

Multi-Domain Situational Awareness

Seabed-to-Space Situational Awareness (S3A)

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NATO STO-CMRE



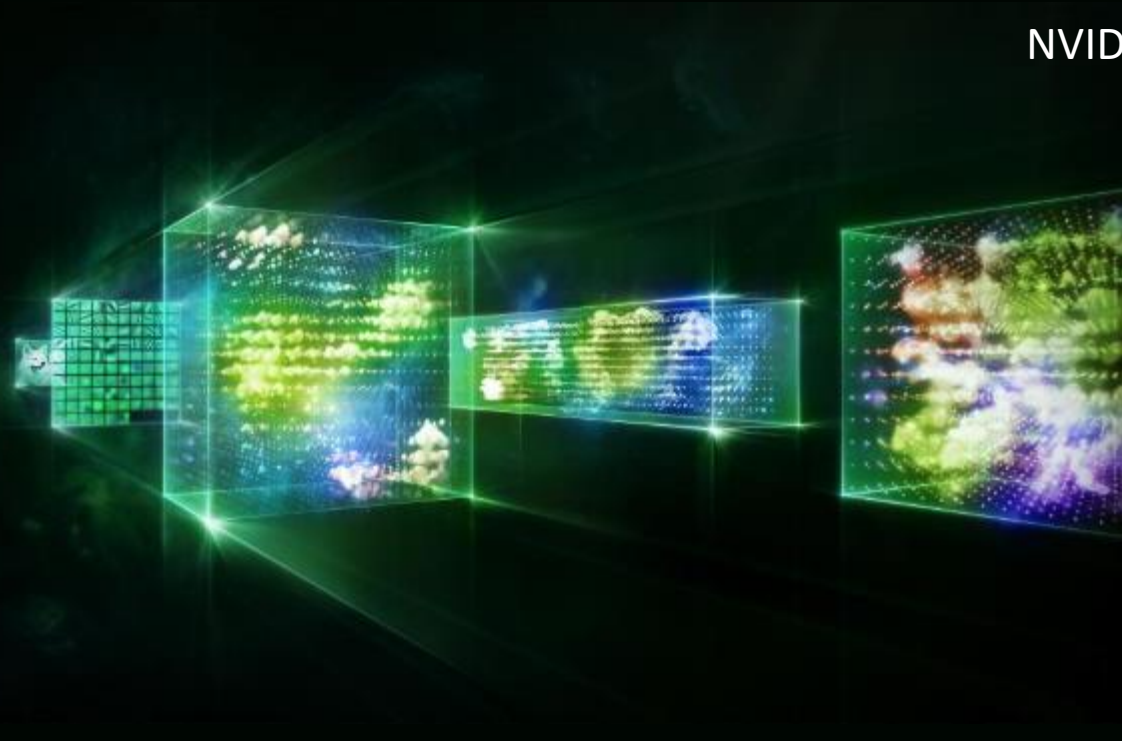


Outline

- **Artificial Intelligence (AI) and Deep Learning Breakthroughs**
- **Multi-Domain Operations and *Seabed-to-Space Situational Awareness (S3A)***
- **Advances in AI and Information Fusion (AI2F) applied to Maritime Domain**
 - *Long-term vessel prediction*
 - *Maritime Patterns of Life*
 - *Scalable Multi-Sensor Multi-Target Tracking*
 - *S3A for monitoring Underwater Critical Infrastructures (UCIs)*
- **Machine Learning (ML) Performance Explained by Asymptotic Statistics**
- **Data-driven approach to COVID-19 data**
- **Next-Gen AI-based All-Domain Situational Awareness C4**
- **Conclusion**

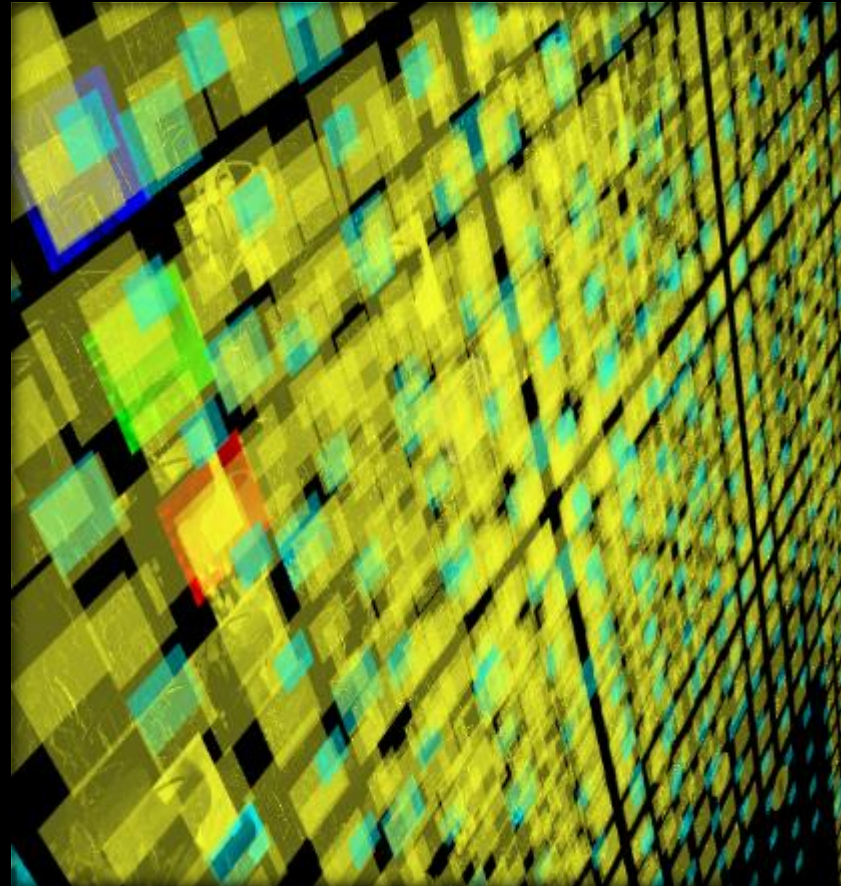
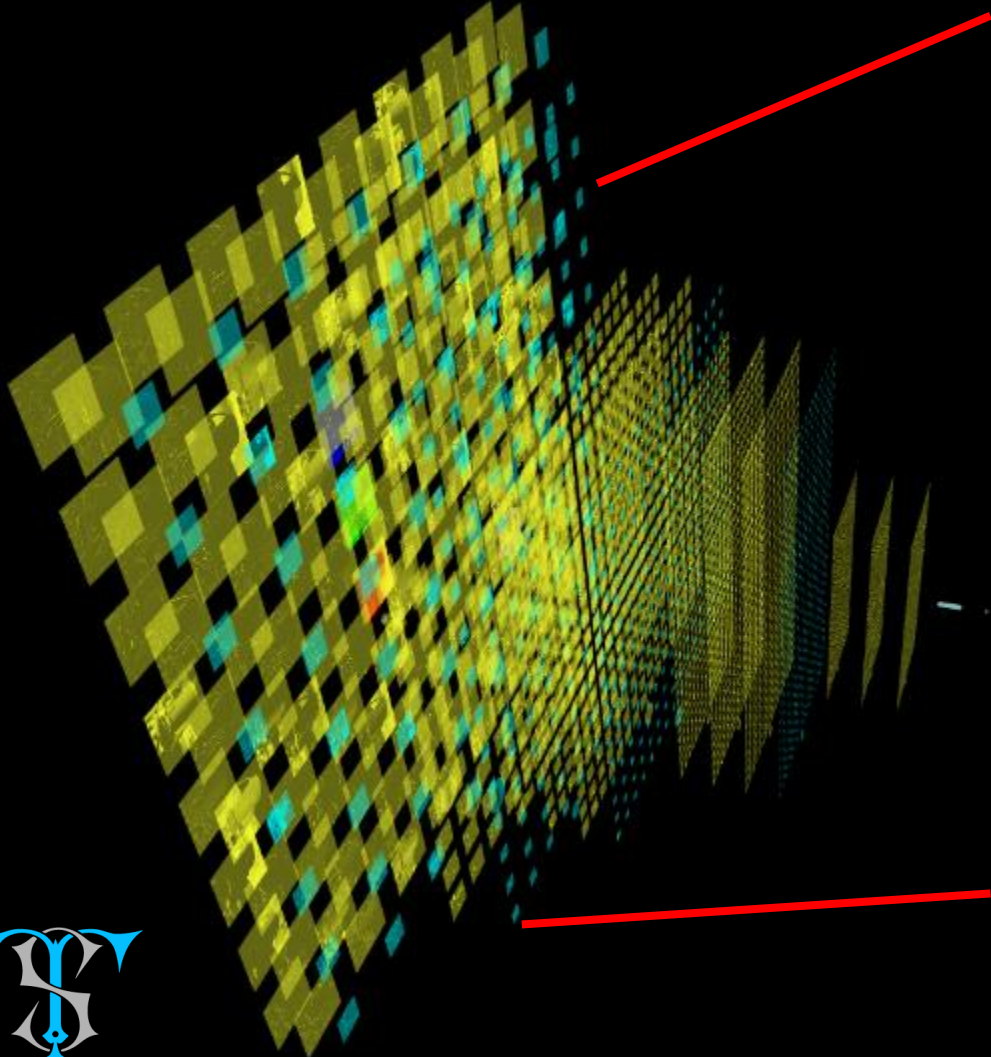
AI and Deep Learning

NVIDIA



- AI – the ability of machines to perform tasks that typically require human intelligence – is transforming the international security environment in which NATO operates. [AI Strategy for NATO 2021]
- Deep Learning is a type of machine learning based on artificial neural networks in which multiple layers of processing are used to automatically extract progressively higher level features from data.

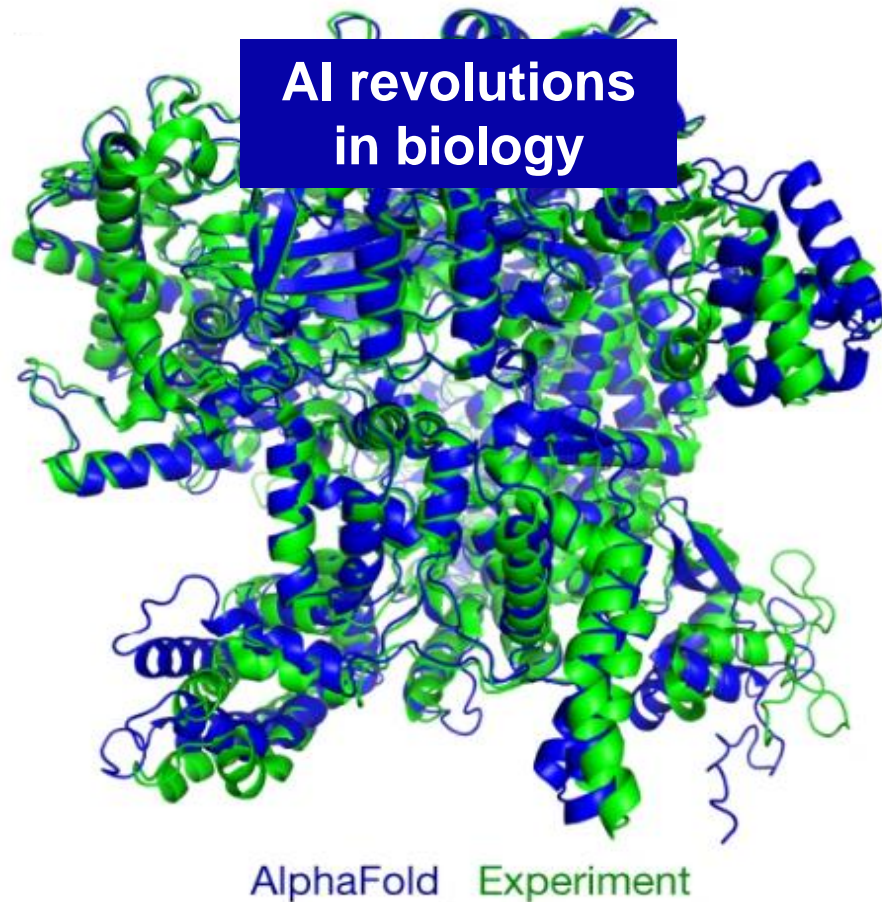
3D Visualization of Deep Learning – TensorSpace VGG-16



VGG-16 is a convolutional neural network that is 16 layers deep

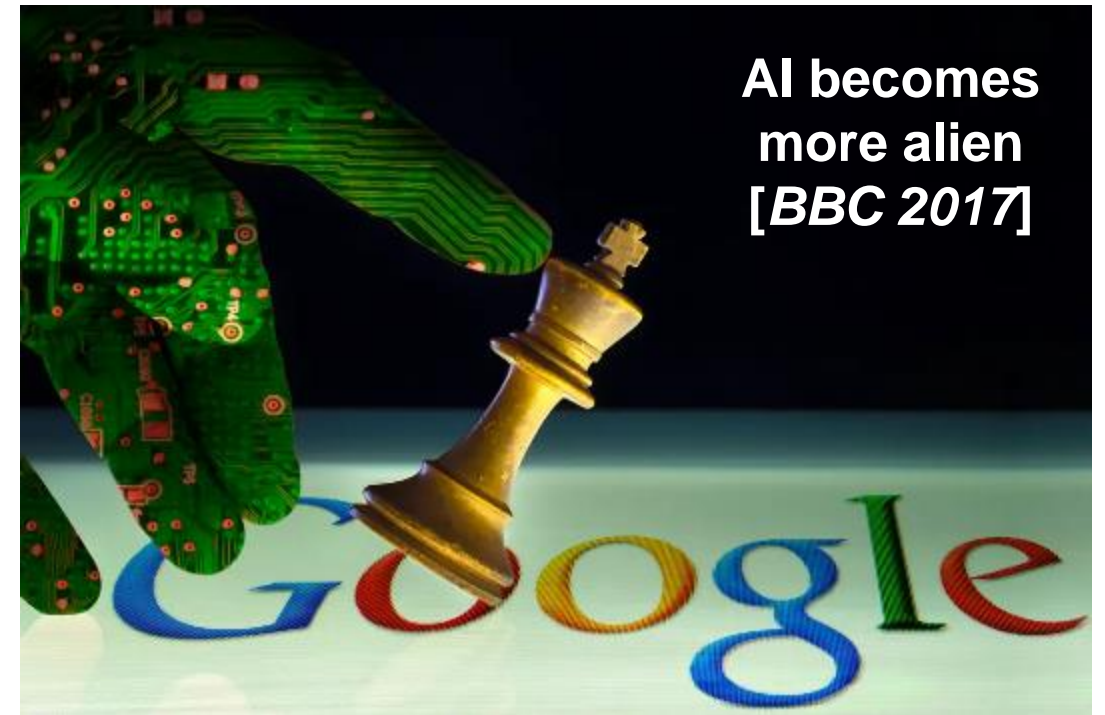


Google's AI Applications



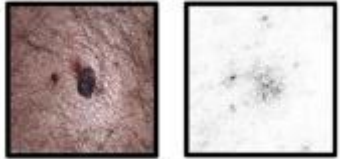
AlphaFold prediction of 3D protein structure from its amino acid sequence [*Nature* 2021]

AlphaGo Zero AI has triumphed at chess against world-leading specialist software within hours of teaching itself the game from scratch.

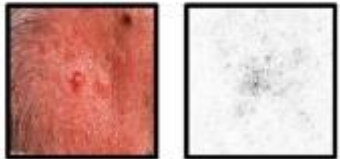


AI and Deep Learning Medical Applications

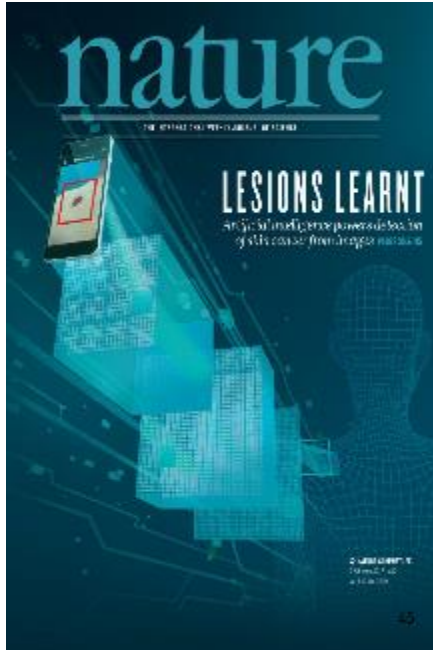
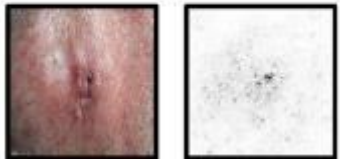
Malignant Melanocytic Lesion



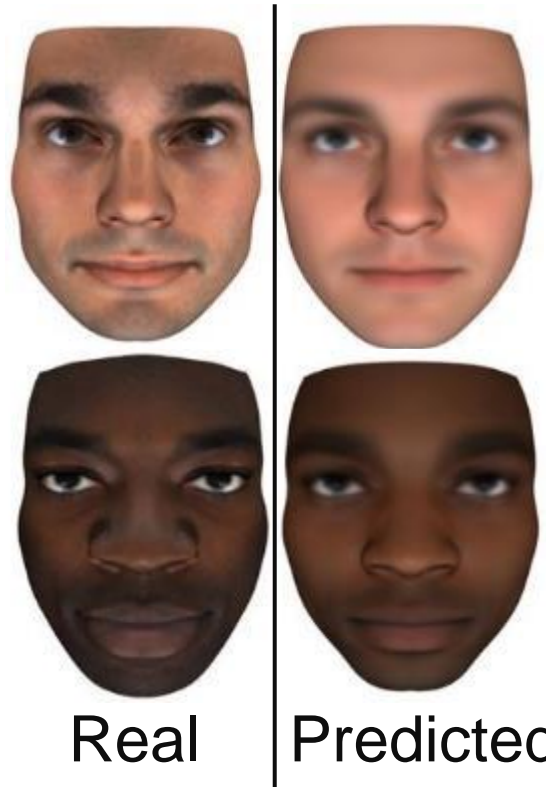
Malignant Epidermal Lesion



Malignant Dermal Lesion



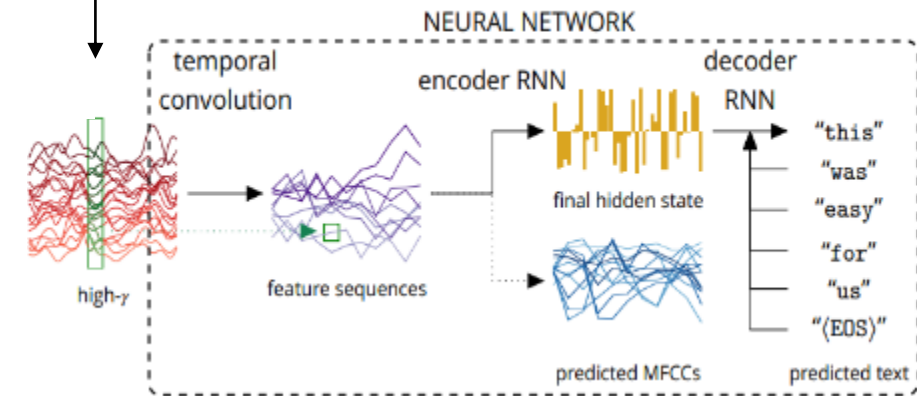
Dermatologist-level Classification of Skin Cancer with Deep Neural Networks
[*Nature 2017*]



Prediction of human physical traits from genomic data
[*PNAS 2017*]



Decode the electrocorticogram with high accuracy and at natural-speech rates
[*Nature Neuroscience 2020*]



New-gen autonomous systems



**Mercedes-Benz Autonomous Car
ADAS Level 3**



**MV Yara Birkeland
Autonomous 120 TEU container ship**

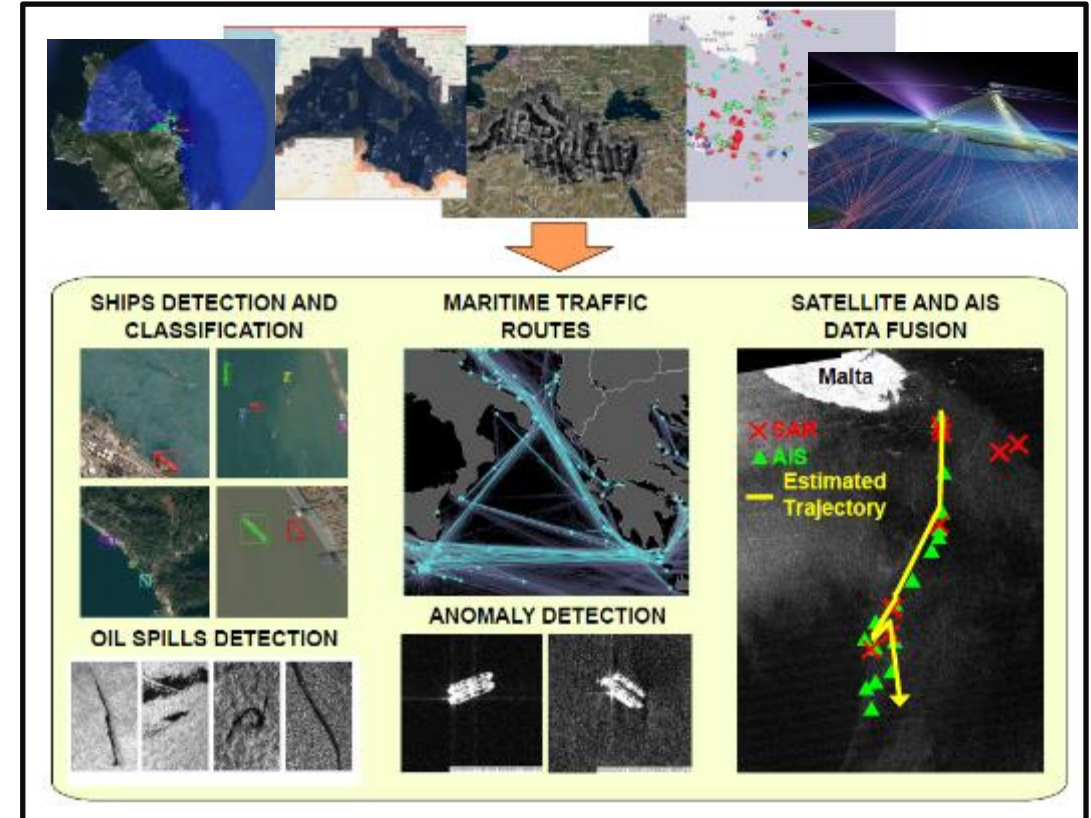
Multi-Domain Operations. Towards Joint All-Domain Command and Control

