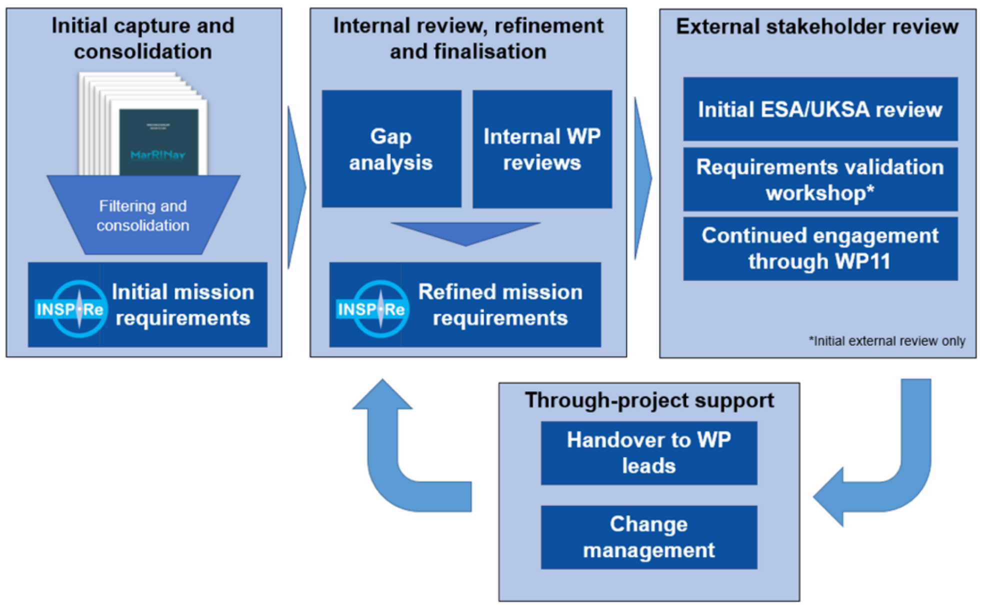
Use Case Analysis

Extant Standards

A.1046(27)
A.915(22)

Stakeholder Engagement





Requirements structure

Concept of Operations

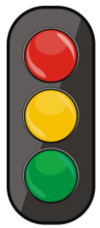
- **“The ability to provide users with warnings within a specified time when the system should not be used for navigation due to detected faults or an inability to detect faulted conditions.”**
- UK EEZ, ideally extensible; Fault conditions articulated by INSPIRe; safety of operations.
- User- and system- levels considered.

Functional & Performance

- Able to detect and potentially mitigate faults
- Configurable for different voyage conditions and performance requirements.
- Assesses navigation solution safety and issues alerts.
- Performance requirements depend on phase of navigation.
- IMO A.1046(27) defines ‘core’ requirements; Availability, TTA, Continuity, and 95th percentile accuracy.

Non-Functional

- Compatible and integrable – installation, degrees of redundancy, realistic signal environment, vessel configuration (e.g. mask angles), NMEA-0183.
- Compatible with multi-sensor systems, and able to provide separate fault detection and isolation.
- Three-tier integrity output (RAG)



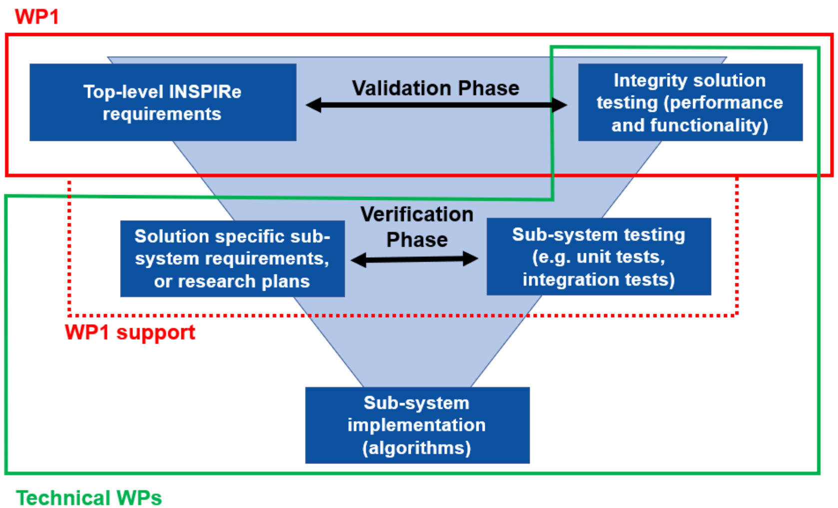
  - Do not use.
  - Caution; no faults detected but the conditions for a green light are not met.
  - Safe to use, no faults detected and output is deemed safe for navigation in accordance with the integrity method applied.

Future Requirements

- Future functional around dynamic integrity assessment, cause identification, and disruption.
- Future performance requirements were based on IMO A.915 and the GSA autonomy survey. These were formulated in terms of integrity risk and more stringent than IMO A.1046 per phase.

Verification and Validation

- Top-level requirements handed over to consortium members; all solutions were developed based on the same requirements set enabling comparability and ensuring compatible solutions.

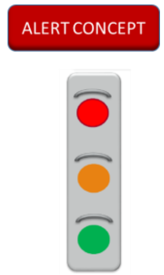


- Requirements development continued through the project to reflect additional knowledge and stakeholder input, particularly informing future requirements.
- Our approach was to explore the art of the possible and inform near-term and future solutions.

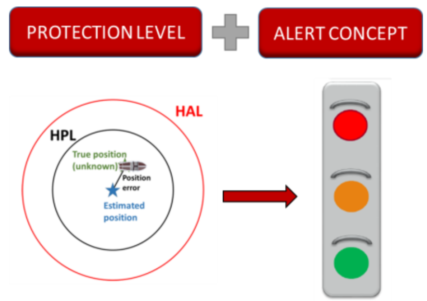
User-Level Integrity Algorithms & Tools

Three user level algorithms have been developed and tested in software to demonstrate improving monitoring capabilities

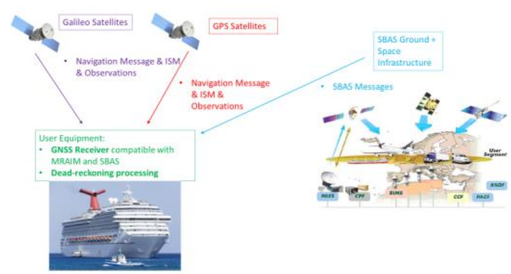
- **MG-RAIM (Maritime General Receiver Autonomous Integrity Monitoring)**
  - RAIM-type solution to improve user-level integrity without major changes to receivers
  - Considering current equipment (GPS L1 receivers)
  - Aligns with EGNOS V2 integrity information
  - Aligns with current procedures (red, amber, green)
  - Algorithms to improve current user-level integrity without major changes to requirements
    - Geometry, accuracy, fault detection



- **M-RAIM (Maritime Receiver Autonomous Integrity Monitoring)**
  - Adaptation of the aviation ARAIM to capture the particularities of the maritime domain
  - Considering future equipment (GPS+GAL L1/L5 receivers)
  - Aligns with future EGNOS V3 integrity information
  - Aligning as far as possible with current procedures (red, amber, green status)
  - Algorithms to improve user-level integrity and looking to future requirements
    - Geometry, accuracy, fault detection, Protection Levels



