Digital Twins: Virtual Platforms for Real-World Breakthroughs

The growth of digital twin applications has been significantly driven by advances in big data and artificial intelligence (AI). They now provide powerful tools for simulating, analysing and optimising real-world systems in virtual/hybrid environments. But what is a digital twin? OpenSpace looks at how they have evolved and are being used in a range of scenarios and markets, making real-world differences.

Throughout history, simulation and modelling have been widely used across various fields. In the space sector, for example, software-based simulators and mission models have long been employed to support spacecraft design, validation and operations preparation, and to predict and analyse satellite anomalies while in orbit. Yet only in recent years, with advancements in technology, have we been able to develop 'digital twins' – virtual replicas powered by near-real-time data feedback.

Although digital twins are relatively new, the concept of using replicas, twins, models and simulations dates back thousands of years. A good example of this is the tomb of the Mausoleum of the First Qin Emperor that was built in the town of Lingtong District in the city of Xi'an, China. Dating back to around 210 BCE, it contains potentially one of the first models we are aware of. Relatively recent excavations around the complex discovered in the region of 7,000 statues of terracotta warriors, horses, officials, acrobats, strongmen and musicians created to serve the emperor in his afterlife. In more recent years, using non-invasive techniques such as geo radar and gravimeter investigations, archaeologists have determined that the 'palace' measured 140 x 110 x 30m. Interestingly, they found mercury being used in the tomb to simulate the hundred rivers, the Yangtze, the Yellow River and the Great Sea, which sat below a representation of the heavenly constellations.

What is a digital twin?

The first practical definition of a digital twin originated from NASA in an attempt to improve physical model simulation of spacecraft in 2010 – it believed a digital twin can be defined as a model-based approach with digital implementations.

Today, the definition of a digital twin varies depending on who you are talking to, the market it is used in, what it is created to represent and the intended use. It can be a simulation or emulation of a system that is updated with data from the operation of that system and therefore works as a twin of the real system. In recent years, people have started calling a broader set of models, simulations or emulations "digital twins", but this is incorrect. A digital twin must be supplied with the relevant data to enable it to represent the full life cycle of a product or system, updating continuously via real-time data feeds.

Federico Antonello, System and Applications Engineer at the European Space Agency (ESA), comments: "To me, a system qualifies as a true digital twin only when it incorporates active feedback from the physical asset to support informed decision-making. It begins with a model that is continuously refined using test and/or operational data to improve its accuracy and ensure alignment with the actual asset. The digital twin uses data from tests and operations to refine the design of an asset – either during development or for future versions – and to support ongoing operations and troubleshooting.

"During the testing phase, the digital twin enhances outcomes by integrating real-time test data into simulation models, helping to identify optimal strategies and detect anomalies early. This enables timely adjustments to the asset itself. In operation, digital twins support both day-to-day decision-making and long-term planning by providing insights into asset health, consumables and system status – ultimately boosting performance, efficiency and scientific return."

Jose Pizarro, AI and Data Science Engineer at ESA, adds: "If you look at a cybersecurity operations centre, you model your network of assets and the interactions of all the communications. In the event that one part of the network fails or someone hacks into the system, you can use your digital twin to identify how it affects the rest of the network. You can model the operating system on each asset, detect the vulnerability and patch it without bringing down the whole network. This is a different perspective, but because a lot of the time what we do in cybersecurity is the same as we do in space operations, it's just called fault diagnostics or fault tolerance and fixing stuff that's broken. In space operations we fix things that are just broken: in cybersecurity we fix things that have been deliberately broken."

Emulation vs model-based digital twins

There are two common approaches for digital twins: emulation-based and model-based. Each offers distinct advantages.

Image © ESA

Digital models can provide an interactive emulation of a real-life system for testing, development and operational analysis.

Emulation-based digital twins aim to replicate real devices, systems and networks with high fidelity, enabling a true-to-life digital environment. Their ability to interact dynamically with changing conditions makes them ideal for real-time testing, development and operational analysis.