- The concept of **Multi-Domain Operations** (MDOs) builds on the 1980s U.S. Army doctrine "Air-Land Battle"
- MDO leverages the most advanced technology to improve command and control of forces.
- Moving towards the **Joint All-Domain Command and Control (JADC2)**, which is the US Department of Defense's concept to **connect sensors from all of the military services** —Air Force, Army, Marine Corps, Navy, and Space Force— **into a single network.**
- The **challenge is to bring together information** to the decision-makers, preferably in concert with newer technology, which would facilitate their decision making.
- The better joint operations are led and executed, the better Allied forces within the NATO political framework can operate in all domains



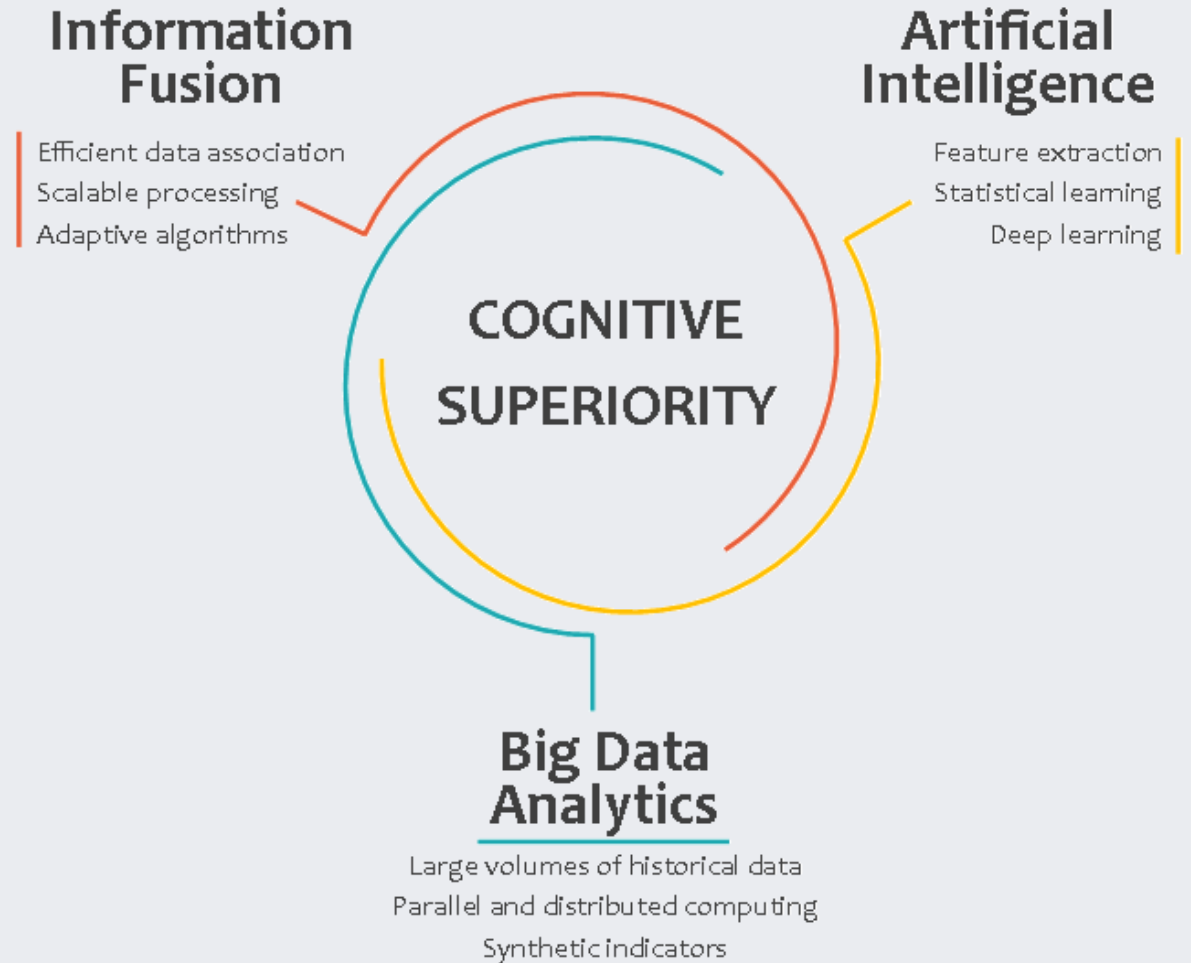
Multi-Domain Data Fusion

Seabed-to-Space Situational Awareness (S3A)



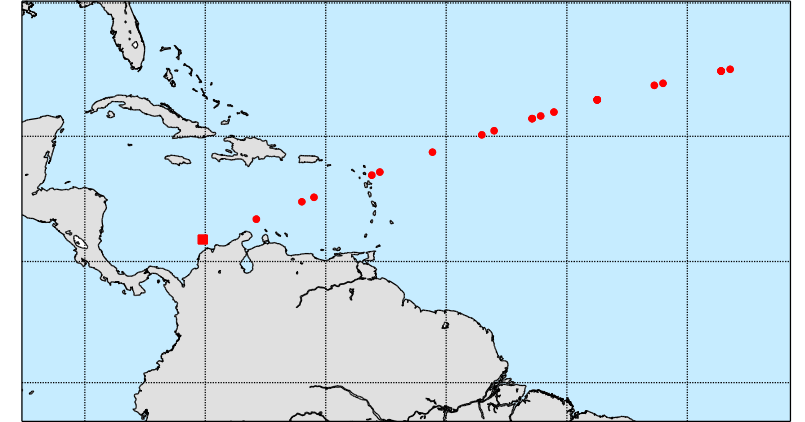
Artificial Intelligence and Information Fusion (AI2F) Maritime Situational Awareness (MSA)

- MSA is “an enabling capability to deliver **Cognitive Superiority**, enabling informed decision-making processes, in order to increase operational effectiveness”.
- Main **challenges**:
 - The amount of data and information available in the era of **Big Data** makes the nature of the work performed by analysts and operators more complicated and different from the past.
 - Information **sources** are **heterogeneous**, **noisy**, and data flows may be **intermittent**, **corrupted**, etc.
- Inspired by human cognitive abilities, the **objective** was to address these key issues by developing and advancing **Maritime Artificial Intelligence and Information Fusion (MAI2F)** techniques.



Long-term vessel prediction

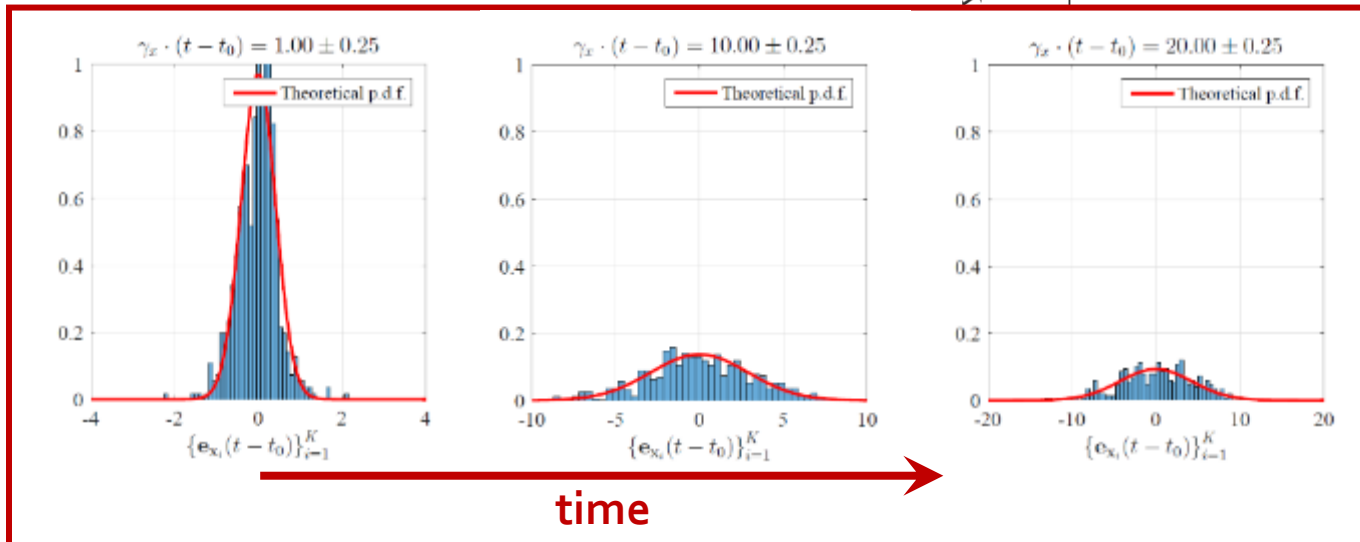
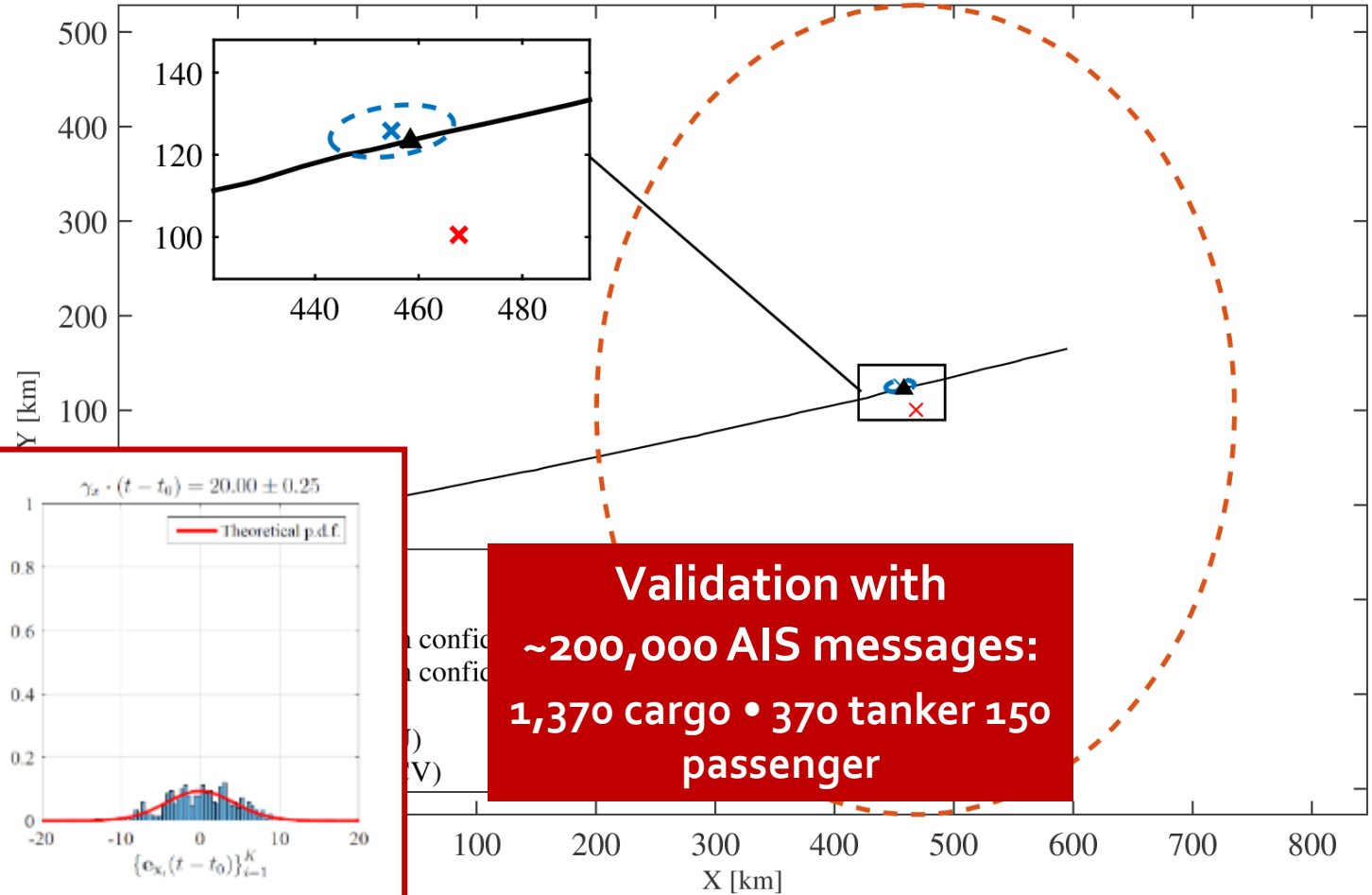
- Need to monitor vessels in open seas and across **sensor coverage gaps**
- Accurate **long-term** state prediction is **crucial** to, among other possibilities:
 - Maritime **traffic modeling**
 - **Search and Rescue (SaR)** operations
 - **Association of time-sparse data**, such as AIS and detections/tracks from radar/SAR
- Prediction covariance determined by **motion model** for non-maneuvering vessels
 - **Traditional motion models** (e.g. nearly-constant velocity [**NCV**]) can **overestimate** the actual prediction uncertainty
 - **Mean-reverting** models (Ornstein-Uhlenbeck [**OU**])
- *Results validated against a large real-world dataset*



Long-Term Vessel Prediction

- **Traditional motion models** (nearly-constant velocity [**NCV**]) **overestimate** the actual prediction uncertainty
- **Mean-reverting models** (Ornstein-Uhlenbeck [**OU**])

L. M. Millefiori, P. Braca, K. Bryan and P. Willett, "Modeling vessel kinematics using a stochastic mean-reverting process for long-term prediction," in *IEEE Transactions on Aerospace and Electronic Systems*, vol. 52, no. 5, pp. 2313-2330, October 2016.