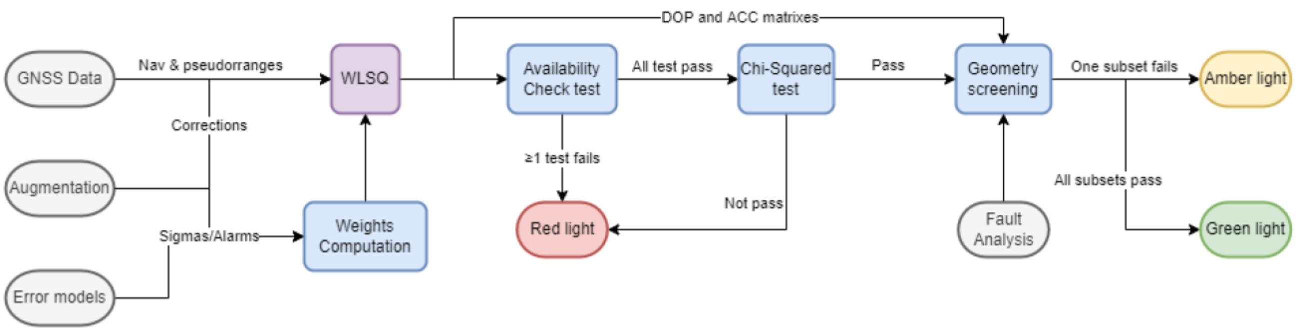
- **VAIM (Vessel Autonomous Integrity Monitoring)**
  - Integration of DFMC GNSS and dead-reckoning to create a VAIM solution (analogous to aviation AAIM)
  - Assess the feasibility of a maritime VAIM solution (considering technical issues and affordability)
  - Considering future equipment (GPS+GAL L1/L5 receivers) and sensor integration (IMU and speed sensors)



Maritime General RAIM (MG-RAIM)

- A snapshot weighted least squares navigation solution is computed on each epoch as normal. This may be GPS and GAL or use SBAS corrections and integrity information where applicable
- The algorithm is based on three sequential steps once the position is calculated:
  - Availability check
  - Fault detection
  - Geometry screening

MG-RAIM conceptual flowchart without augmentation

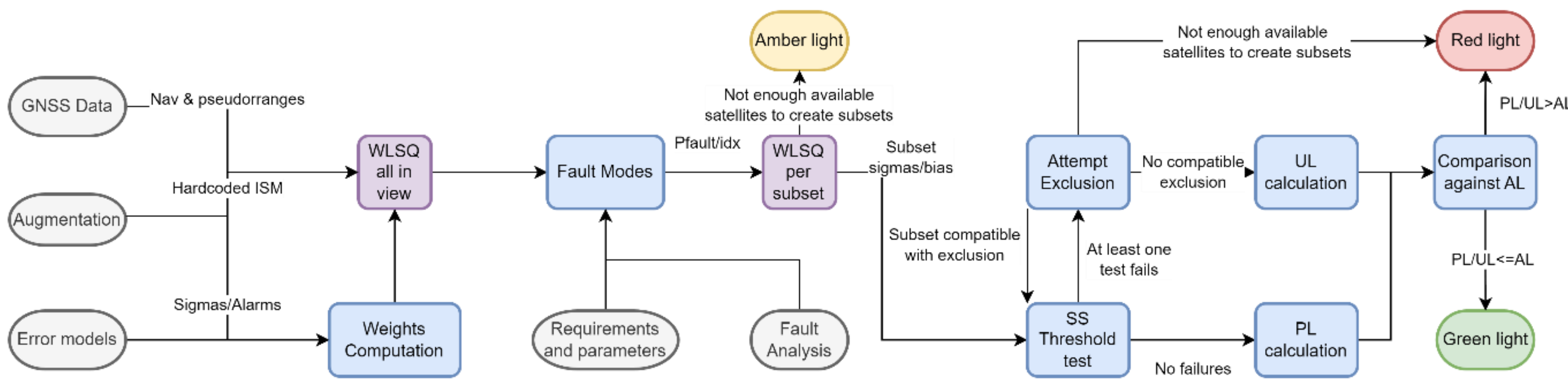


- Performance benefits
  - In the fault-free case, GPS L1 alone can meet the performance requirements for the ocean case (100m accuracy)
  - The use of EGNOS allows the coastal performance requirements to be met in fault-free case
  - The fault detection part of the MG-RAIM algorithm can detect many cases where the range errors are excessive and help protect against the largest position errors that would occur

Maritime RAIM (M-RAIM)

- M-RAIM proposed is an adaptation of the aviation ARAIM to capture the particularities of the maritime domain
- User algorithm:
  - Fault Detection and Exclusion: Each failure mode defines a reduced-subset solution, which excludes the potentially faulty measurements.
  - Protection Level calculation: The horizontal protection level is computed that considers all monitored failure modes, nominal errors and nominal biases.

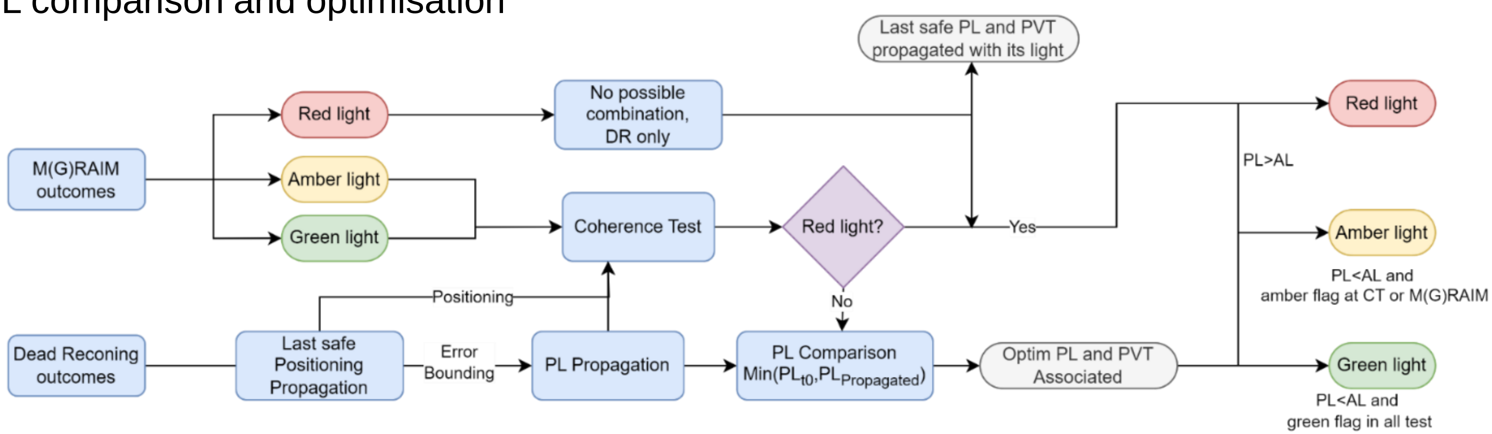
M-RAIM conceptual flowchart with augmentation



- Performance benefits
  - For MRAIM, the algorithm provides an additional metric (the HPL) for checking if the solution is ‘valid’. This metric provides a more representative estimate of the true position error that can be achieved.

Vessel Autonomous Integrity Monitoring (VAIM)

- VAIM integrates dual frequency, multi-constellation GNSS and dead reckoning. It expands the capabilities of the integrity algorithms for sensor fusion.
- Dead reckoning estimates the current position using a previously known position and measurements of distance (or integrated velocity) and direction travelled.
- The VAIM algorithm was developed as an additional integrity monitoring layer on top of the MG-RAIM and M-RAIM algorithms. It has the following main modules:
  - Extract GNSS and dead reckoning information, including positioning and integrity information from integrity algorithms and the dead reckoning outcomes.
  - PVT and positioning bounding extrapolation
  - Coherence Test
  - PL comparison and optimisation