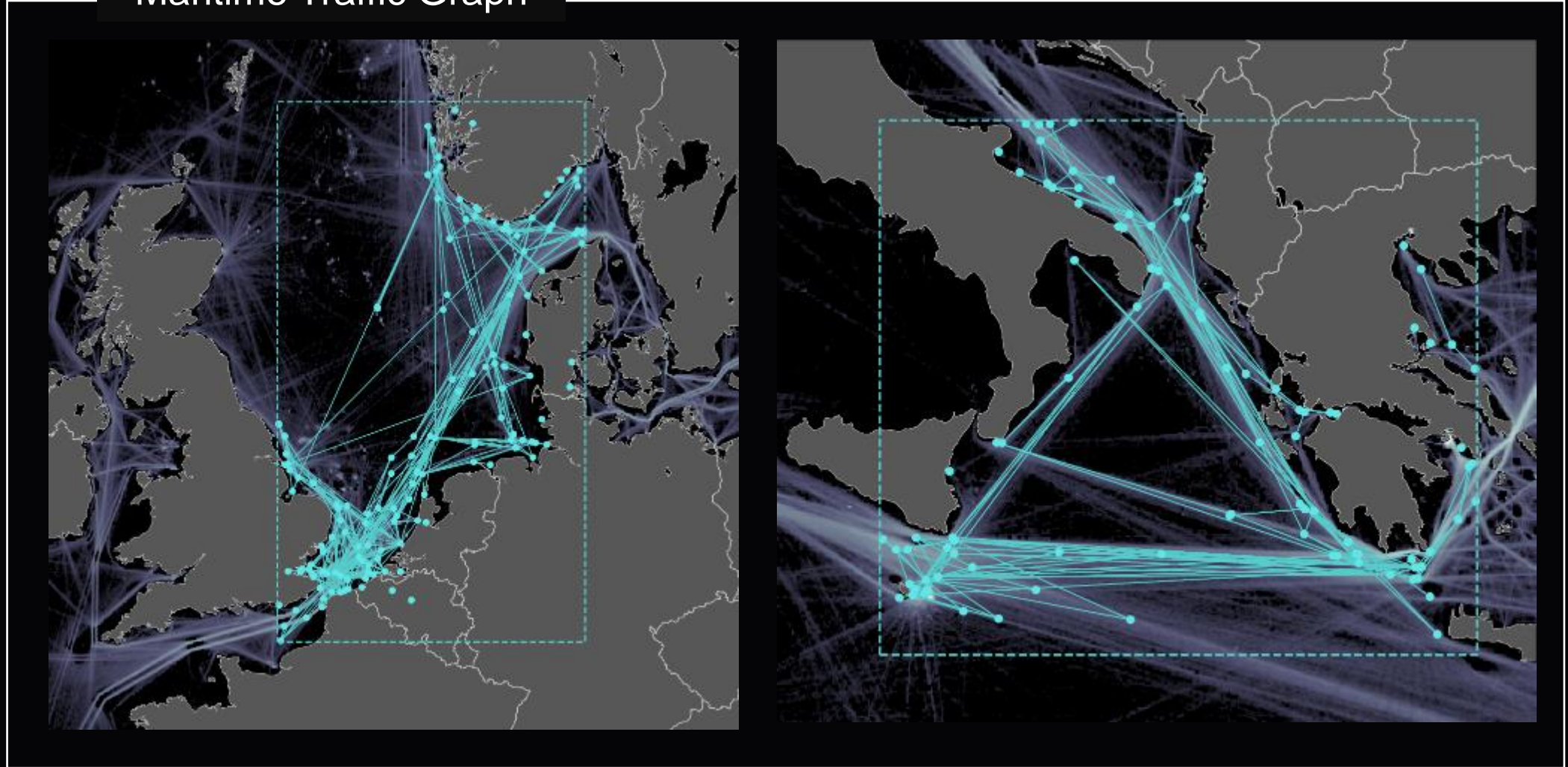


**Validation with
~200,000 AIS messages:
1,370 cargo • 370 tanker 150
passenger**

Advances in AI2F

Maritime Traffic Knowledge Discovery

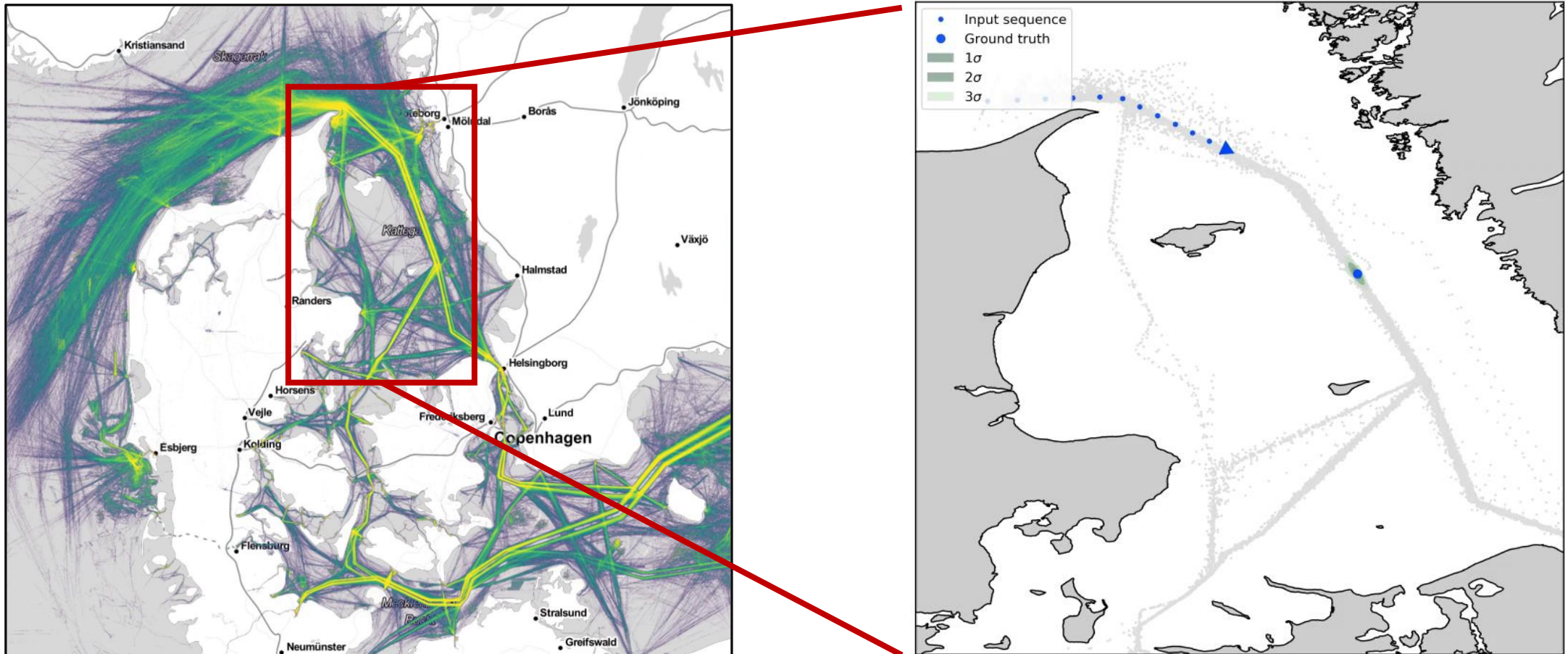
Maritime Traffic Graph



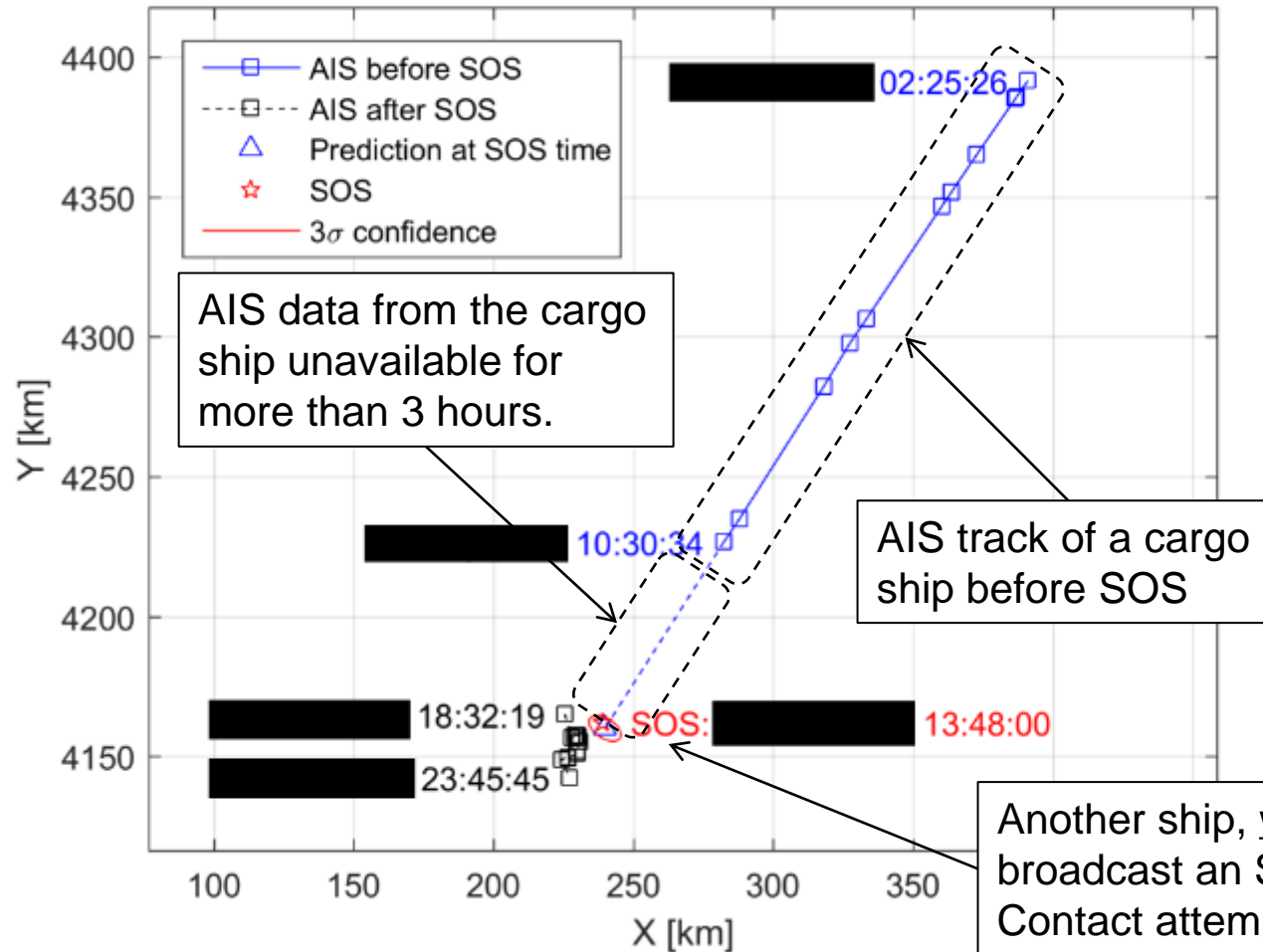
G. Soldi, D. Gaglione, N. Forti, A. Di Simone, F. Daffina, G. Bottini, D. Quattrociochi, L. Millefiori, P. Braca, S. Carniel, P. Willett, A. Iodice, D. Riccio, A. Farina, "Space-based Global Maritime Surveillance. Part II: Artificial Intelligence and Data Fusion Techniques," *IEEE Aerospace and Electronic Systems Magazine*, 2021.

Advances in AI2F

Deep Learning for Long-term Ship Trajectory Prediction



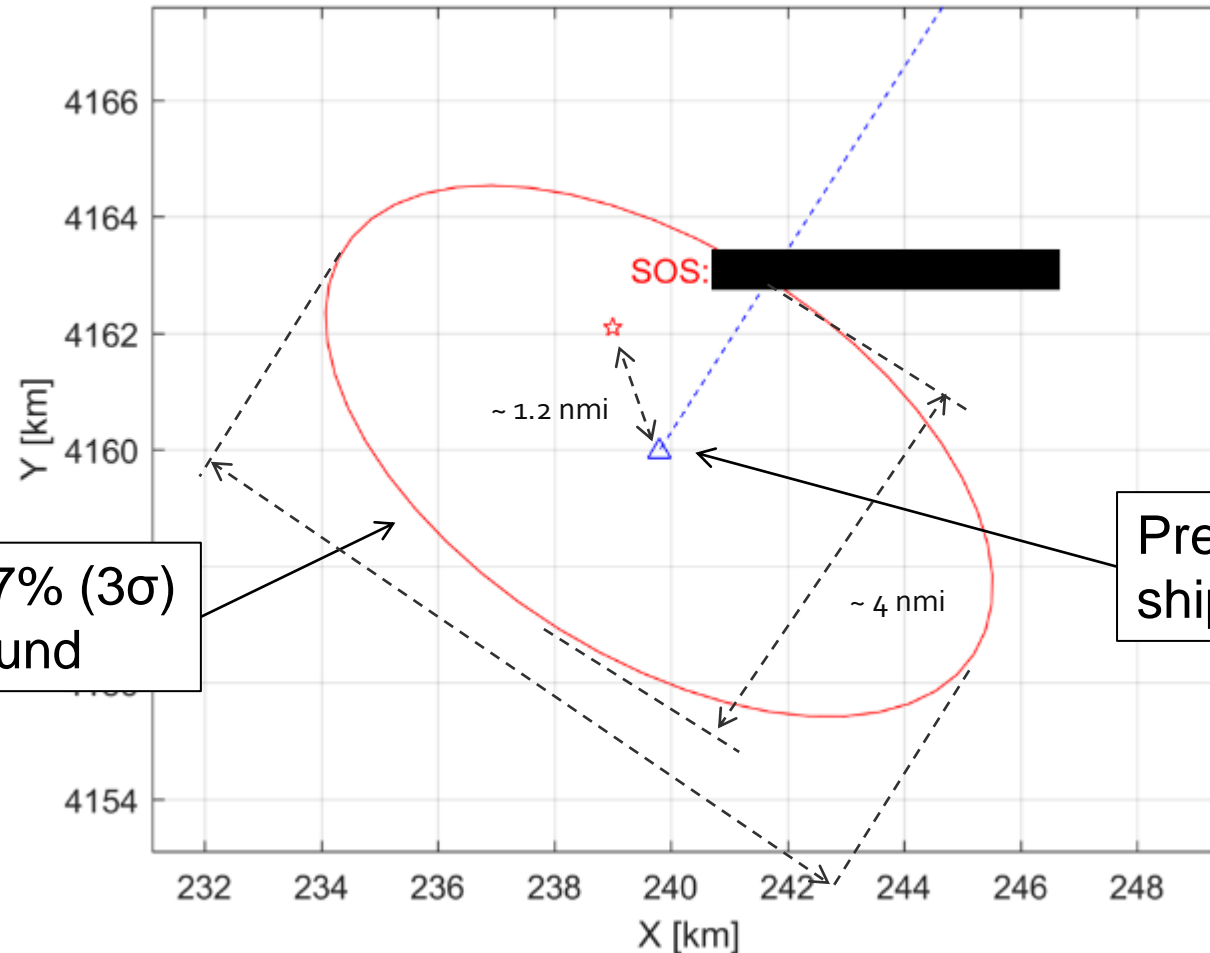
Long-term prediction for SaR - *A real example (I)*



- SOS message from a sailing boat EPIRB (Emergency Position Indicating Radio Beacon) is received at 13:48
- Contact from the closest ship to the SOS position is at 10:30
- SaR operations start after over one hour

Long-term prediction for SaR - *A real example (II)*

Q: Could a collision have taken place?



Prediction 99.7% (3σ)
confidence bound

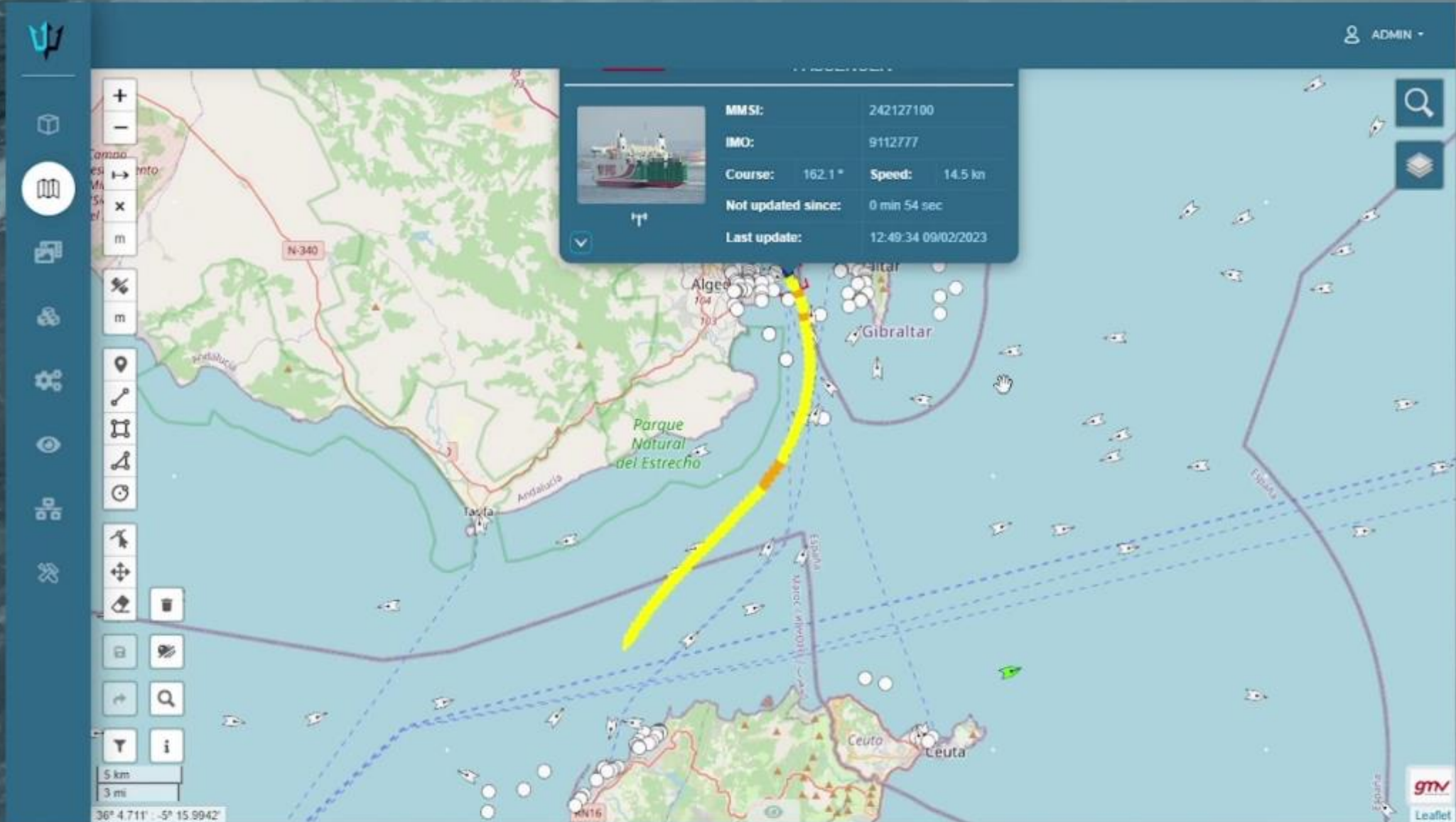
Predicted position of the
ship at the time of the SOS



promenade

IMPROVED MARITIME AWARENESS BY MEANS OF AI AND BD METHODS

Promenade project - EU H2020



International Maritime Exercise (IMX19)



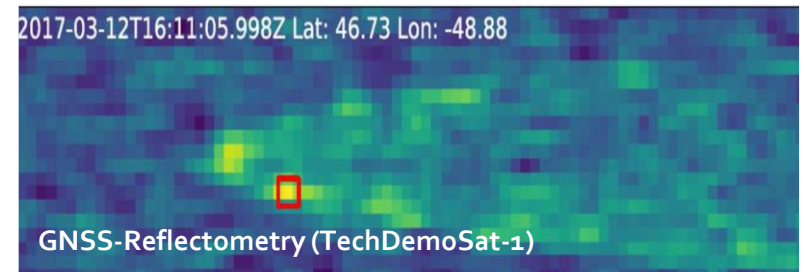
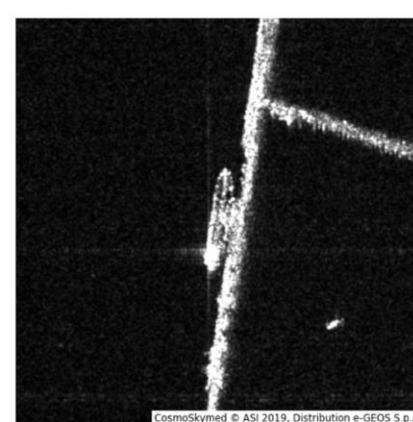
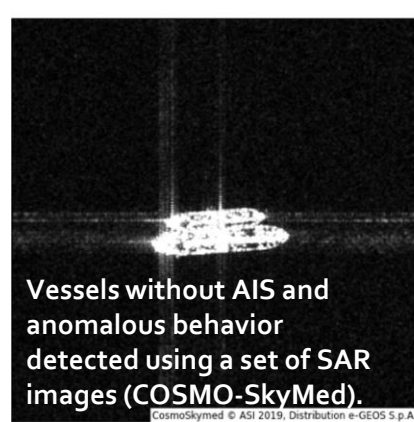
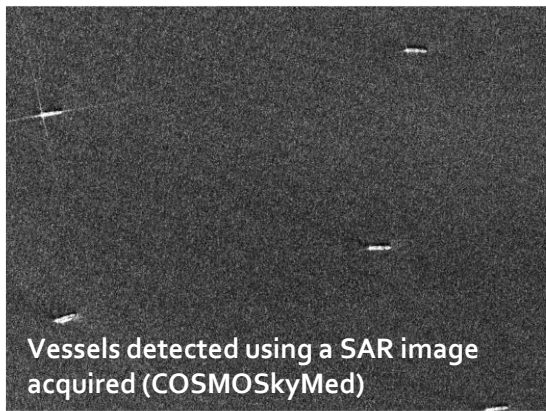
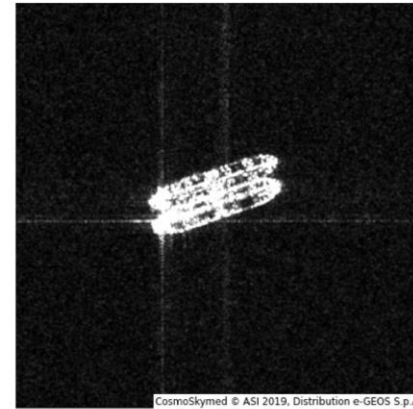
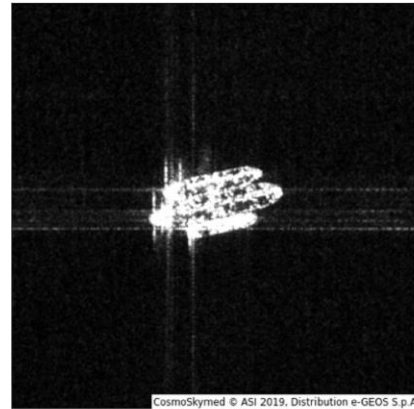
Advances in AI2F

Scalable multi-sensor multi-target tracking: From seabed to space



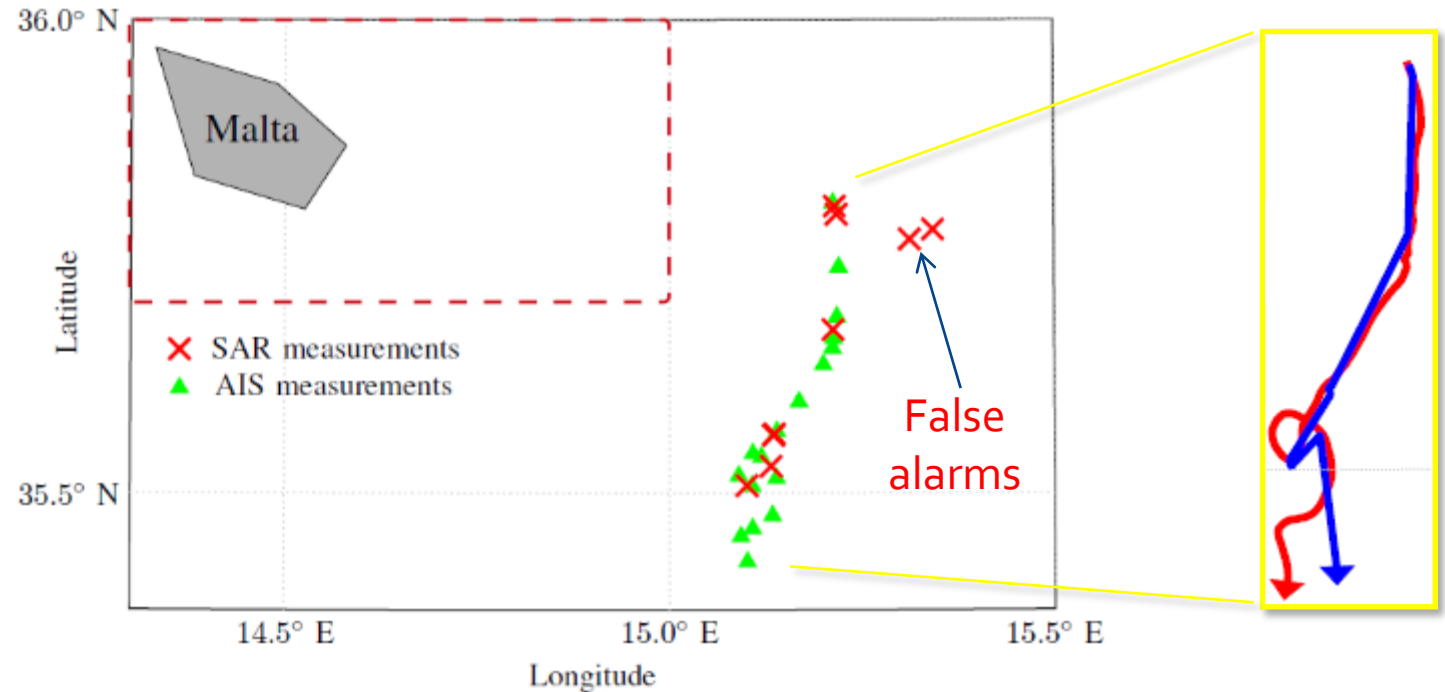
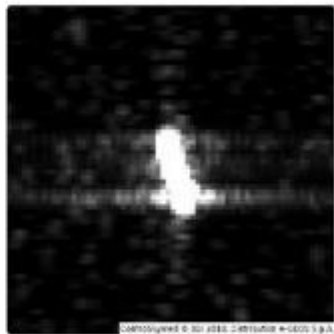
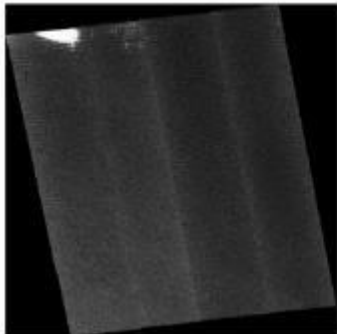
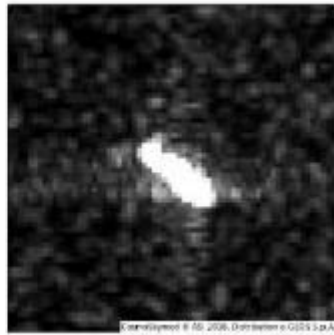
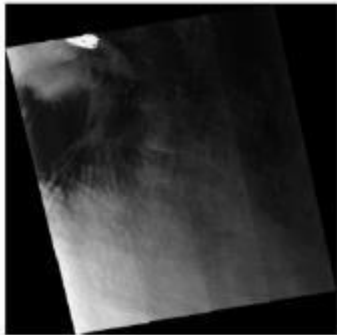
Advances in AI2F

Space-based Maritime Surveillance



Advances in AI2F

Target Tracking and Fusion of Quicklook SAR images and AIS

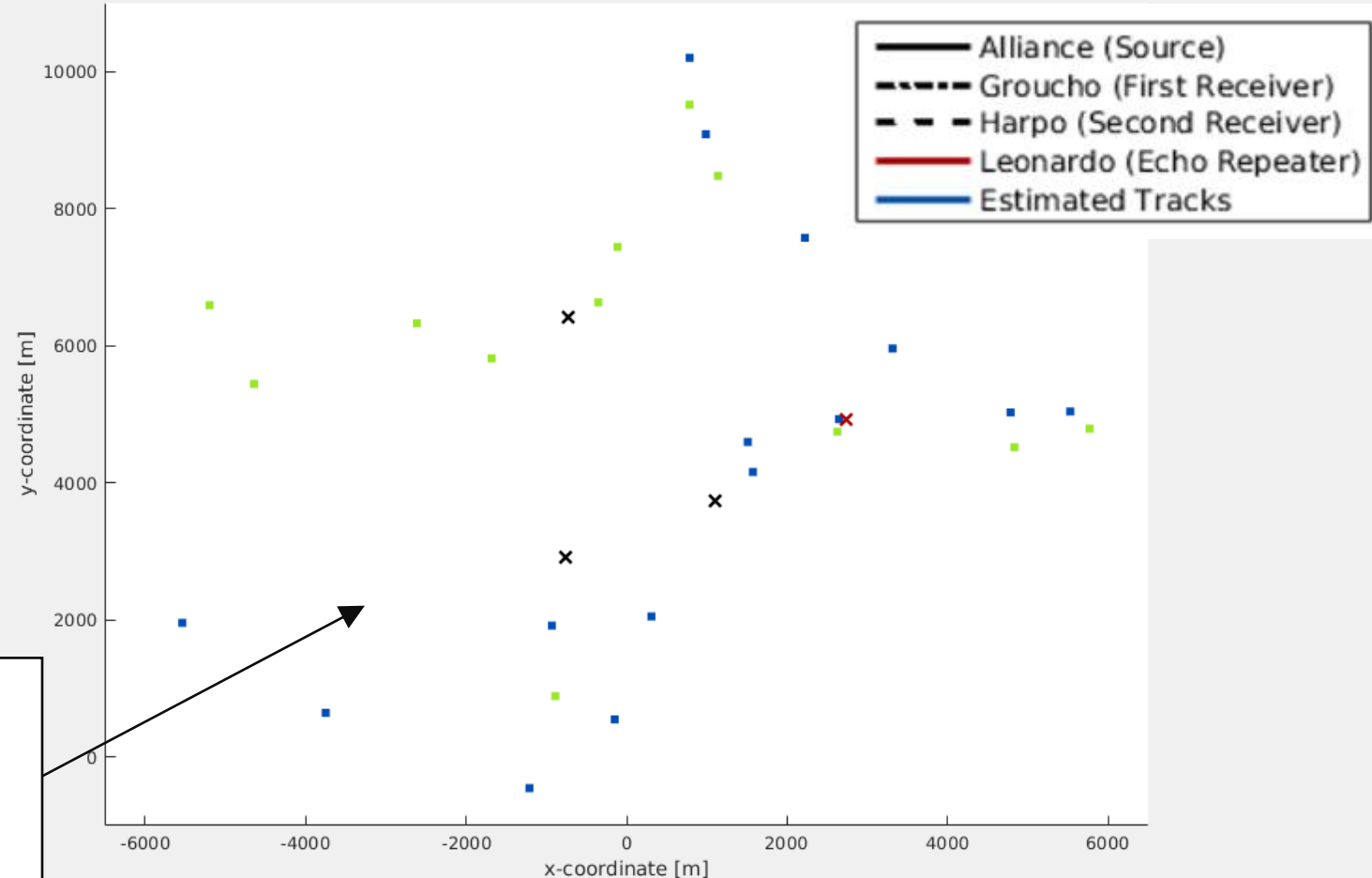


Advances in AI2F

Continuous Active Sonar (CAS) – Tracking and Data Fusion



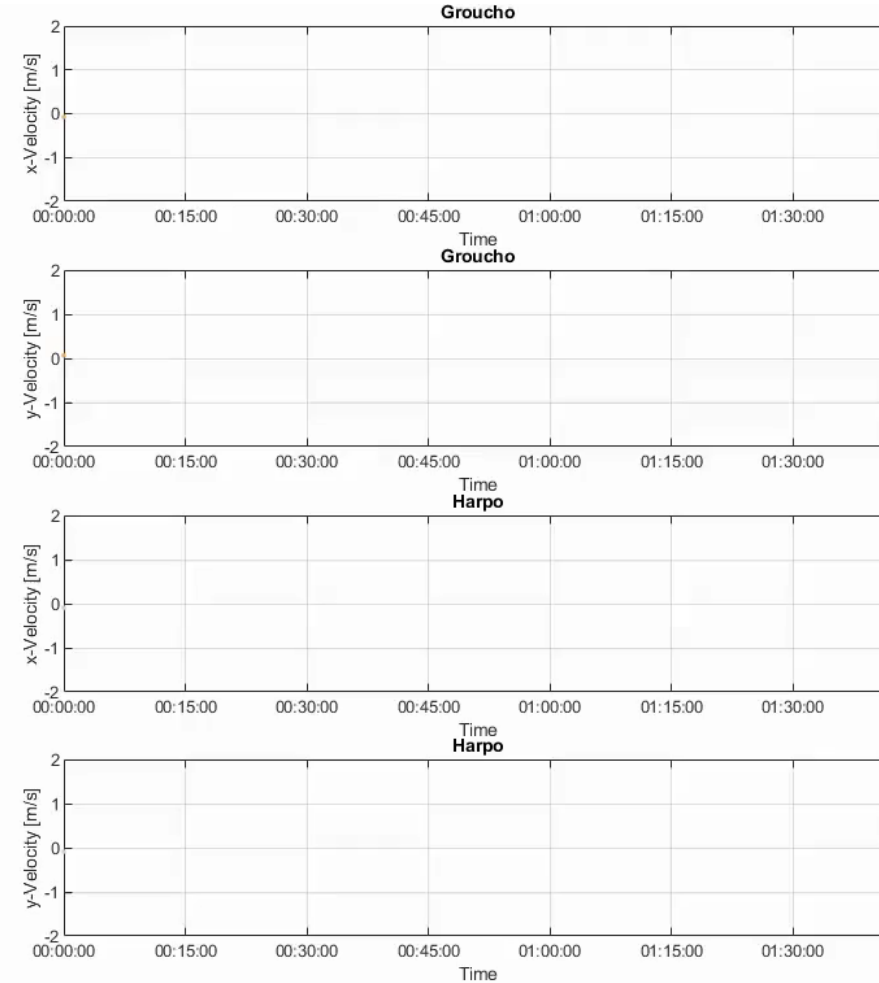
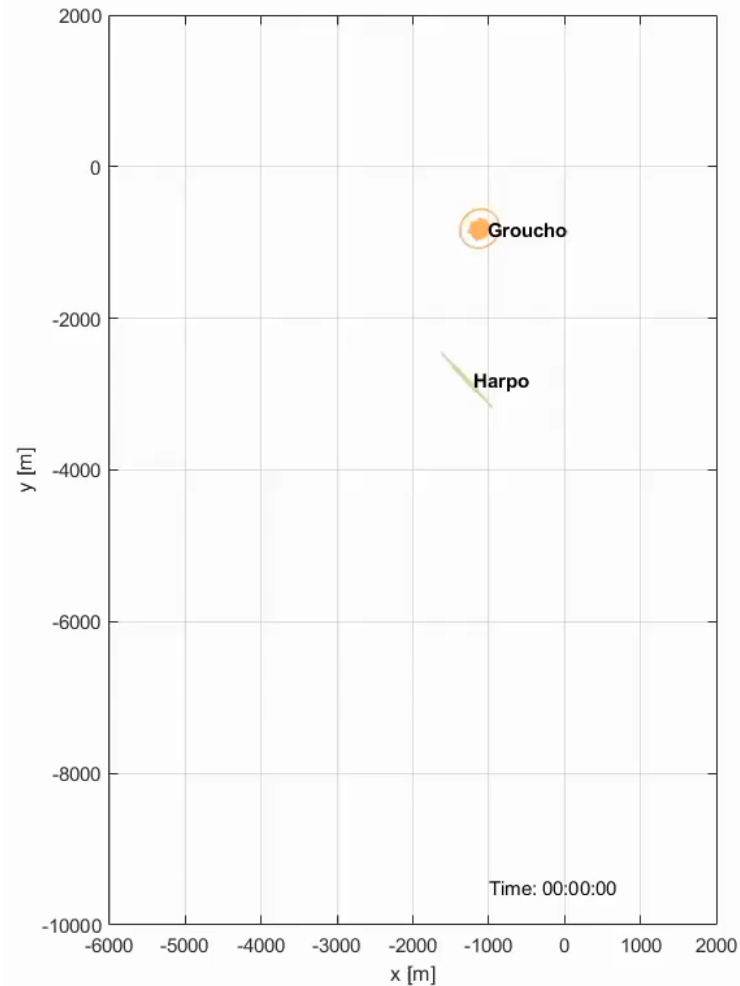
Receiver arrays are towed by AUVs (Harpo and Groucho)



Dots represent all the possible target locations in a given scan

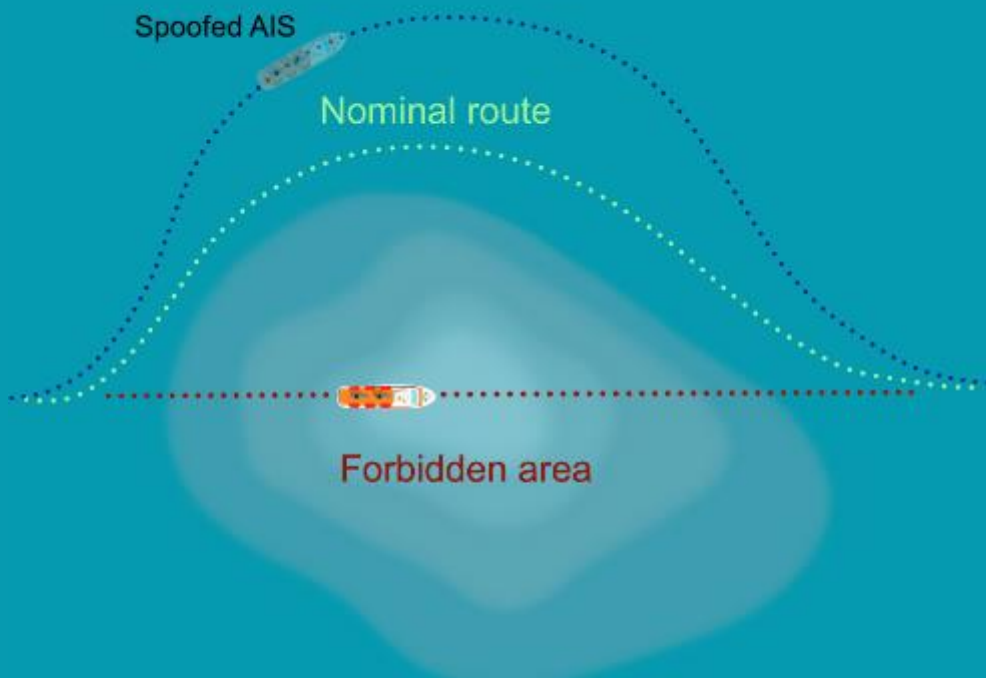
Source: NRV Alliance (right)
Target: Echo repeater towed by the NRV Leonardo (left)

Cooperative Multitarget Tracking and Localization



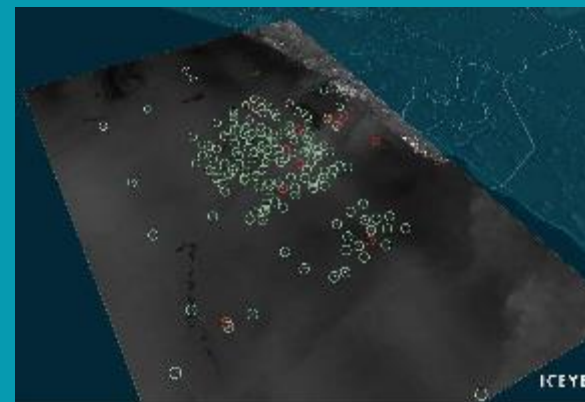
Advances in AI2F

Maritime Anomaly Detection



E. d'Afflisio, P. Braca, P. Willett, "Malicious AIS Spoofing and Abnormal Stealth Deviations: A Comprehensive Statistical Framework for Maritime Anomaly Detection," *IEEE Transactions on Aerospace and Electronic Systems*, 2021.

DARK ACTIVITIES



ILLEGAL FISHING

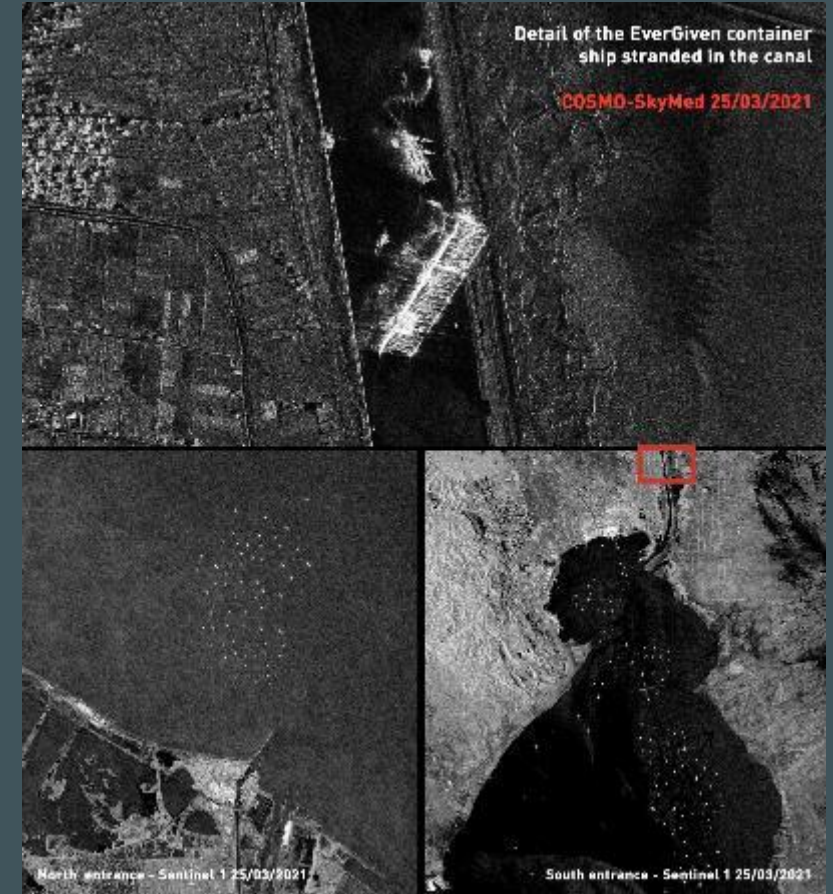


TRANSHIPMENT



Next-Gen Intelligent Systems for Maritime Surveillance and Autonomous Navigation

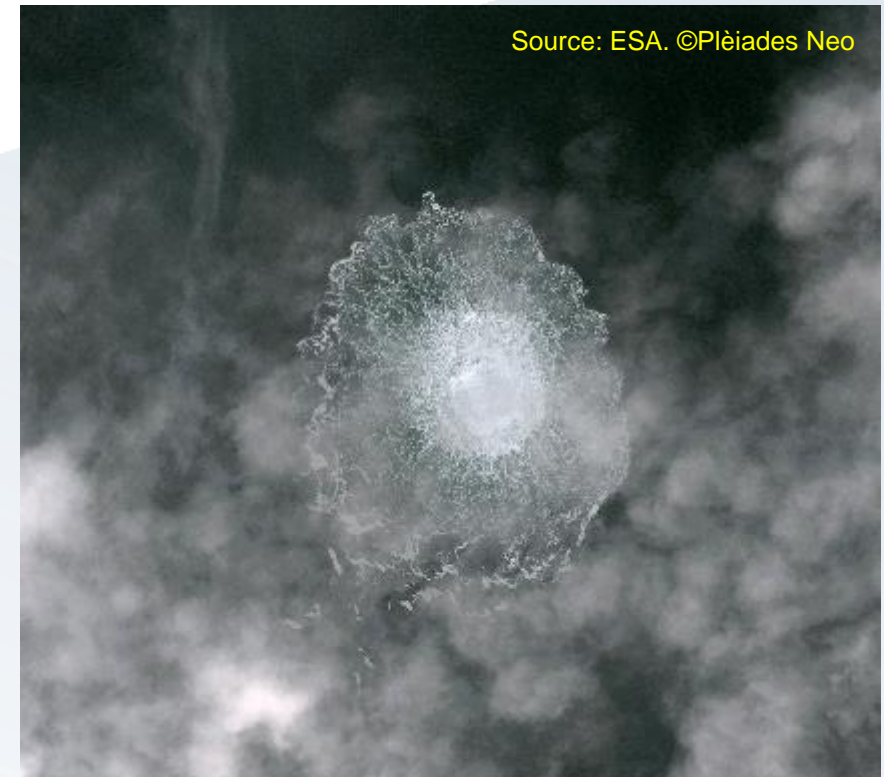
SPINNING S&T TECHNOLOGIES TO ANIMALIA AND
CENTRE FOR MARITIME RESEARCH & EXPERIMENTATION



N. Forti, E. d’Afflisio, P. Braca, L. M. Millefiori, P. Willett, S. Carniel, “Next-Gen Intelligent Situational Awareness Systems for Maritime Surveillance and Autonomous Navigation,” *Proceedings of the IEEE*, 2022.

Underwater Critical Infrastructures Monitoring

- Nord Stream
- Strait of Otranto



Seabed-to-Space Situational Awareness (S3A) for monitoring Underwater Critical Infrastructures (UCIs)

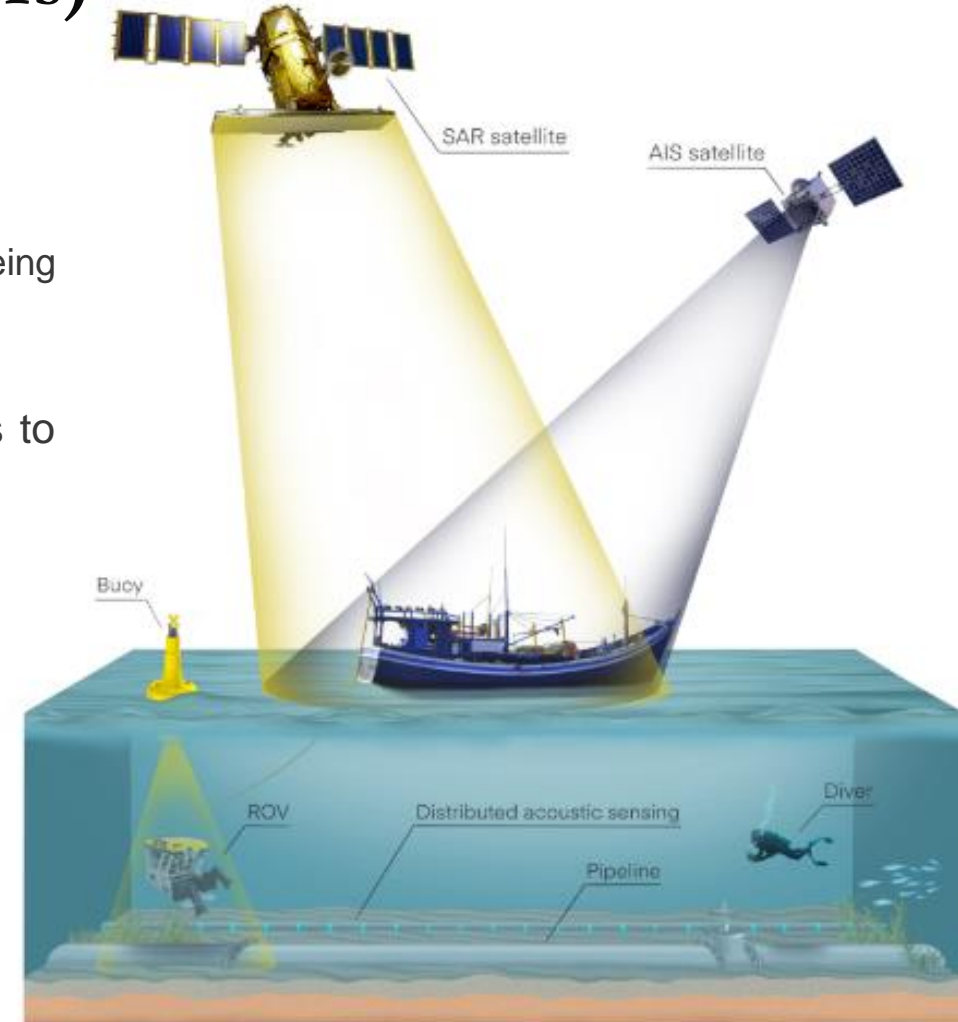
- The objective is to **detect** possible **anomalous behaviors** of surface assets (especially commercial and civilian) close to UCIs.
 - Any anomalous (uneconomical) behavior can be an indication of illicit activity being performed close to UCIs.
- There is not a **silver bullet** for the problem; the best monitoring strategy is to combine different sources of information.