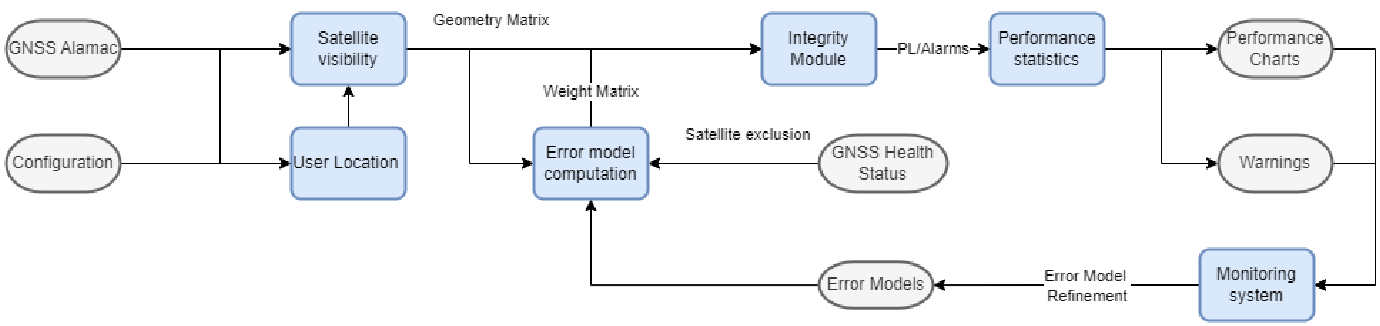


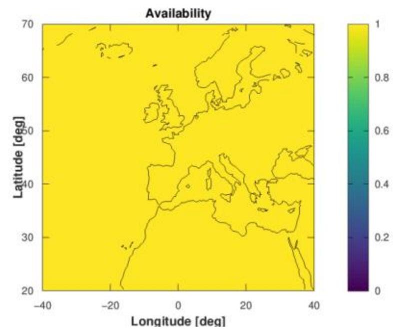
VAIM conceptual flowchart

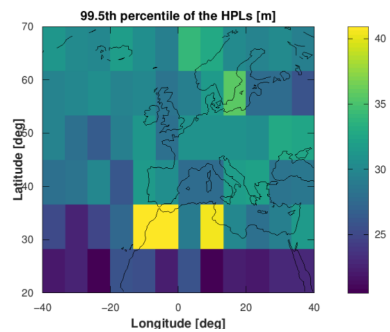
RAIM Performance Prediction Tool

- The tool provides a RAIM availability prediction capability consistent with the three tiers of user-level algorithms; it is developed and validated to a prototype level tool
- Users can predict the availability of the MG-RAIM and M-RAIM algorithms across the limits of the UK Territory exclusive economic zone (EEZ)
- Users can configure the tool based on equipment capabilities (GPS L1, or GPS+GAL L1/L5 receivers, and EGNOS)
- The tool enables users to forecast the availability of their navigation solution over their voyage to the required level of integrity

M(G)RAIM Performance Prediction Prototype Tool







System-Level EGNOS Monitor

EGNOS Monitor

- Network of EGNOS-enabled GNSS receivers which monitor the EGNOS solution
  - Dual-frequency L1 + L5, GPS + Galileo for future monitoring of EGNOS V3

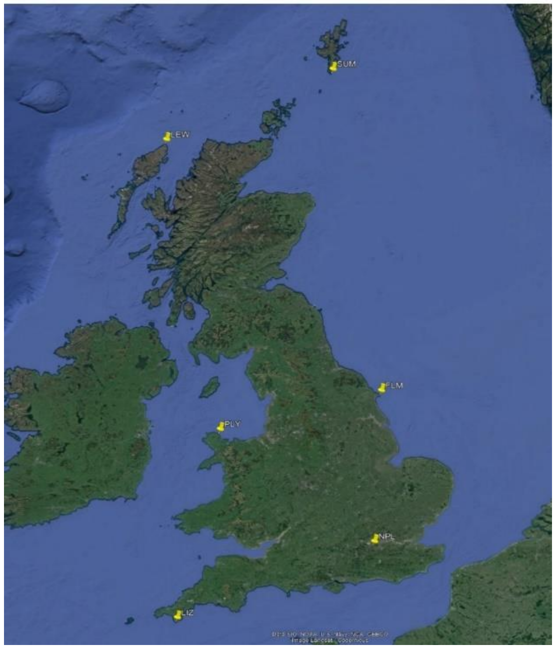
- Monitor locations limited to mainland UK
  - Geometry of satellite observations is poor
  - Geographical extent of ionosphere pierce points is poor
  - **Cannot elaborate integrity bounds without better geometry!**

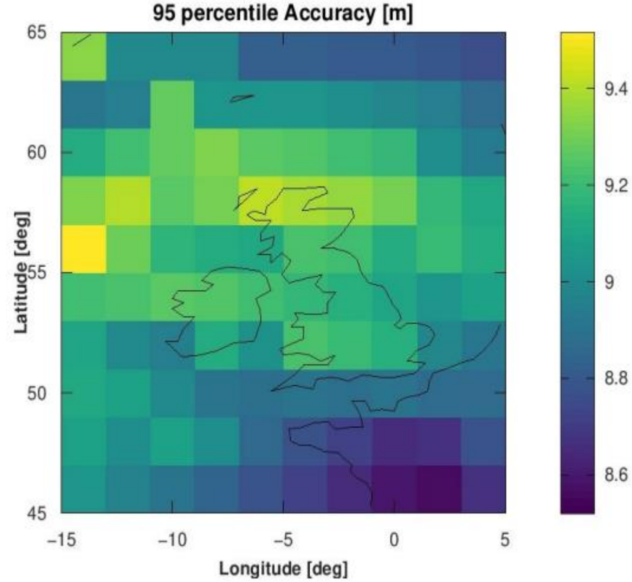
- Solution: EGNOS User Position Monitor (UPM)
  - Modelled after the WAAS UPM
  - Verifies that no catastrophic failure of service has been detected
  - **Does not elaborate true integrity bounds!**

- Solution supports UK Government entity rather than user directly
  - Monitor does not communicate to the user
  - Monitor can provide UK Govt. with assurance that EGNOS has not suffered a failure
  - Provides indicative coverage of the system
  - If deemed suitable, Govt. could then extend Safety of Life guarantee to users (subject to caveats)

EGNOS Monitor

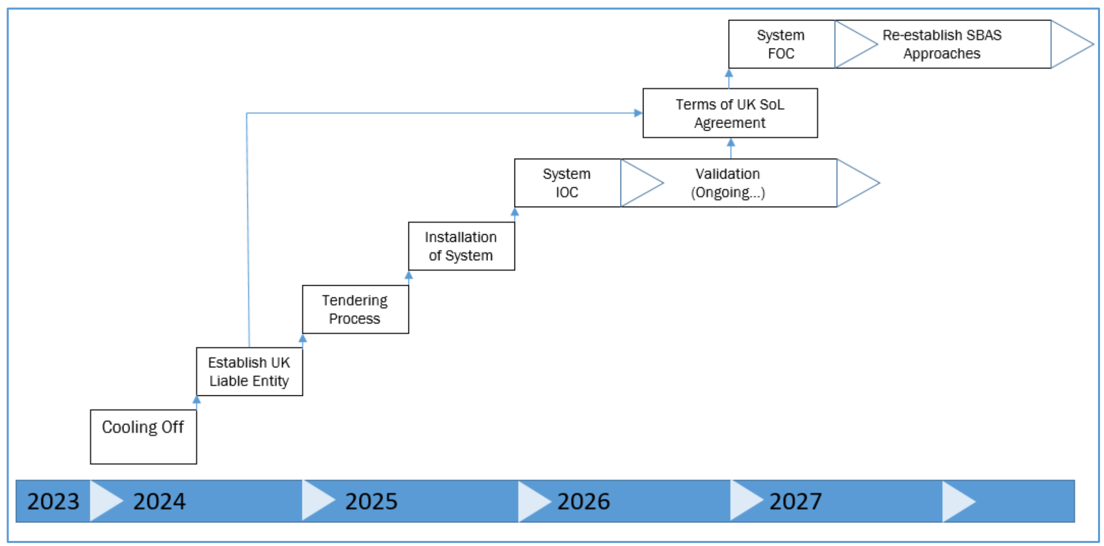
Monitor Network





Expected Maritime-User Performance

Implementation Timeline (Indicative only)