Sensor information

- Data from the AIS
- Radar contacts/tracks
- Satellite detections
 - SAR, optical, hyperspectral, etc.

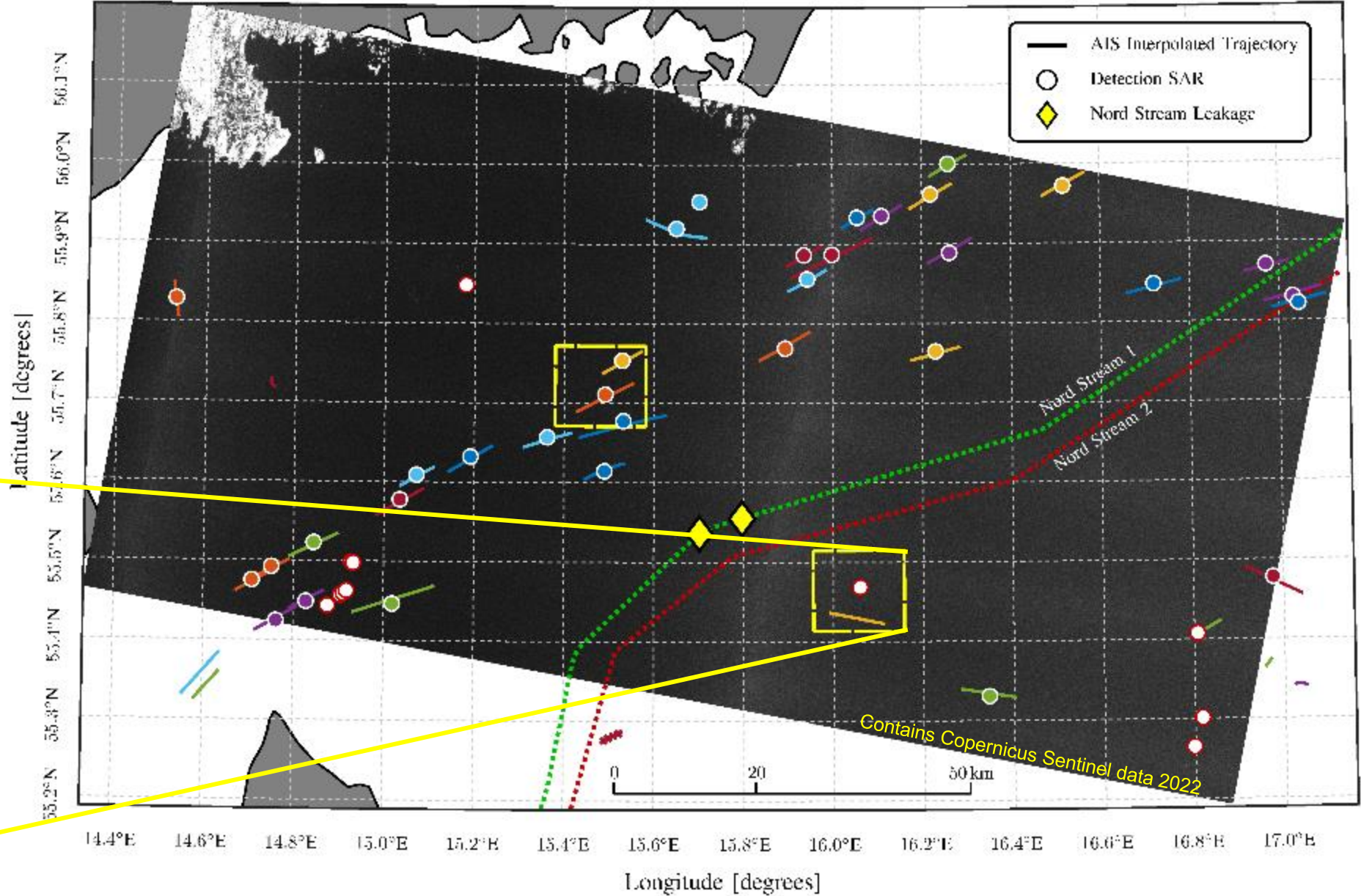
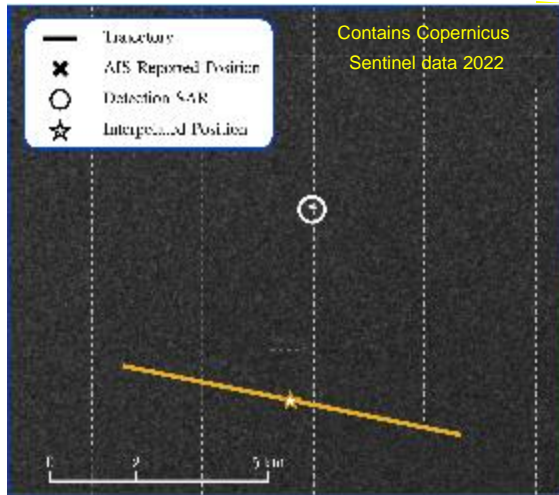
Contextual information

- Bathymetry
- Recurrent patterns
- Infrastructure map positions
- Weather conditions
- Ship ownership / Ship risk



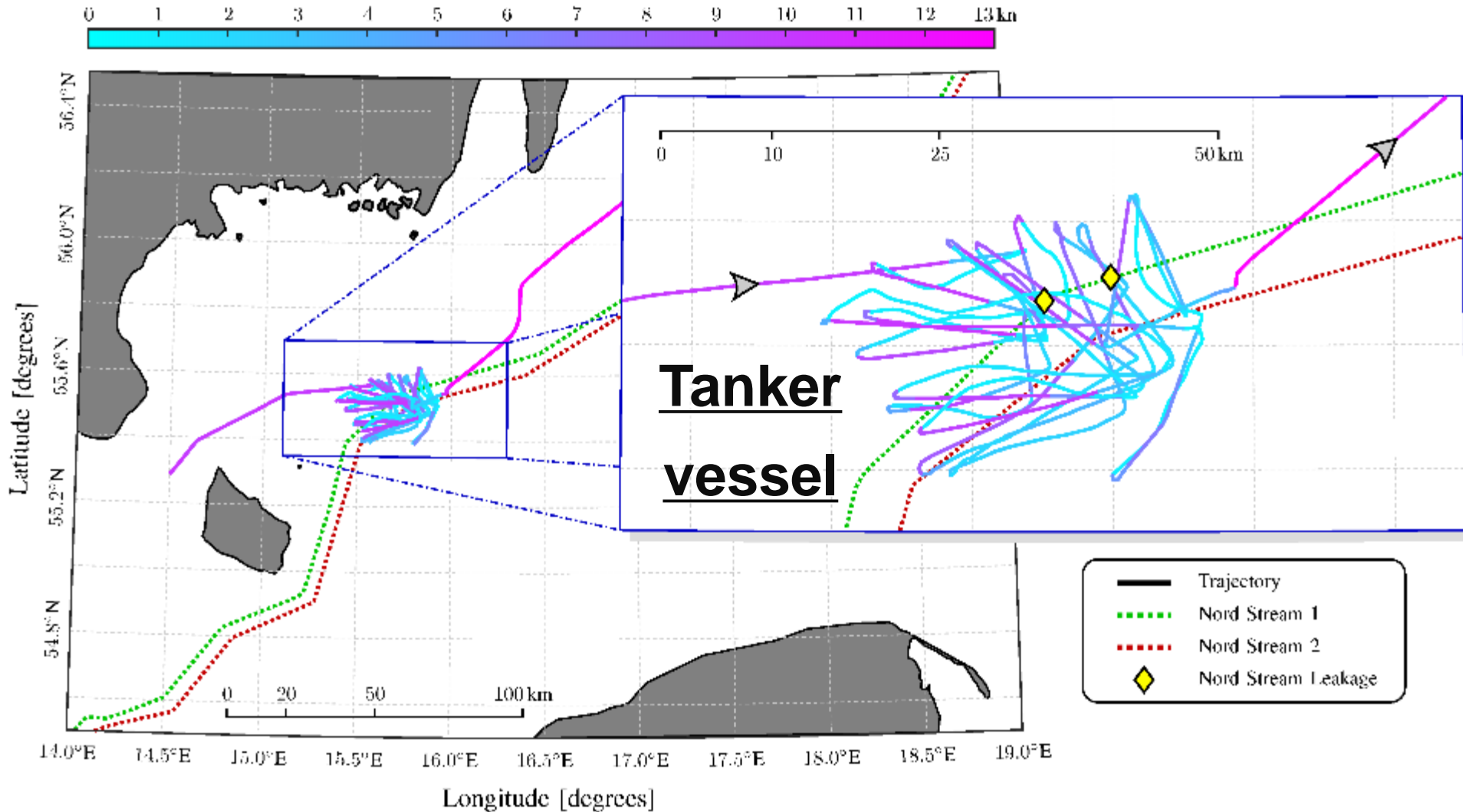
The analysis of SAR images before the event highlights the presence of vessels without AIS transponders in the area

G. Soldi, D. Gaglione, S. Raponi, N. Forti, E. d'Afflisio, P. Kowalski, L.M. Millefiori, D. Zisis, P. Braca, P. Willett, A. Maguer, S. Carniel, G. Sembenini, C. Warner, "Monitoring of Underwater Critical Infrastructures: the Nord Stream and Other Recent Case Studies," *IEEE Aerospace and Electronic Systems Magazine* (under review).



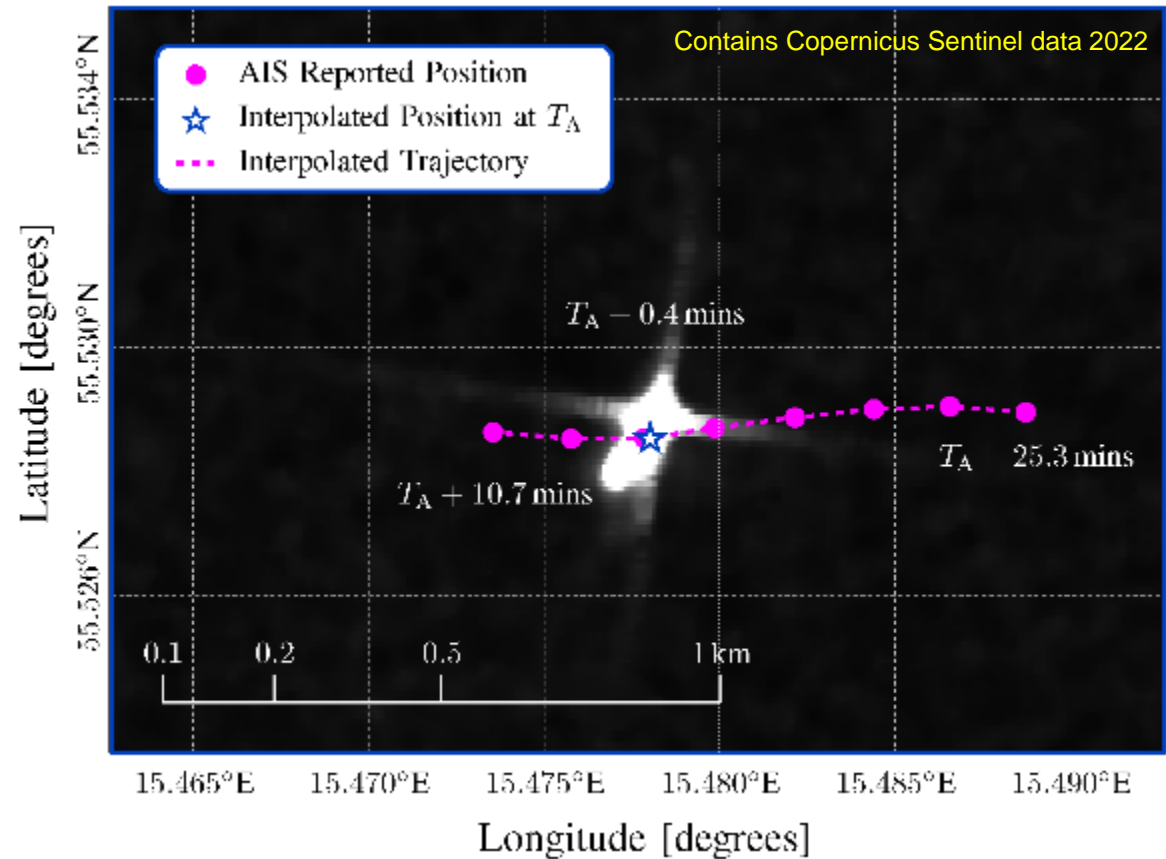
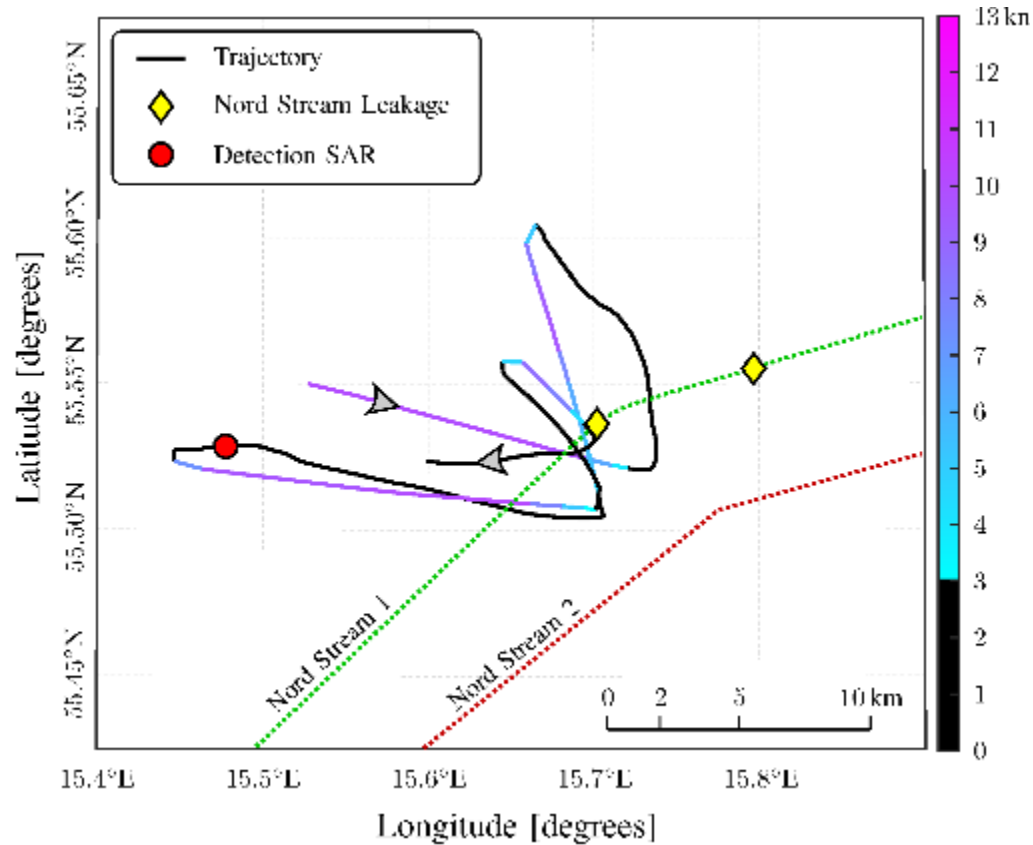
*Kinematic anomaly close to the explosions
in the days prior to the event*

Anomalous AIS Trajectory



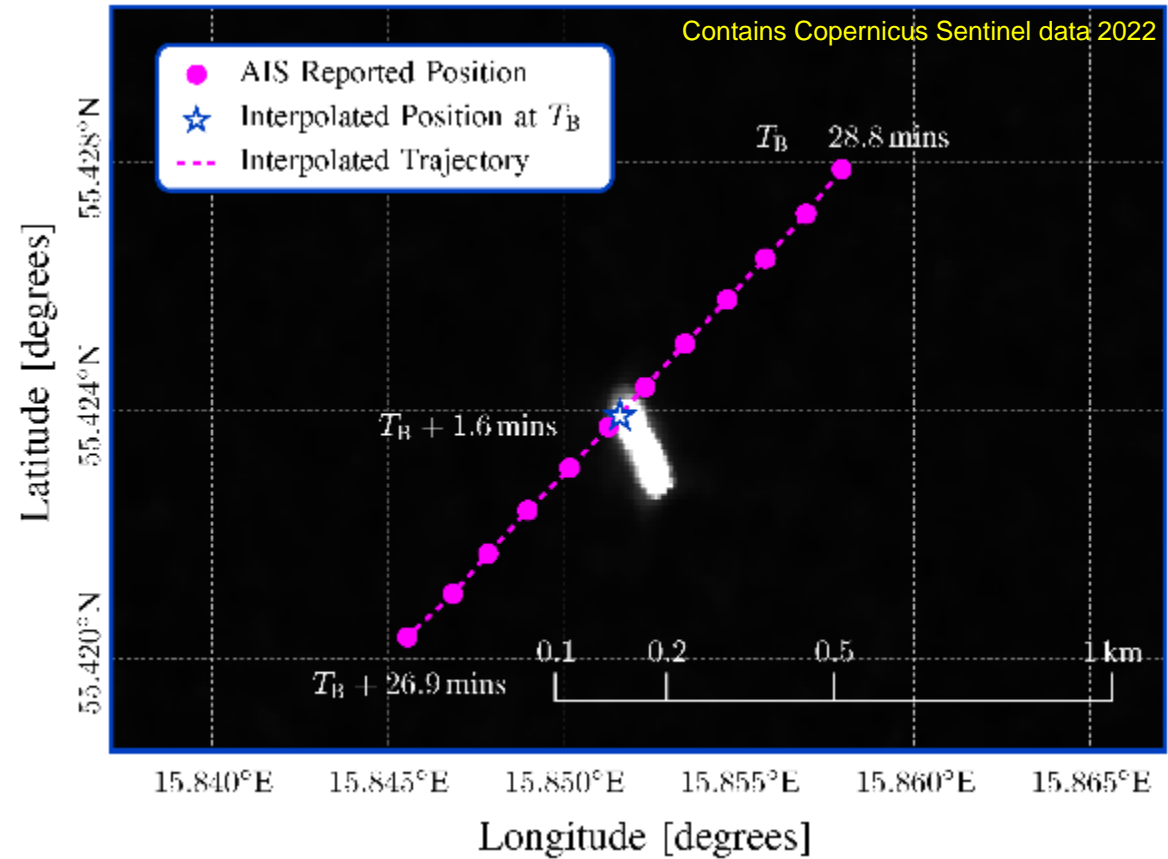
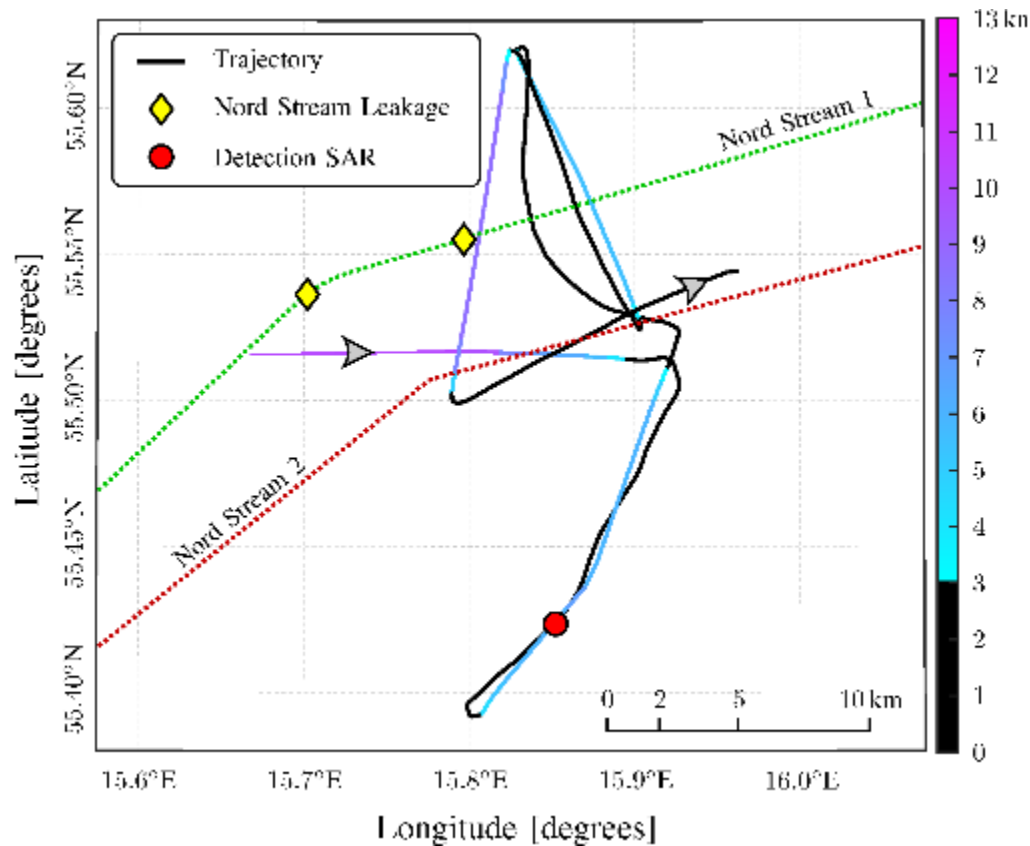
AIS/SAR Cueing (I)