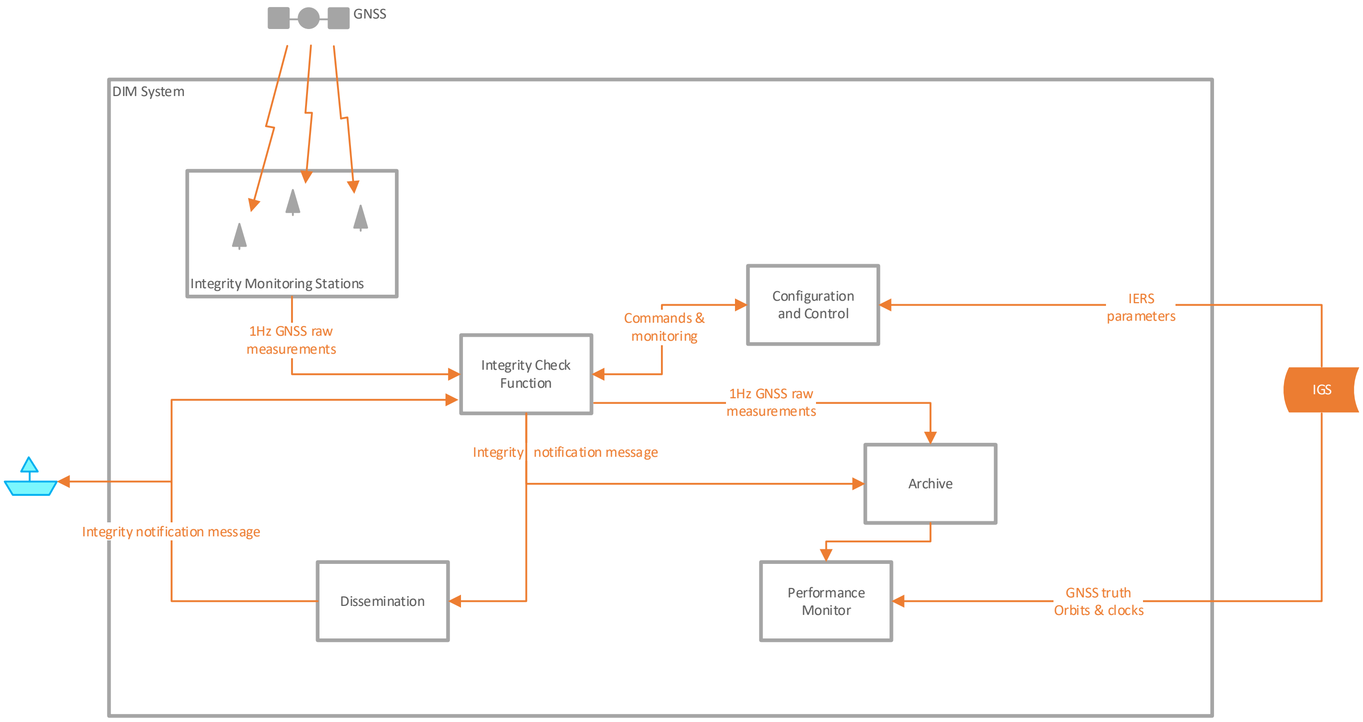


System-Level DFMC Integrity Monitor

DFMC Integrity Monitor

Objective of Providing a UK DFMC Integrity Monitoring Service

- Notifying alarms on GNSS satellite status (broadcast position or clock, signal degradation, etc.) within tight time to alarm
- For dual frequency multi-constellation user receivers
- To aid user RAIM positioning as part of a system of systems approach to integrity



Service Architecture

- Precisely surveyed Monitoring Stations (GNSS Receivers) take GNSS dual frequency measurements across the UK
- Central Processing uses the collected measurements to monitor and mitigate those types of GNSS error which are best detected centrally
- Integrity information is disseminated to mariners via a range of channels and technologies

DFMC Integrity Monitor - Benefits

Performance Benefits

- Some types of Feared Event are more reliably detected through a central system due to the availability of multiple observations of the same GNSS satellite, such as cycle slips, signal degradations
- In the event of multiple faults, the ability of the central system to isolate each fault is greater due to the number of available measurements
- High specification receivers will allow the DIM system to monitor for conditions such as evil wave forms not available in user receivers
- Continuous monitoring facilitates consistency checks against historic information which a newly initialised user receiver will not possess

Performance - Simulation Results

- Processing of real data did not reach IMO explicit and implicit performance targets, due to the nature and quality of available data
- Performance extrapolation indicates feasibility of the missed detection and false DU alarm rates though not continuity
- Results demonstrate the GDOP impact of a design restricted to UK assets
- Results highlight the importance of measurement quality

DFMC Integrity Monitor – Risks/Issues

Standards

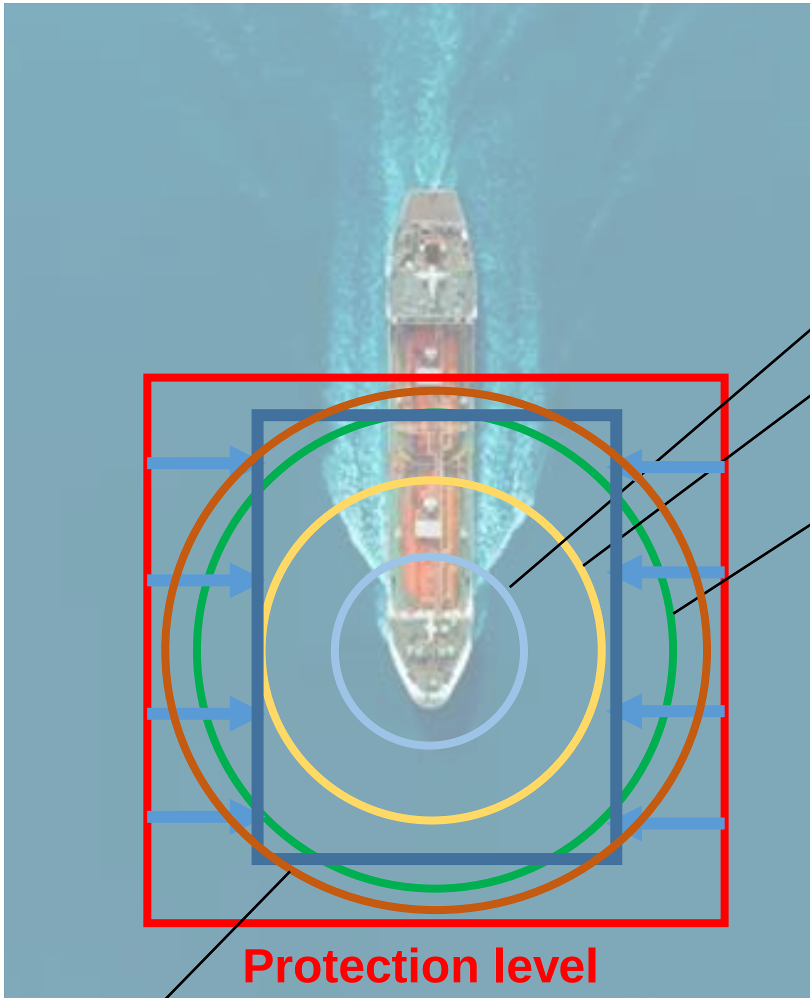
- Existing standards such as MOPS cannot be applied, dedicated standard needed covering:
- Service definitions and performance targets such as availability, continuity, missed detection, false alarm; detailed definition of satellite status published by DIM Service
- User algorithms to calculate the horizontal protection level based on DIM assured satellites including management of inter-constellation bias, applicable of URA / SISA, degradations to be applied by ocean users
- Minimum performance requirements for receiver hardware
- Message structure of the DIM integrity message and other external interfaces

Institutional Framework

- The competent authority for any certification needs to be identified and engaged ahead of any development
- All new standards need to be adopted by competent authorities
- Dissemination channels