The analysis of SAR images confirms the presence of a tanker vessel compatible with the position broadcast via AIS (i.e., the AIS signal was not spoofed)



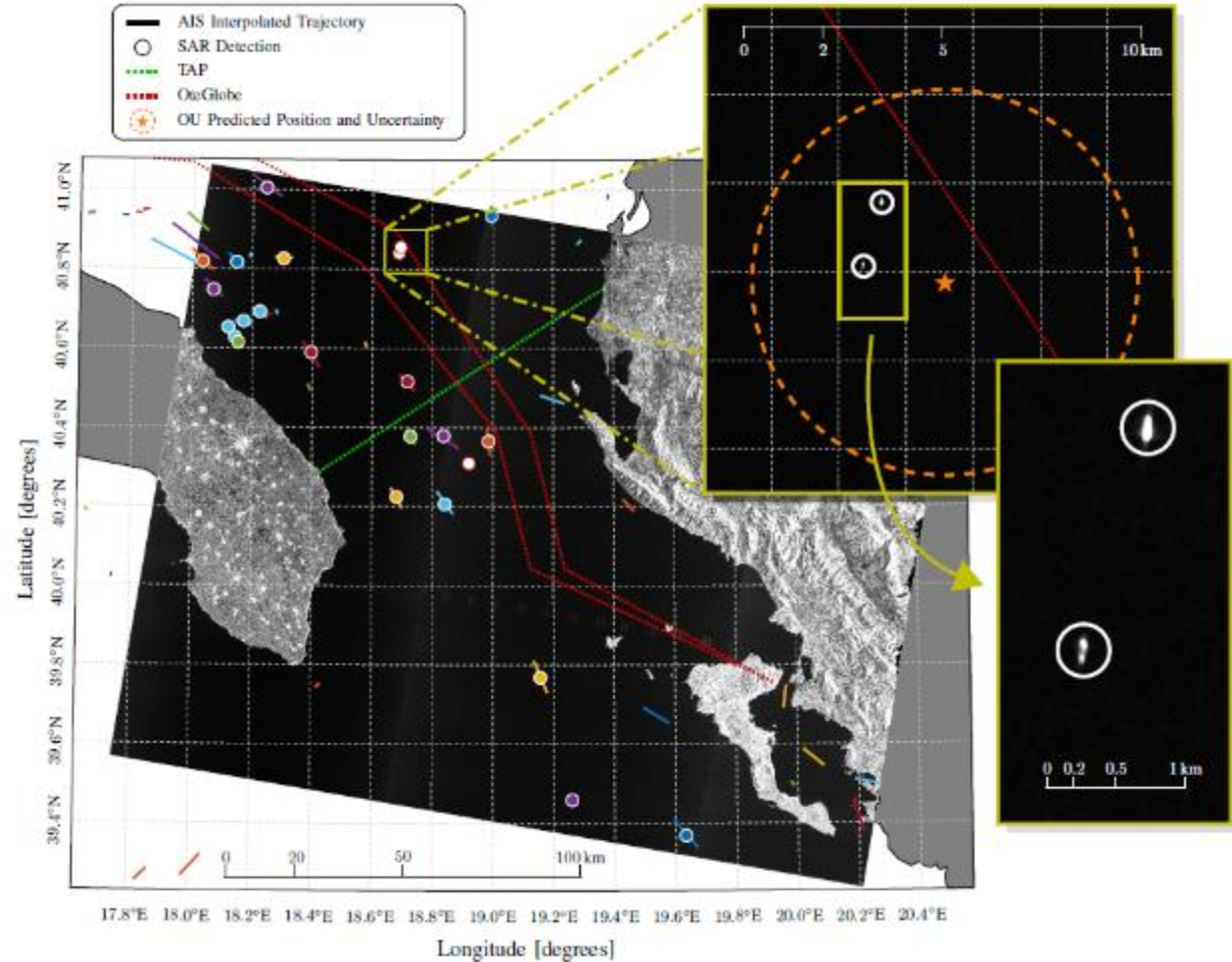
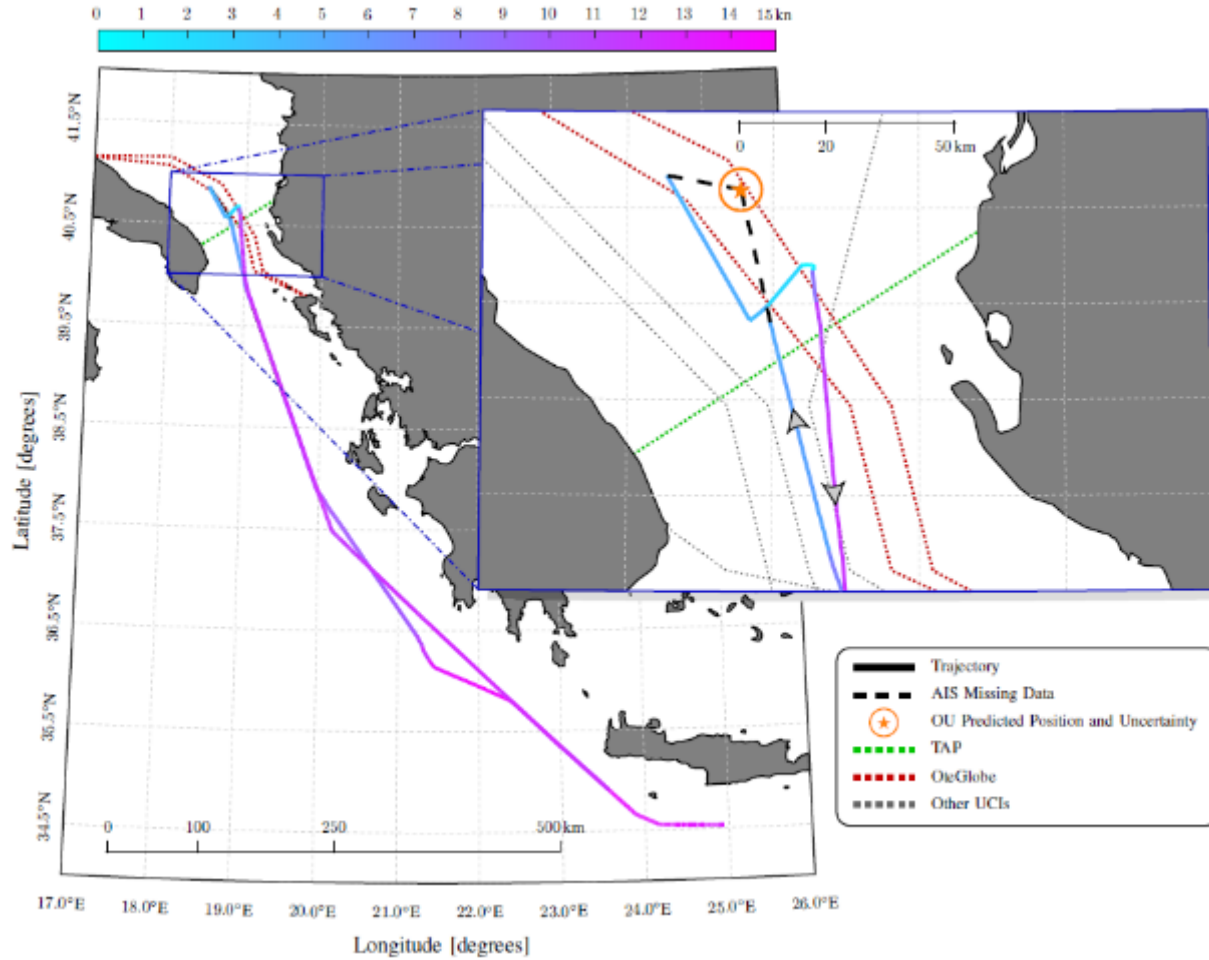
AIS/SAR Cueing (II)

The analysis of SAR images confirms the presence of a tanker vessel compatible with the position broadcast via AIS (i.e., the AIS signal was not spoofed)



Strait of Otranto - December 2022

Adriatic sea



ML Classification Performance Explained by Asymptotic Statistics

Observations

$$\mathcal{X}^{(n)} = \{x_1, x_2, \dots, x_n\}$$

Data-Driven Decision Function (D3F) Test

$$\begin{cases} T^{(n)} \geq \gamma_n & \text{decide } \mathcal{H}_1 \\ T^{(n)} < \gamma_n & \text{decide } \mathcal{H}_0 \end{cases}$$

Error probabilities

$$\alpha_n = \mathbb{P} \left[T^{(n)} \geq \gamma_n \mid \mathcal{H}_0 \right] \quad \text{False positive}$$

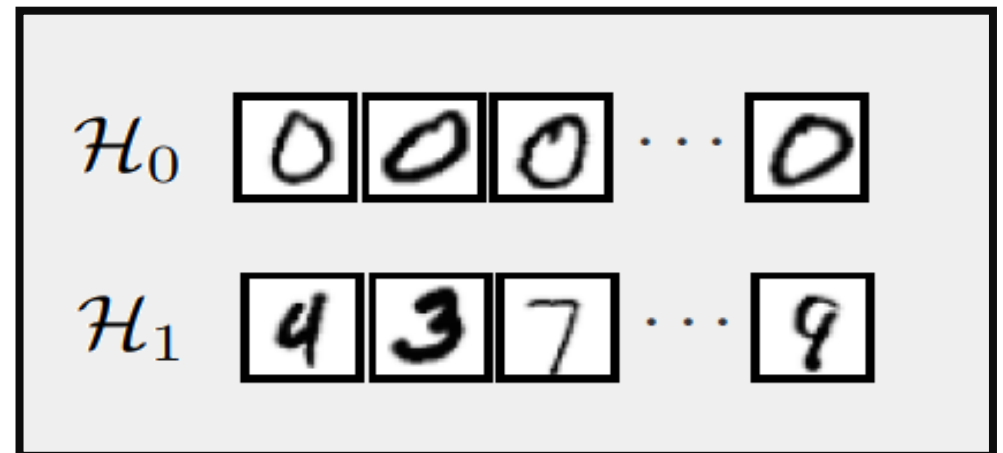
$$\beta_n = \mathbb{P} \left[T^{(n)} < \gamma_n \mid \mathcal{H}_1 \right] \quad \text{False negative}$$

$$\mathcal{Y}_k = \{y_{1,k}, y_{2,k}, \dots, y_{m_y,k}\}$$

$$\mathcal{H}_k, k = 0, 1 \quad \text{Training Set}$$

The D3F is designed to optimize an error metric (e.g. cross-entropy) exploiting the training set

MNIST (Modified National Institute of Standards and Technology) database



MNIST Database: Small and Large Deviations Analysis

Main result

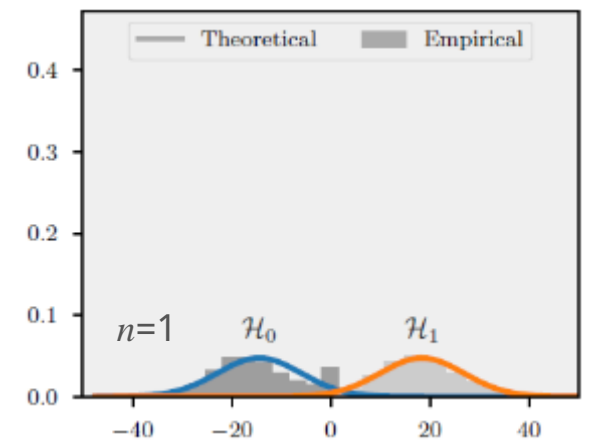
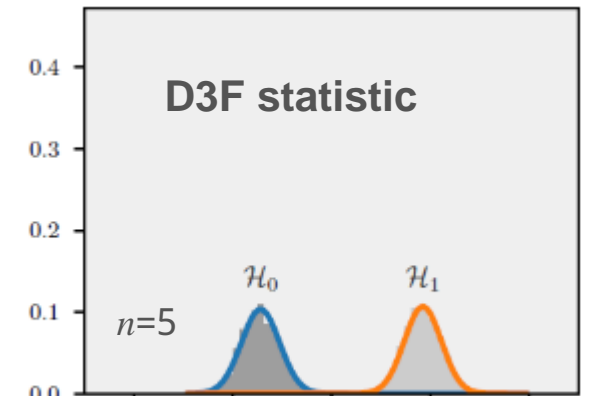
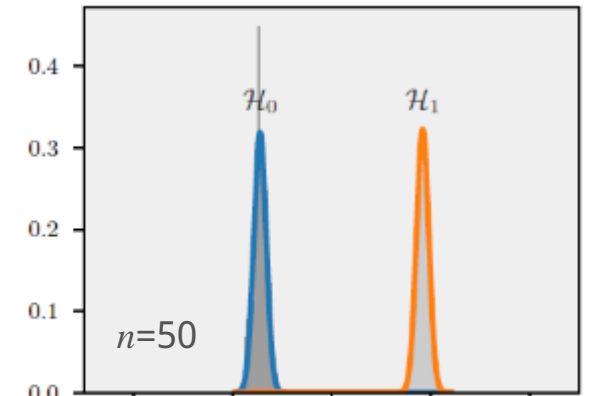
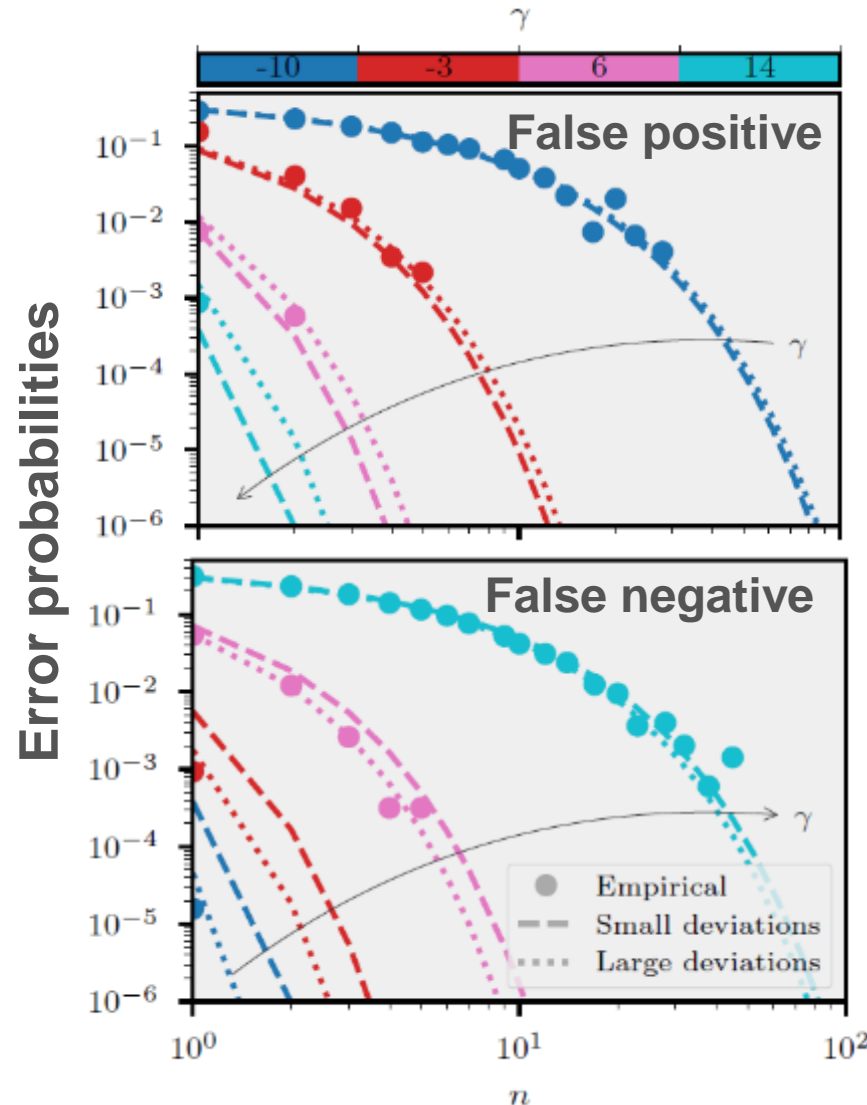
Error probabilities vanish exponentially

$$\sim \exp(-nI + o(n))$$

D3F Test

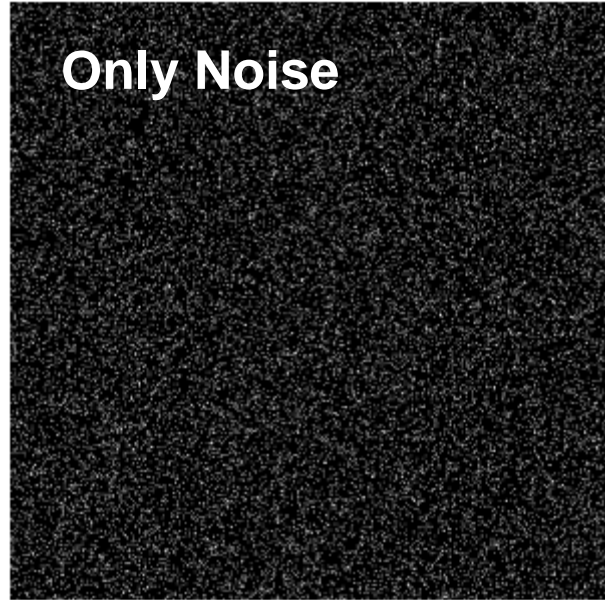
$$\begin{cases} T^{(n)} \geq \gamma_n & \text{decide } \mathcal{H}_1 \\ T^{(n)} < \gamma_n & \text{decide } \mathcal{H}_0 \end{cases}$$

P. Braca, L. Millefiori, A. Aubry, S. Marano, A. De Maio, P. Willett, "Statistical Hypothesis Testing Based on Machine Learning: Large Deviations Analysis", *IEEE Open Journal Signal Processing*, 2022.