Signals of Opportunity

The aim of the study was to reduce the Protection Level to enable Future Performance Requirements



Uncertainty

Error characterisation and overbounding

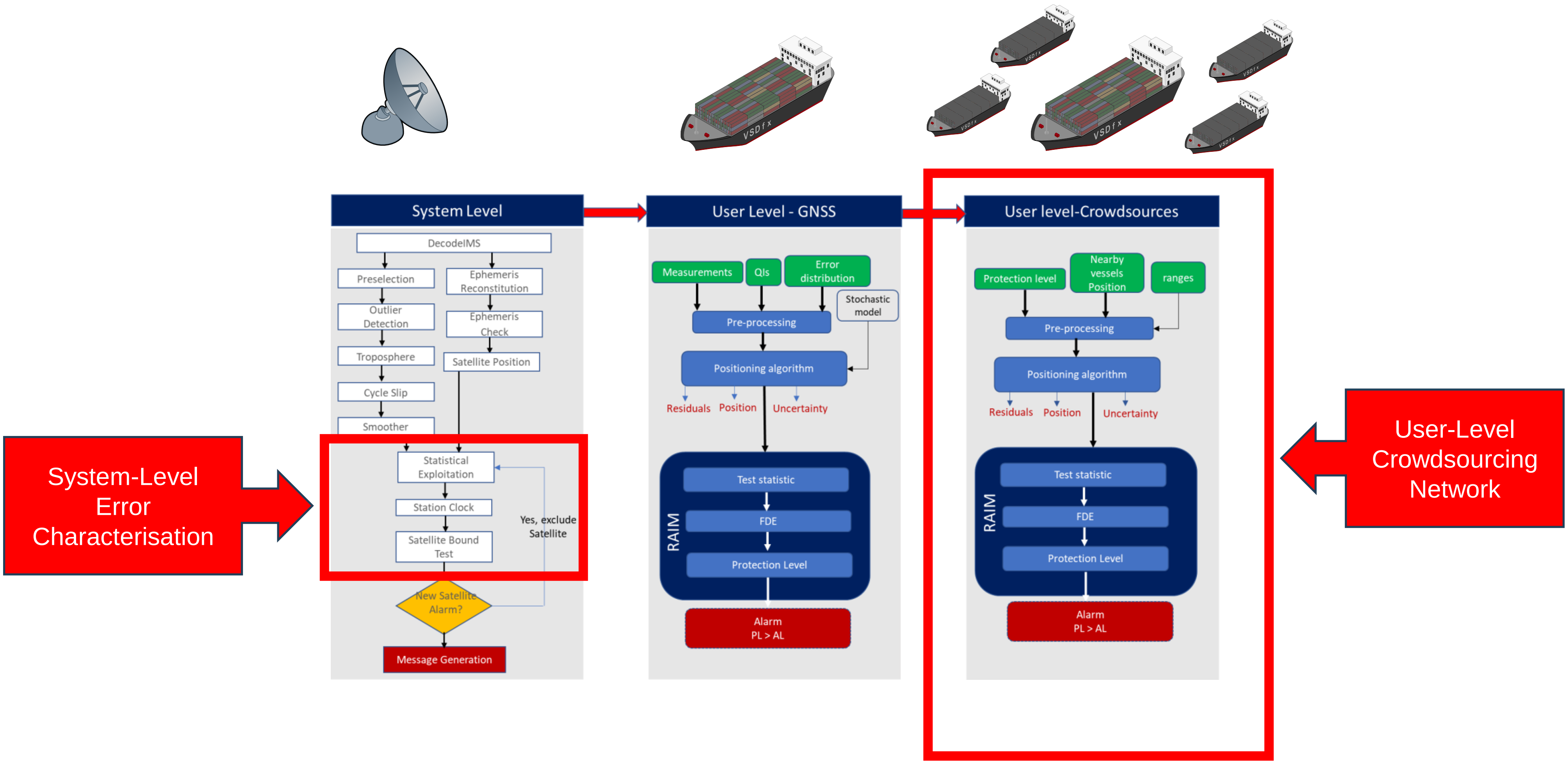
Probability of missed detection and nominal bias ($F(FDE)$)

Additional factors

Future Performance Requirements based on A.915(22).
Port Phase:
- Horizontal Accuracy (95%) 1m
- Availability >99.8%
- Continuity >99.97% per 15 minutes
- Time to Alarm <10 seconds
- Integrity Risk 10^{-5} per 15 minutes
- Horizontal Alarm limit AL of 2.5 m.

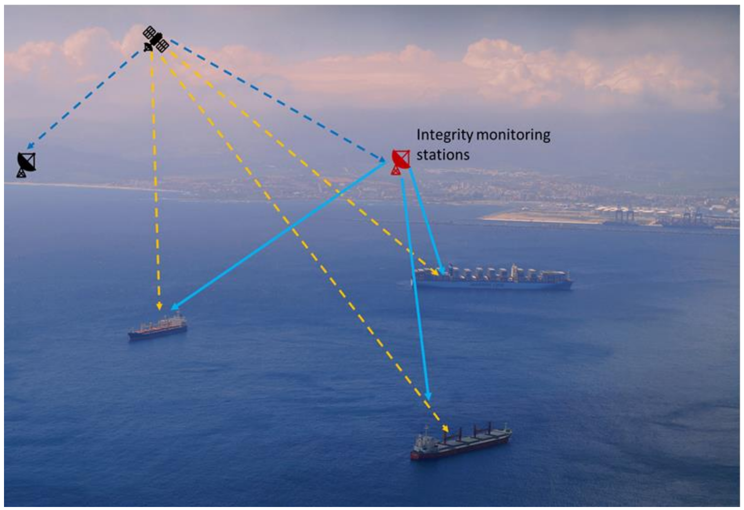
We selected two Signals of Opportunity which have the most potential to improve the Protection Level:
- User level crowdsourcing between vessels
- System Level CORS network

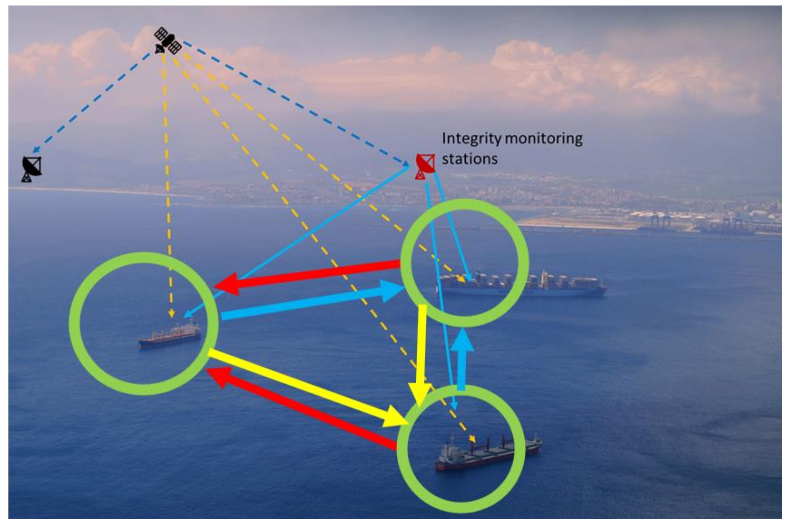
The Signals of Opportunity were investigated in the context of the integrity architecture



Implementing a User Level Crowdsourcing Network

- User level Crowdsourcing adds an additional integrity monitoring layer over the user level algorithms already discussed
- During real time operation the crowdsourcing network functions as follows:
  - the system level integrity sends to the user the required integrity information to ensure safe operation
  - then at the user-level, the GNSS devices receive this information and calculate position
  - users communicate GNSS positioning information with each other and compare this with ranging information (radar, LiDAR) to compute a position and protection level



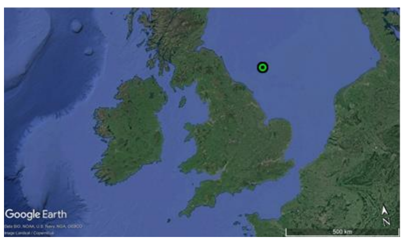


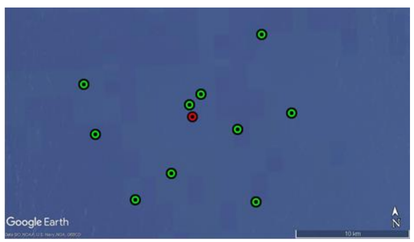
Simulating the performance of the User Level Crowdsourcing Network

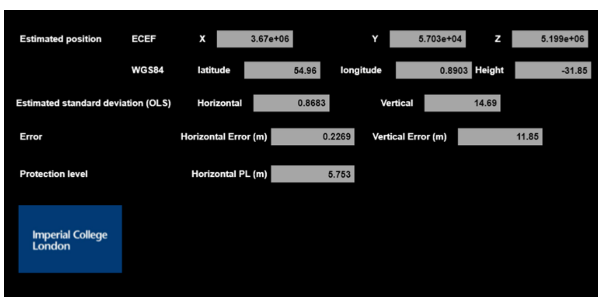
A simulation platform was developed to investigate the potential performance of the User Level Crowdsourcing Network

Key inputs to the simulator:

- Ranging sensor type (Radar IMO Standard, Radar FURUNO, LiDAR)
- Ranging sensor accuracy
- Number of nearby vessels
- Distance between vessels
- Strong or weak vessel geometry
- GNSS positioning accuracy of nearby vessels
- Number of simulations

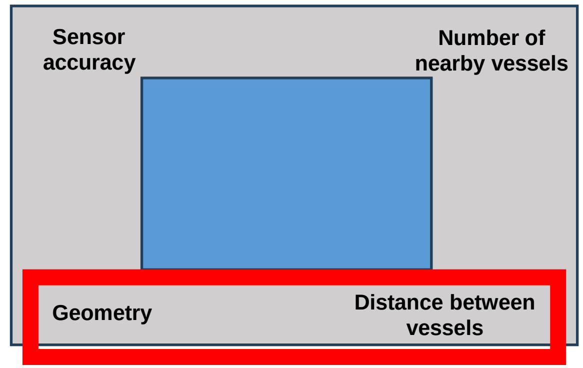


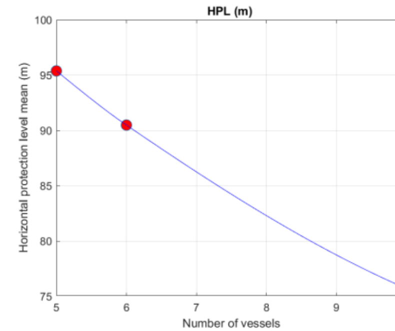




Different scenarios were investigated:

- Ranging sensor accuracy
- Number of nearby vessels
- Geometry of vessels
- Distance between vessels



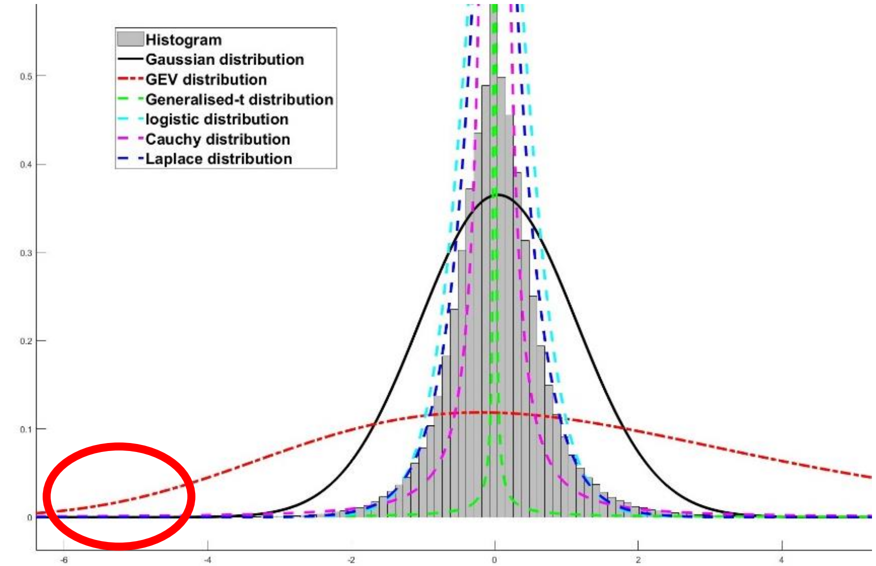


The findings showed that:

- 2.5m HPL was achievable when using LiDAR ranging sensors with 0.5m accuracy with five vessels within 1km
- A strong geometry and short distance between vessels were the largest factors impacting performance
- Increasing the number of vessels in range from 5 to 10 also had a positive effect on performance

Improving System Level Error Characterisation to reduce the Protection Level

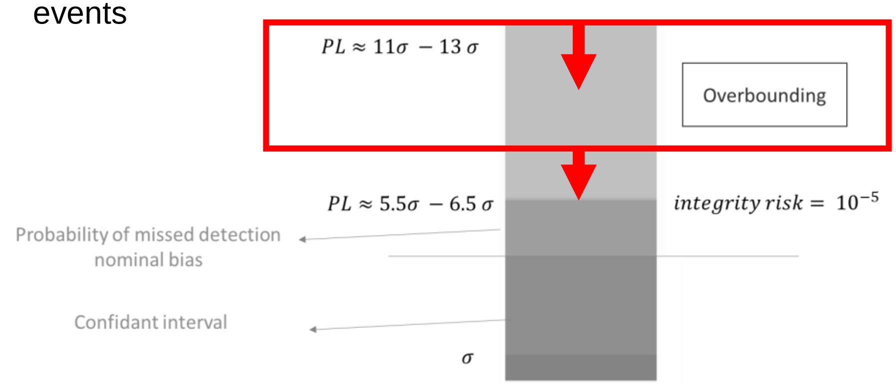
- Faults in a GNSS solution can be unpredictable
- Gaussian distributions are normally used to model errors in RAIM and Integrity Monitoring
- But they are not always the best model to use
- This study aims to test different distributions to better characterise errors to result in:
    - Better safety/integrity
    - Better availability
    - Better reliability
    - Better characterisation of extreme events



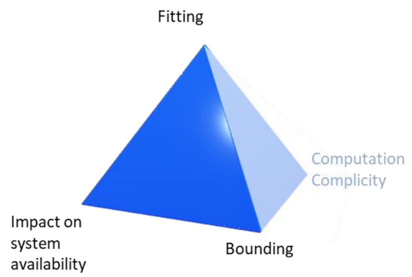
Mapping extreme events

Six distributions were tested:

- Gaussian
- Generalized-t
- GEV
- Logistic
- Laplace
- Cauchy distributions



A comparative evaluation showed that the performance of the distributions varied depending on scenario



Aspect		Impact on the system	Assessment: Graphical assessment	Assessment: Kolmogorov-Smirnov (KS)	Assessment: Availability assessment
Fitting	Overall fitting	System reliability	✓	✓	
	Tail fitting	Mapping extreme events	✓		
	Bounding	Safety/integrity	✓		
impact on system availability		availability			✓

Error characterisation evaluation aspects

- **Kolmogorov-Smirnov test results**

	Gaussian	Generalised-t	GEV	LOGISTIC	CAUCHY	LAPLACE
Best	0	0	1	12	4	3
second	7	2	5	2	3	1
third	6	2	4	5	1	2

- **Availability results**

	10^{-4}	10^{-5}	10^{-6}	10^{-7}
Gaussian	6	7	8	8
GEV	9	10	12	13
Logistic	6	7	8	10
Laplace	6	7	8	10
Generalised t	7.44543×10^{39}	6.2481×10^{51}	5.24645×10^{63}	4.40575×10^{75}
Cauchy	2170	44677	53180	131692