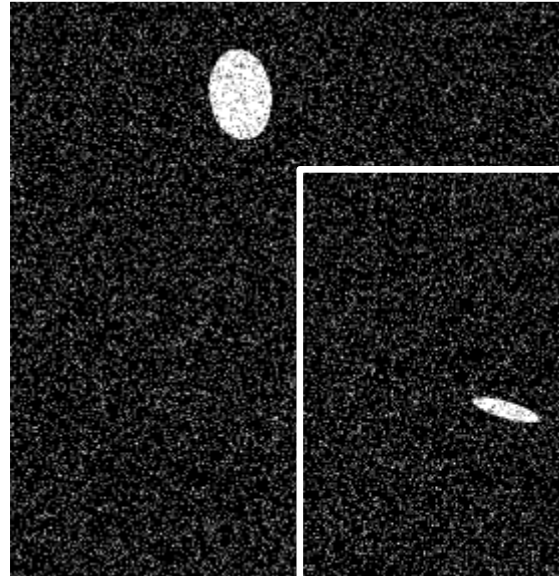


ML Performance Explained by Asymptotic Statistics

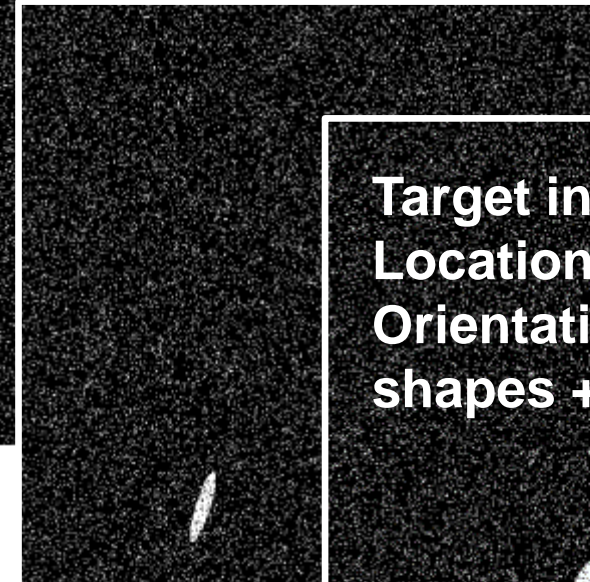
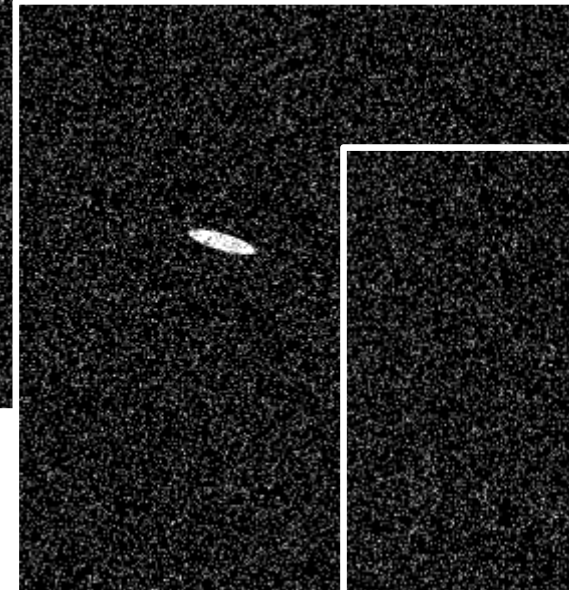
Target Detection based on a Deep CNN Synthetic Training Dataset



\mathcal{H}_0

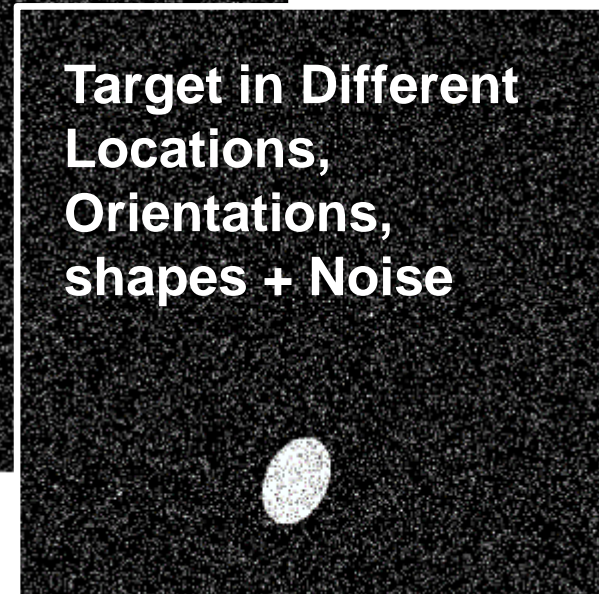


\mathcal{H}_1



Training

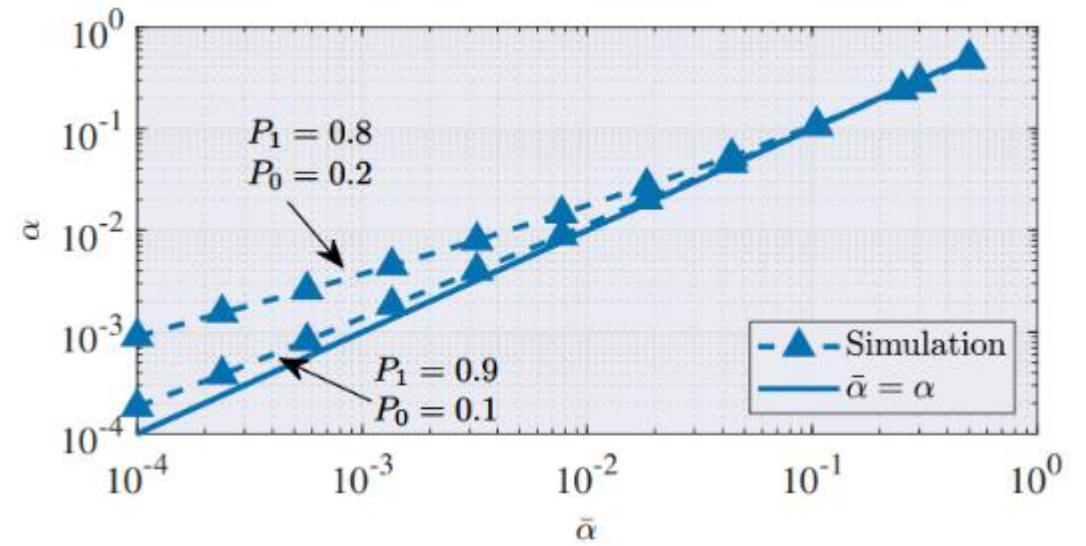
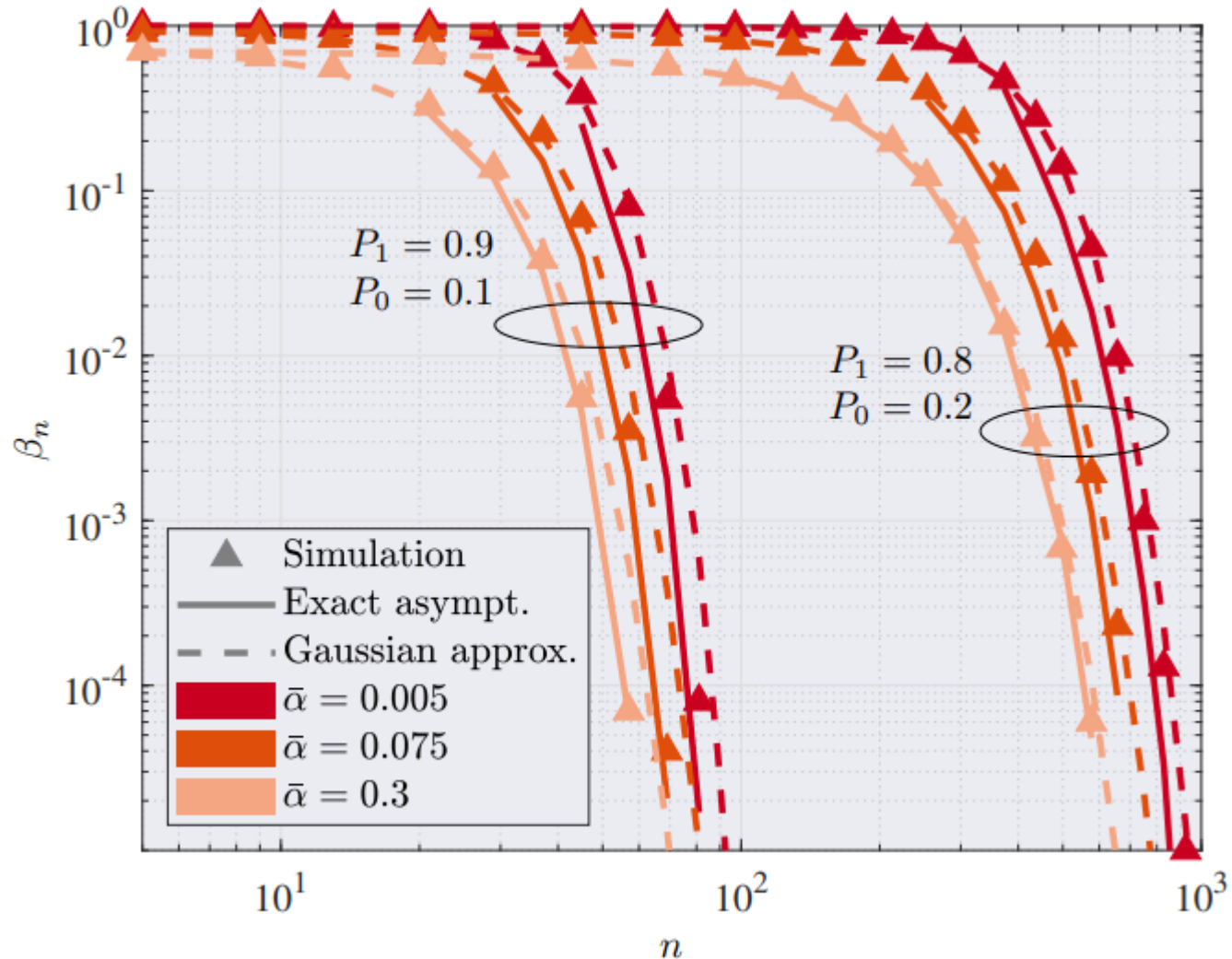
76800 images, of which 25600 generated from the null hypothesis, and 51200 from the alternative one (one half are targets with elliptical shape and the other half are targets with rectangular shape)



Binary Image: 500 by 500 pixels



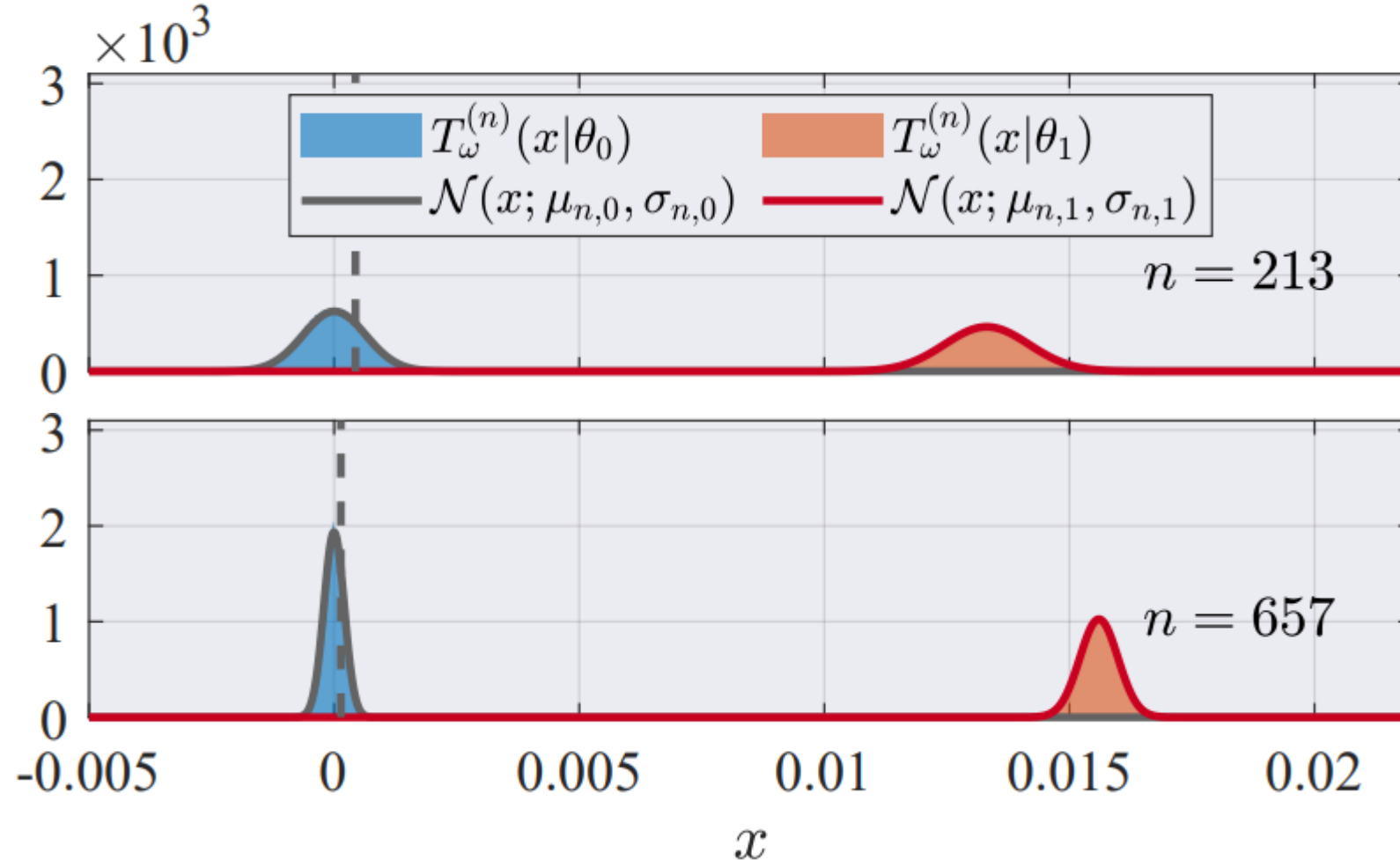
Extended Target Detection based on a Deep CNN



- P_1 and P_0 are the pixel-wise error probabilities;
- The training is done with $P_1=0.9$ and $P_0=0.1$.

Extended Target Detection based on a Deep CNN

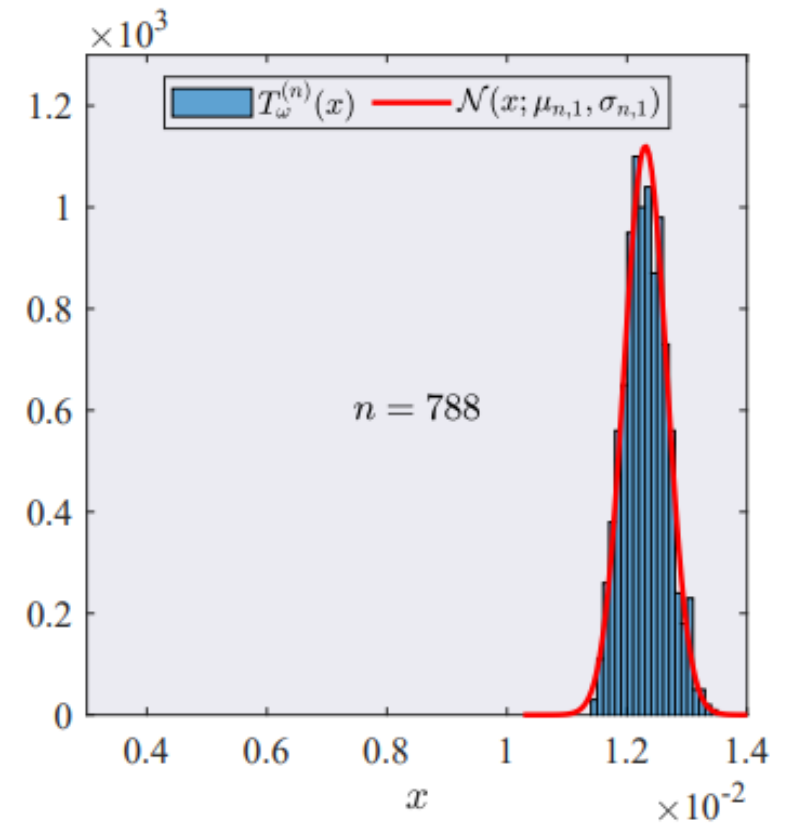
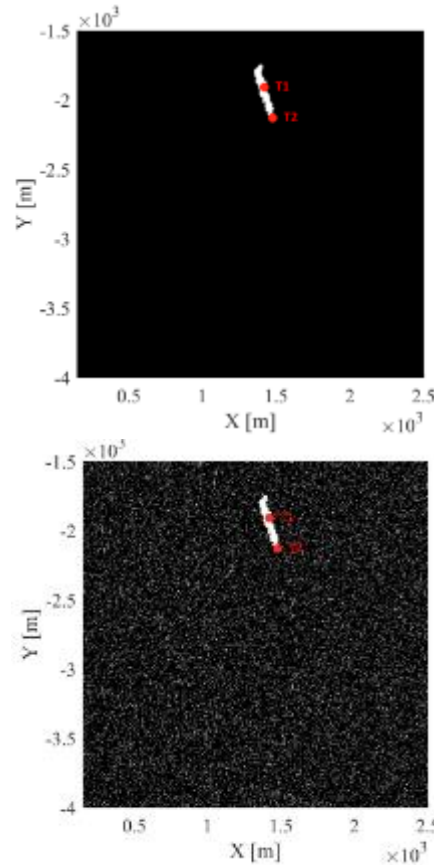
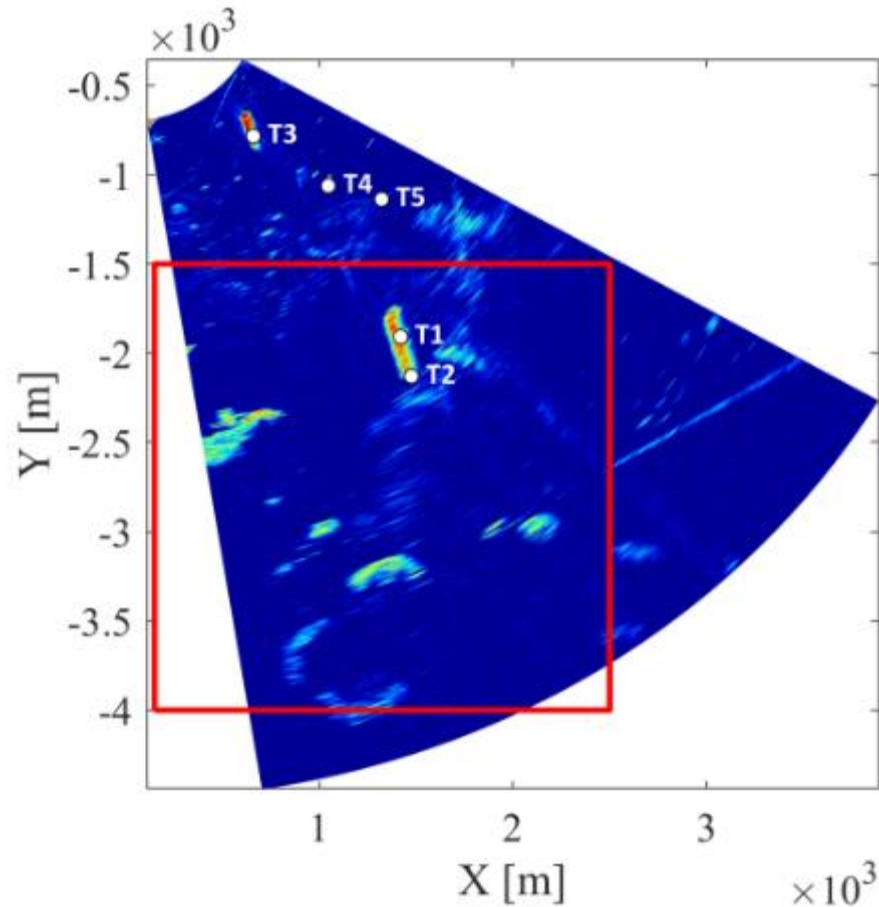
Small Deviation



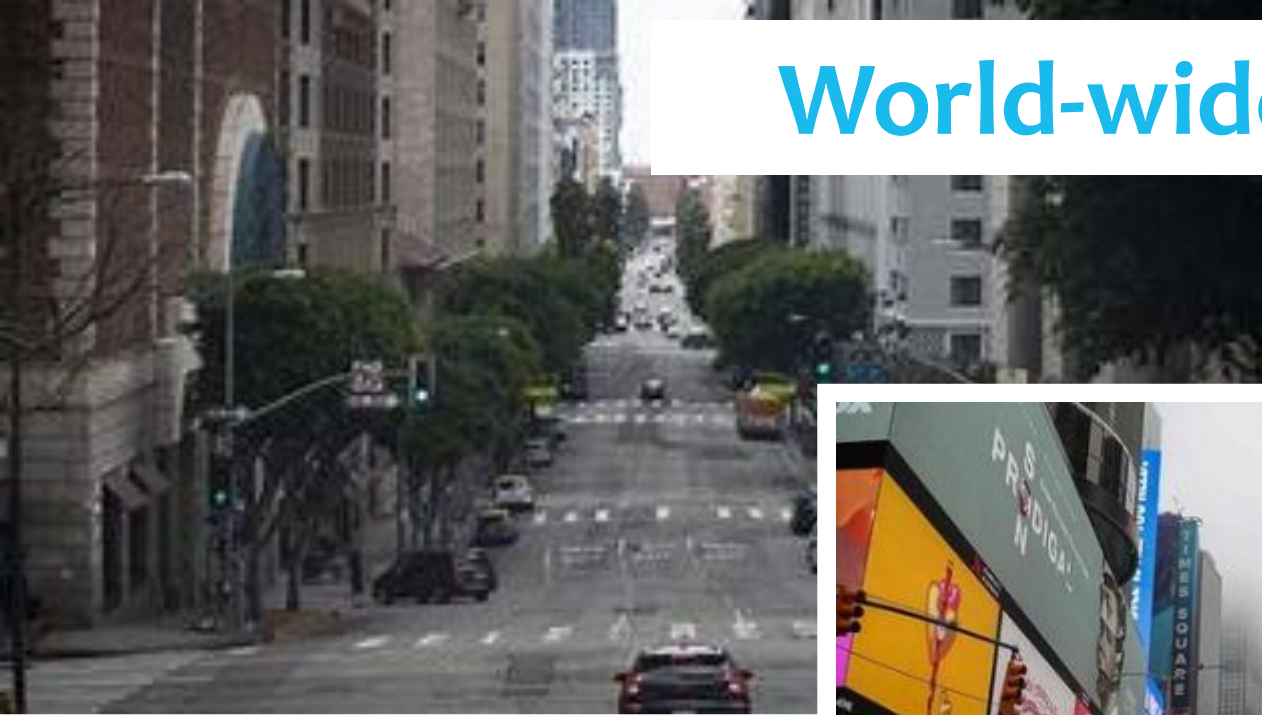
ML Performance Explained by Asymptotic Statistics

Target Detection based on a Deep CNN

High-Resolution Radar Data

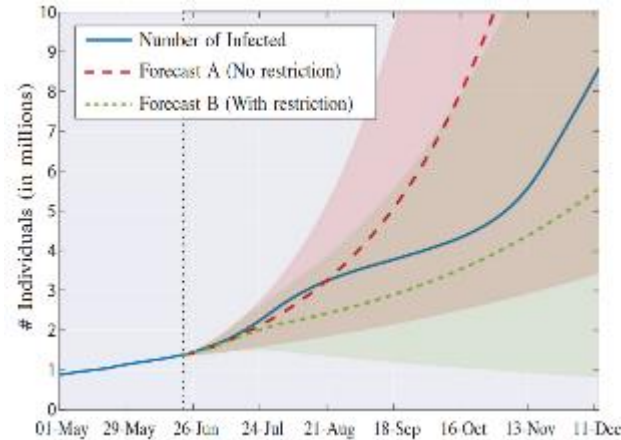


World-wide lockdown

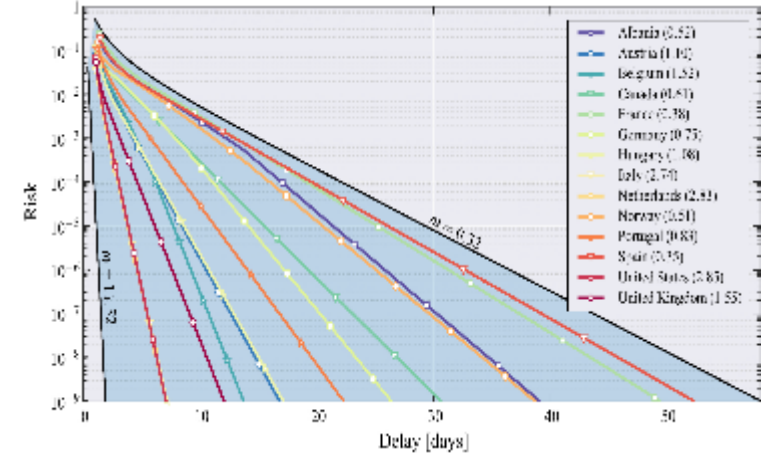


Data-driven approach to COVID-19 data

- Data-driven approach to COVID-19 data
 - **Global maritime mobility**
 - Epidemiological curve (upper plots)
 - Risk vs Detection Delay
 - Forecast evolution
- Unprecedented data analysis of the maritime mobility
 - Historical Automatic Identification System (AIS) dataset
 - **55 TB** stored in a big-data architecture
 - **1 trillion AIS messages** from more than **50,000 ships**
 - Terrestrial network of over **4,500 receiving stations** from 140 countries.
 - The processing is based on a distributed Apache Spark™ cluster of 40 virtual cores and 128 GB of RAM.

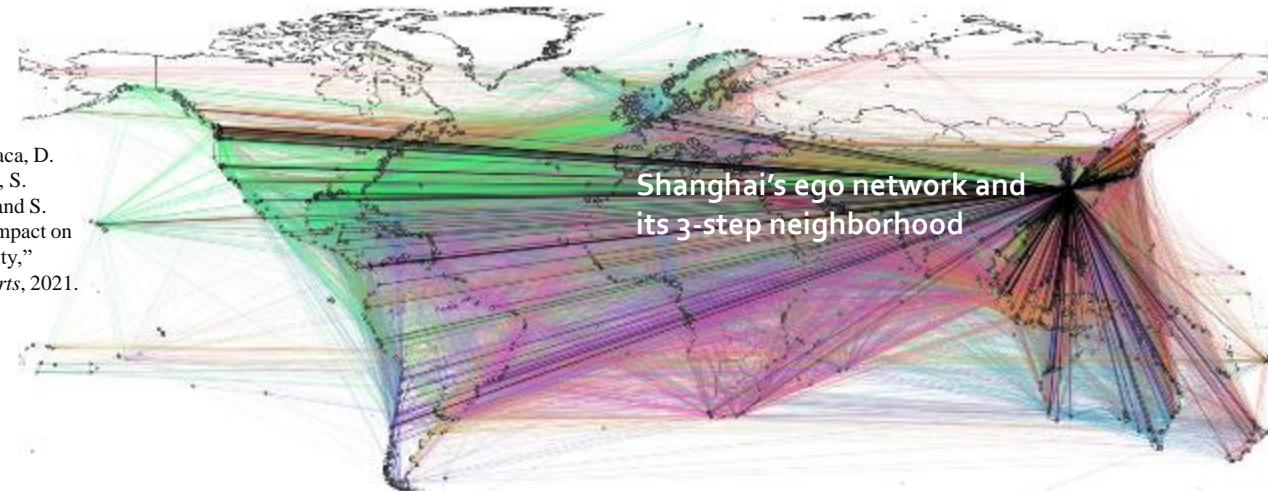


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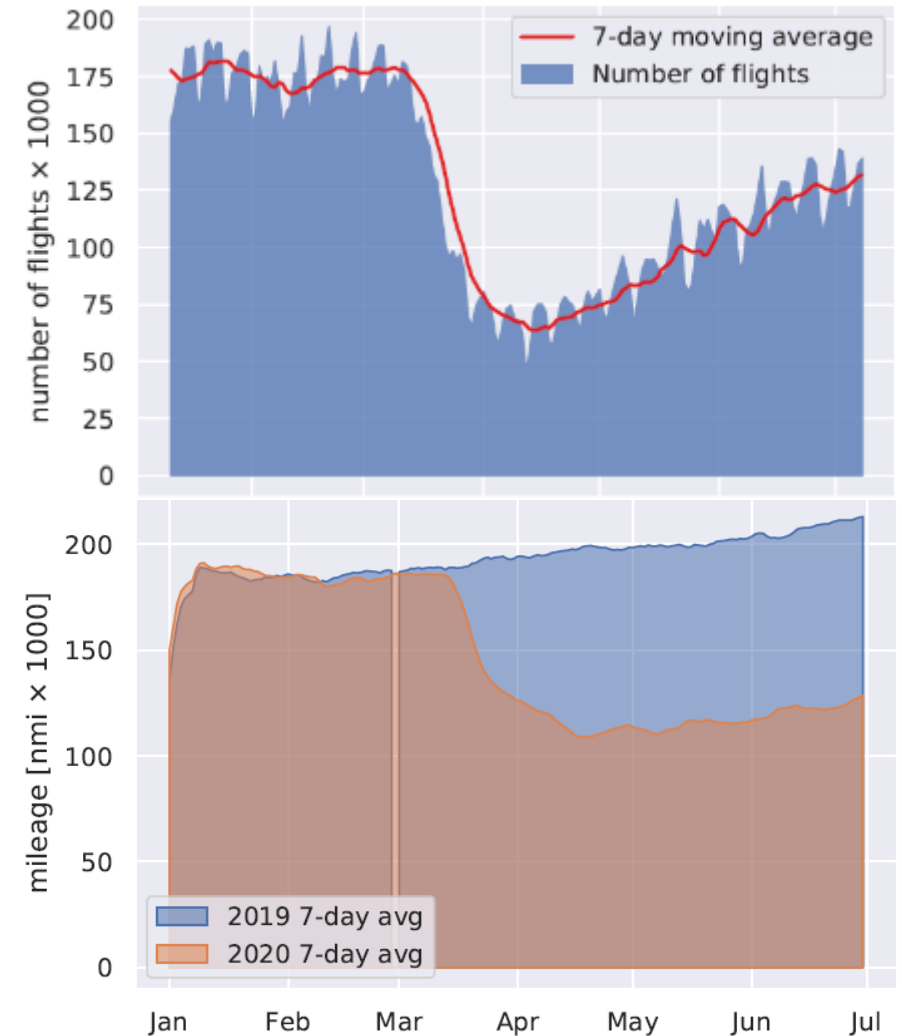
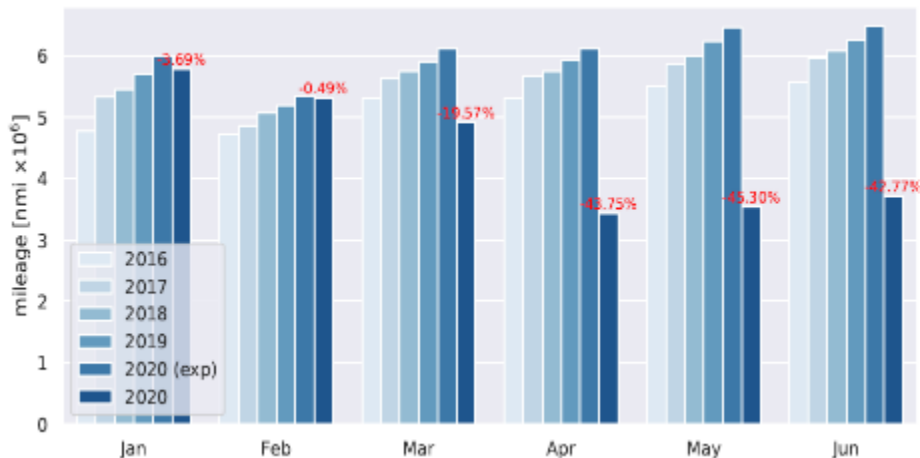
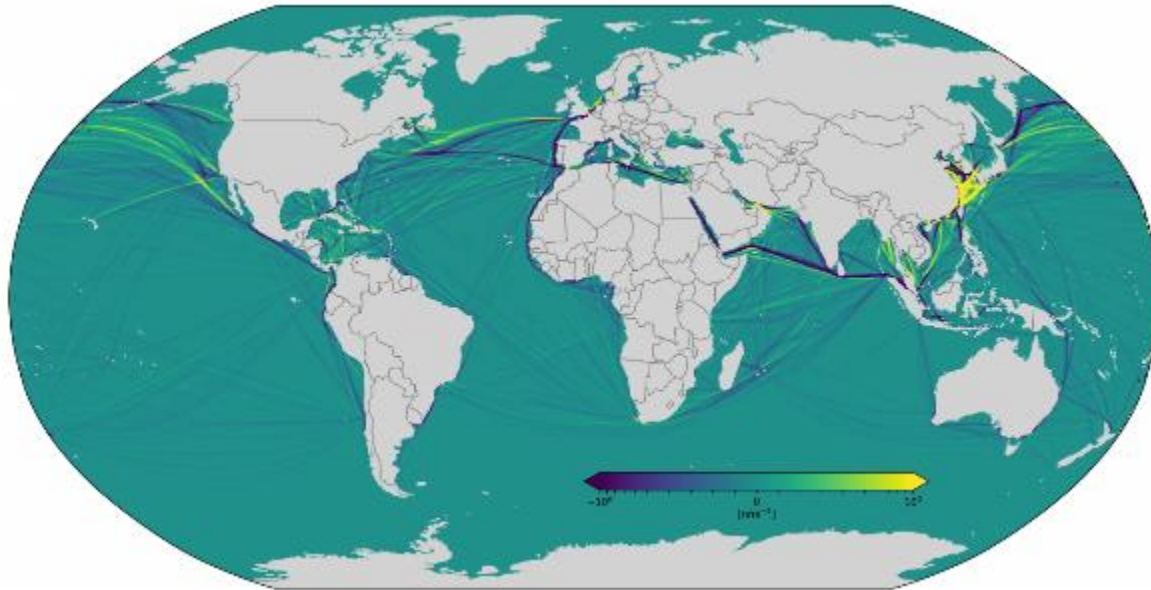


Braca, P., Gaglione, D., Marano, S. et al. Decision support for the quickest detection of critical COVID-19 phases. *Nature Scientific Reports*, 2021.

L. M. Millefiori, P. Braca, D. Zisis, G. Spiliopoulos, S. Marano, P. K. Willett and S. Carniel, "COVID-19 impact on global maritime mobility," *Nature Scientific Reports*, 2021.



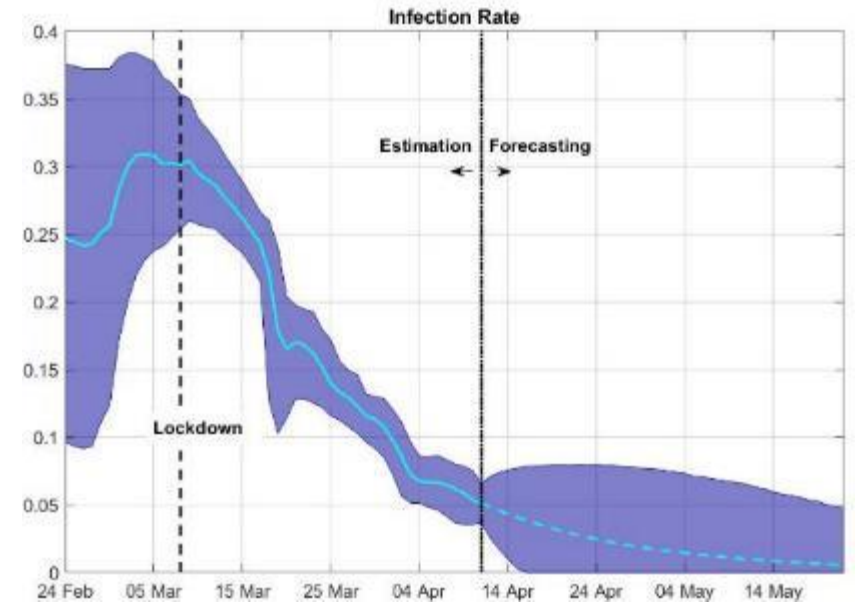
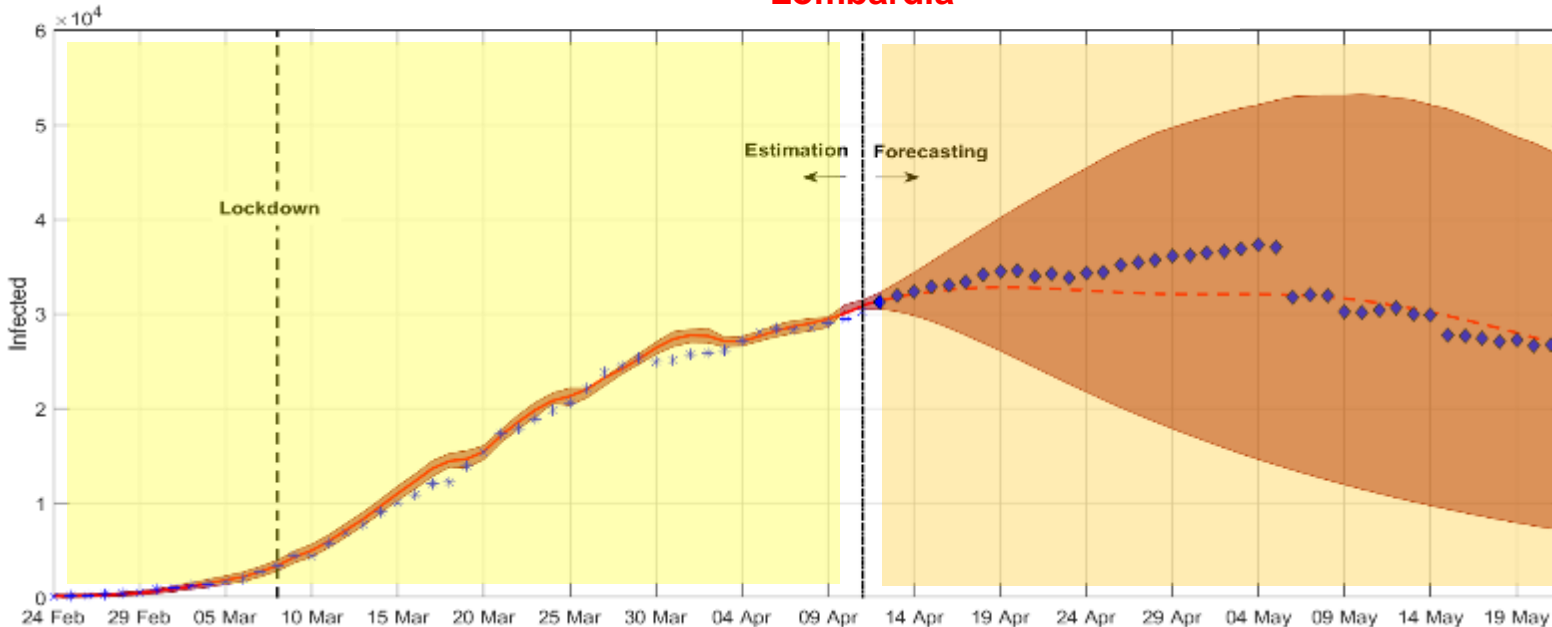
COVID-19 impact on global maritime traffic



L. M. Millefiori, P. Braca, D. Zissis, G. Spiliopoulos, S. Marano, P. K. Willett and S. Carniel, "COVID-19 impact on global maritime mobility," *Nature Scientific Reports*, 2021.

Adaptive Bayesian Learning and Forecasting of COVID-19 Outbreak

Lombardia



- **Blue stars:** actual number of infected persons, data from the Italian CPD, used for learning
- **Red line:** Estimated number of infected persons
- **Blue diamonds:** actual number of infected persons; data from the Italian CPD, used for comparison
- **Predicted number of infected persons in red with 90% confidence area (last observation: April 10)**

Key aspect:
Infection rate is time-varying

D. Gaglione, P. Braca, L. M. Millefiori, G. Soldi, N. Forti, S. Marano, P. K. Willett and K. Pattipati, “Adaptive Bayesian learning and forecasting of epidemic evolution—Data analysis of the COVID-19 outbreak,” *IEEE Access*, 2020.

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Towards All-Domain Situation Awareness

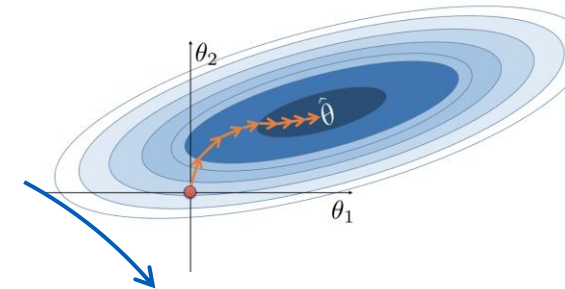


Next-Generation All-Domain Situation Awareness

- Game Theory
- Serious Games
- Mathematical Modeling
- Statistical Modeling



Gamification Modeling



- Reinforcement Learning
- Deep Learning
- Optimization Theory
- Quantum Computing

Information Acquisition

C4

AI

- Human in the loop
- Human-Machine Interaction
- Decision-Making
- Trustworthy AI



Decision



- Unmanned Assets
- Autonomy
- Collective Intelligence
- Multi-Domain
- Decentralized

Conclusion

- Today, thanks to the AI revolution we have reached unprecedented performance in several fields of application.
- Modern defense systems will be more and more influenced by AI, Big Data and Autonomy.
- Next-gen C2 system will fully exploit all the AI and Big Data Analytics capabilities.
- The role of an AI will be more and more important when the number of autonomous systems will significantly increase.





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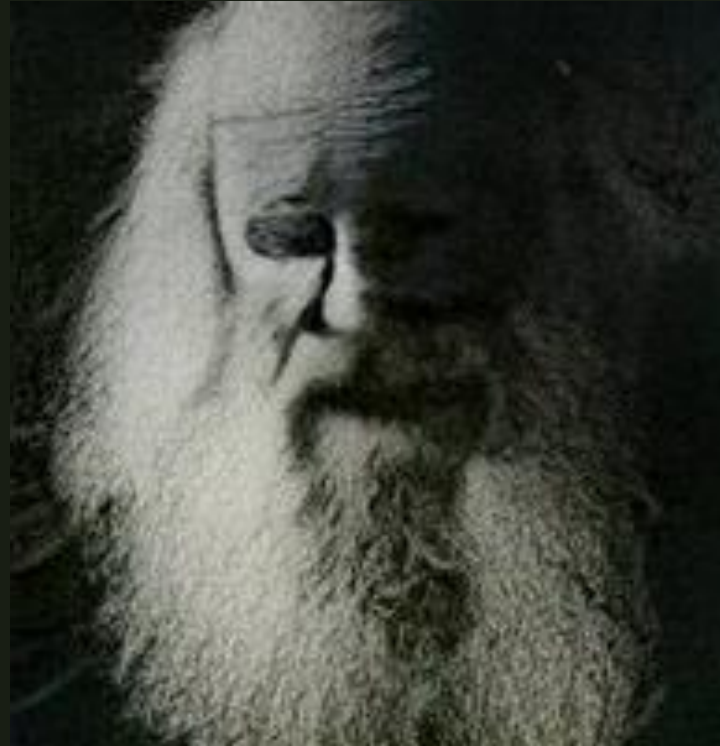
POLITECNICO
MILANO 1863



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Norwegian University of
Science and Technology

“Self-Portrait” of DALL-E AI system



DALL-E is an AI system that generates images from text prompts

Chat GPT



What was the color of the white horse of Napoleon?

The white horse of Napoleon is famously known as Marengo, and as its name suggests, Marengo was a white horse.

Wait a second, my wife said that this horse is black, and she is always right!

I apologize for any confusion, but Marengo was actually a gray Arabian stallion. Marengo's coat color was a mix of white, black, and gray, with a darker mane and tail. While Marengo was not a black horse, it is possible that some depictions or artistic representations of the



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AI-generated images from texts

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