Evaluation results for KS and Availability Assessments

The results showed:

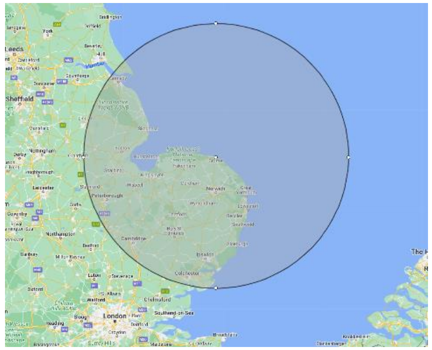
- Potential for adaptive error models depending on the type of errors experienced
- Potential application to both system-level and user-level integrity solutions

Cost Benefit Analysis of the Solutions

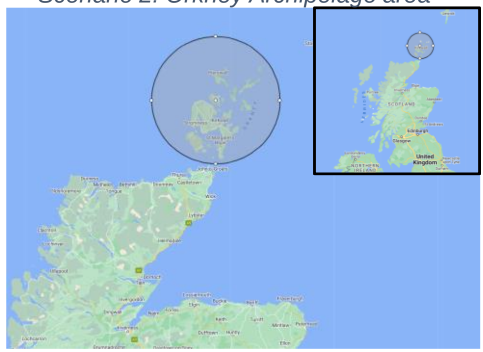
Cost Benefit Analysis: approach

- Use case-driven CBA of benefits to the UK of integrity information
- Maritime use cases including safety-of-life operations and automation
- Two geographies considered:
  - North Sea
  - Orkney Archipelago
- Scenario-based approach to estimate:
  - Costs of provision
  - Economic value generated by each use case
  - Share of economic value plausibly lost due to incidents preventable with sufficient user-level integrity information
  - Share of this lost economic value that INSPIRe could protect – and hence value of INSPIRe solution in these use cases
- E.g., based on the value of an aquaculture accident in 2016, the probability of it happening again, and the current and forecast role of automation, the value of integrity for aquaculture is estimated.
- Two geographies scaled to national level to indicate potential value

Scenario 1: North Sea area



Scenario 2: Orkney Archipelago area



Cost Benefit Analysis: key results

- 8 maritime sectors and 13 use cases
- Over £2.6bn of potential integrity benefits
- Only £30m within scope for INSPIRe and the two geographies
- Majority of potential benefits:
  - oil and gas, carbon capture and storage sector
  - **BUT**: not within scope for INSPIRe due to stringent user accuracy requirements
- INSPIRe benefits mainly from reduced emergencies activities in fisheries and protection of Marine Protection Areas from bottom-trawlers
- Scaling to national level, £2.2bn of potential INSPIRe benefits over 20-year period

- Present value costs: £194m
- Present value benefits: £18.9m (scenario-driven), £1,371m (national)
- NPV: -£175m (scenario-driven), £1,177m (national)

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Cost Benefit Analysis: concluding thoughts and caveats

- The Net Present Value of investment in INSPIRe is below zero for the scenario-driven case (-£175m) but positive for the nationally extended case (£1,177m)
- These results emphasise the need for a national service rather than a geographically contained solution

- The importance of (not) meeting user accuracy requirements for key marine sectors is clear when considering the vast potential benefits that are not captured in either of the oil and gas or carbon capture and storage sectors
- One key driver of these results was the selection of only ‘high’ integrity need use-cases for economic analysis. A broader set of use cases may yet reveal significant additional benefits for the INSPIRe service.

Implementation and Exploitation

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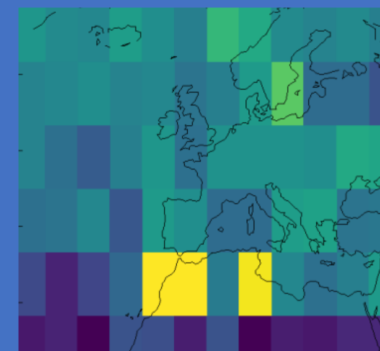
INSPIRe offers opportunities to exploit integrity today

Utilising receiver algorithms in vessels

Source: Stock photo

Educating Mariners on the need for integrity

Implementing RAIM Prediction in voyage planning



Ongoing activities are required to achieve future needs

We have identified three key development areas…

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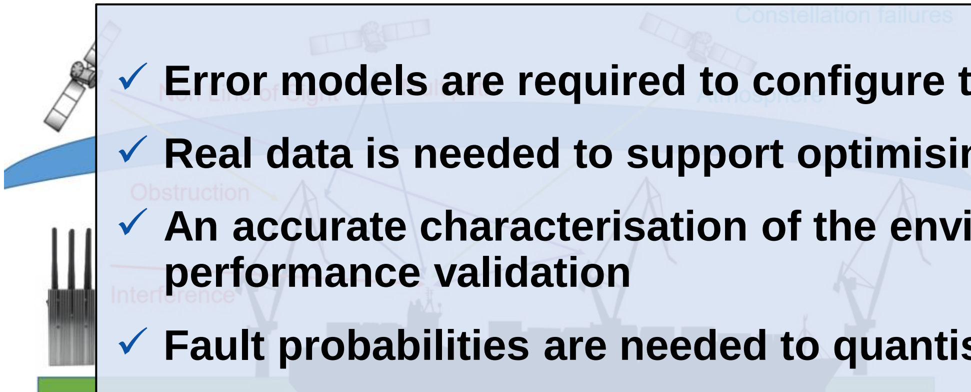
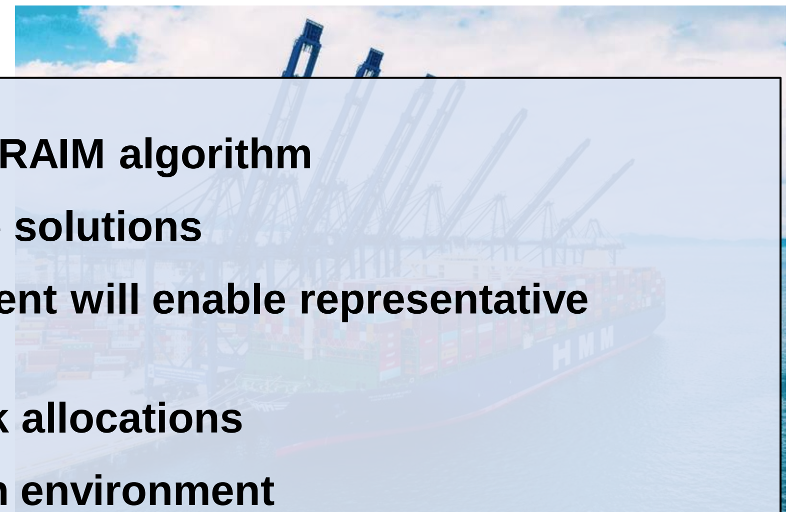
A need to better understand the maritime RF environment

- At present algorithm performance is limited by (lack of) knowledge of the local maritime environment
- Collecting real data to better model the maritime environment is critical for algorithm development:
  - Impact of receiver placement and vessel construction?
  - How often do threats and faults occur, and how significant are they?
  - How does the environment change in Ocean, Coastal and Port phases of a voyage?





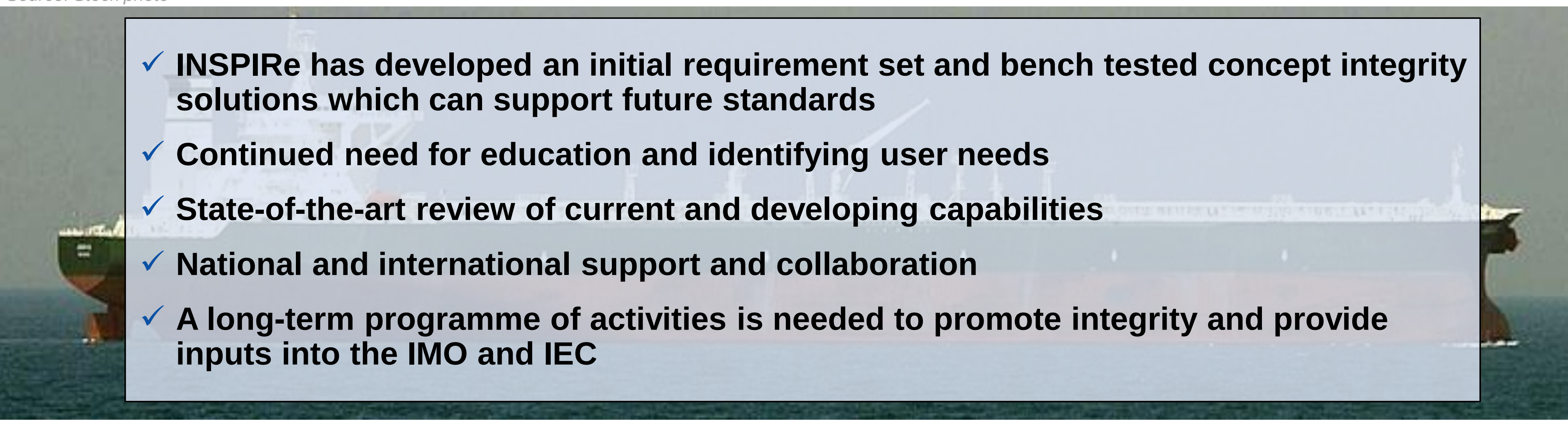
HMM Algeciras, 24,000TEU vessel. Source: Port Technology International

- ✓ **Error models are required to configure the M-RAIM algorithm**
- ✓ **Real data is needed to support optimising the solutions**
- ✓ **An accurate characterisation of the environment will enable representative performance validation**
- ✓ **Fault probabilities are needed to quantise risk allocations**
- ✓ **Standards can be informed based on a known environment**

A need to align how integrity is considered and implemented in international maritime standards

Concept of Operations → Navigation Performance Requirements → GNSS Receiver Requirements → Receiver Test Specifications

Source: Stock photo



- ✓ **INSPIRe has developed an initial requirement set and bench tested concept integrity solutions which can support future standards**
- ✓ **Continued need for education and identifying user needs**
- ✓ **State-of-the-art review of current and developing capabilities**
- ✓ **National and international support and collaboration**
- ✓ **A long-term programme of activities is needed to promote integrity and provide inputs into the IMO and IEC**

A need for ongoing technical development to mature, implement, and improve the integrity architecture

Improving maturity (TRL)

- ✓ Implementing system-level infrastructures
- ✓ Disseminating integrity information to mariners with e-Navigation concepts
- ✓ Real-world validation and safety assurance
- ✓ Integrating sensor fusion approaches
- ✓ Adaptive error characterisations, including ML
- ✓ Addressing jamming and spoofing threats
- ✓ Developing resilience and cascading failure modes

Improving performance

Widen the use cases to expand the benefit

TRL – Technology Readiness Level
ML – Machine Learning

INSPIRe's solutions are not only for maritime, but provide opportunities across many other sectors

- Requirements Development Process
- User Level Algorithm Approaches
- System Level infrastructure
- Development Framework
- Opportunities for improving performance

Source: OpenArtAI

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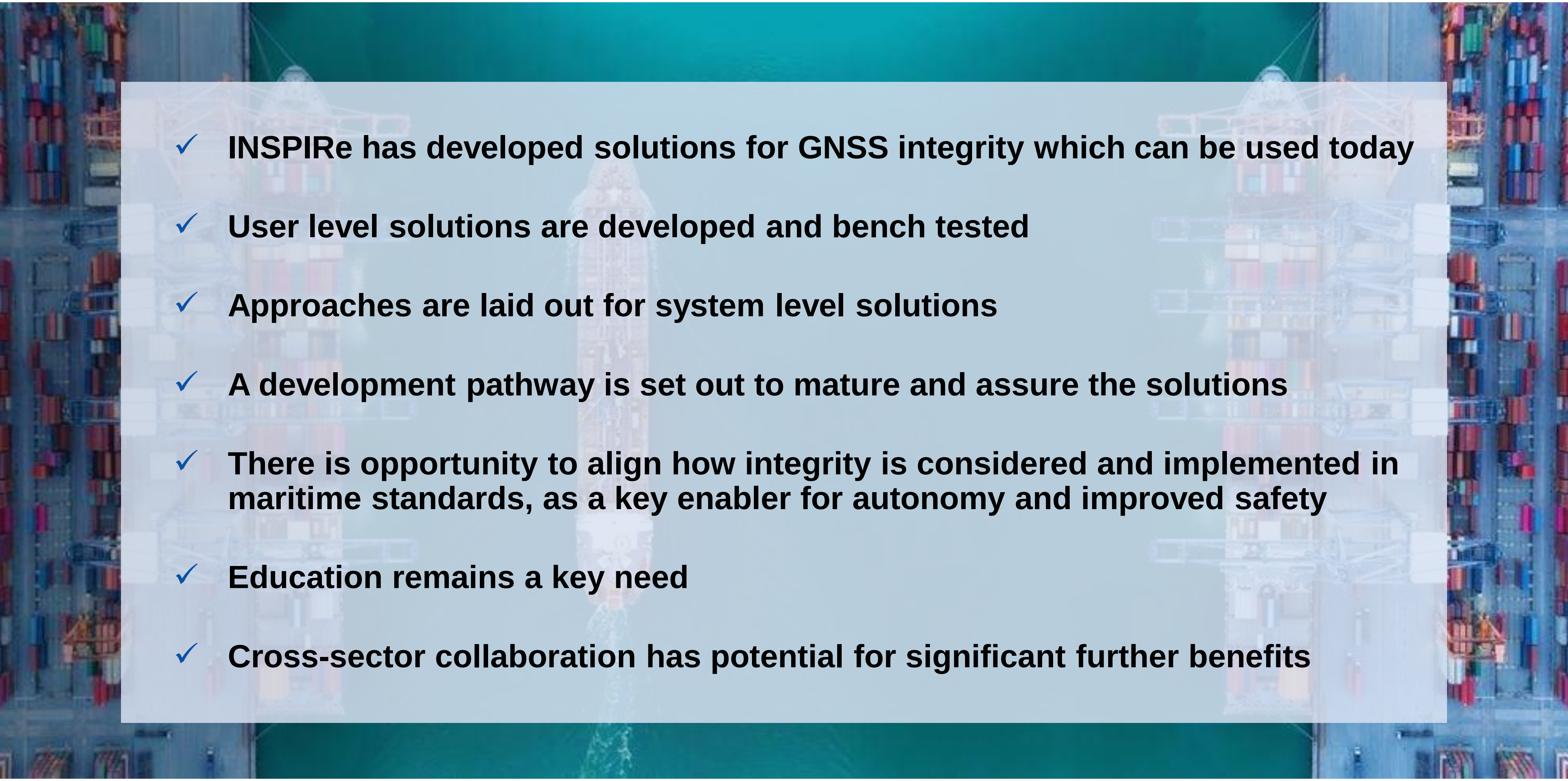
Conclusions

INSPIRe has shown how integrity can be achieved, but realising the benefits requires ongoing collaboration and development

Source: Stock photo



- ✓ INSPIRe has developed solutions for GNSS integrity which can be used today
- ✓ User level solutions are developed and bench tested
- ✓ Approaches are laid out for system level solutions
- ✓ A development pathway is set out to mature and assure the solutions
- ✓ There is opportunity to align how integrity is considered and implemented in maritime standards, as a key enabler for autonomy and improved safety
- ✓ Education remains a key need
- ✓ Cross-sector collaboration has potential for significant further benefits

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Thank you for your attention!

Project reports are available on our website

www.inspire-pnt.com

Questions?