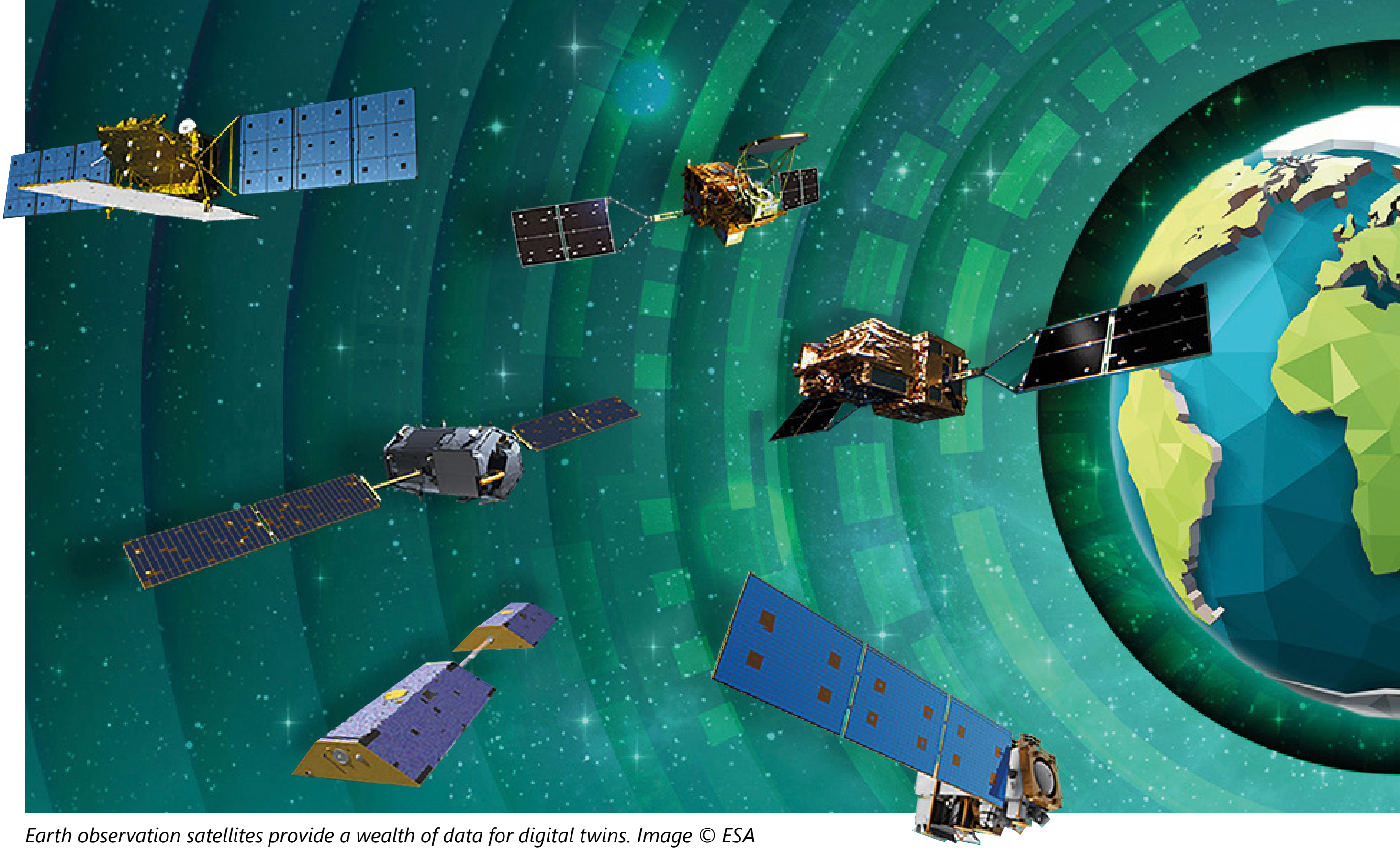
The strength of emulation-based twins lies in their precision and responsiveness. By mirroring actual hardware and network behaviours, they can deliver detailed and accurate results that closely reflect real-world performance. This makes them especially suitable for testing cybersecurity strategies, network configurations and mission-critical systems. However, their reliance on high-fidelity emulation can become a limitation when dealing with components or scenarios that are too abstract, too complex or not feasible to replicate directly.

By contrast, model-based digital twins rely on mathematical models and algorithmic representations of systems. Rather than replicating physical components, they simulate behaviours using rules, formulas and assumptions. This approach is suited to scenarios that require abstraction, such as long-term forecasting, optimisation tasks or systems that cannot be emulated efficiently. While this method often results in lower fidelity and less specificity, it offers scalability and computational efficiency, making it essential in many large-scale or conceptual applications.

The most effective digital twin implementations often combine both approaches. Emulation provides depth and realism where accuracy is critical, while modelling offers flexibility and abstraction where needed. Choosing the right balance depends on the goals of the simulation, the nature of the system and the constraints of the environment. Understanding the distinctions between these two approaches is key to building digital twins that are both reliable and fit for purpose.

Digital twins in the space sector

Within the space sector, digital twins of the Earth are being used to develop a simulation of a system and provide critical insights for tackling global challenges. They can provide a digital representation of the Earth system, spanning scales and domains. Their purpose is to monitor, forecast and assess the Earth system and the consequences of human interventions on Earth. They provide users with the capability to



Earth observation satellites provide a wealth of data for digital twins. Image © ESA

interact with and interrogate the system, and provide decision support systems for addressing environmental challenges. Digital twins can also enhance visualisation and immersive interactions with data and insights.

Digital twins are supporting strategic initiatives such as the European Green Deal, the United Nations Sustainable Development Goals (SDGs) and civil protection efforts by enabling data-driven decisions, optimising resource allocation and fostering collaboration among diverse stakeholders.

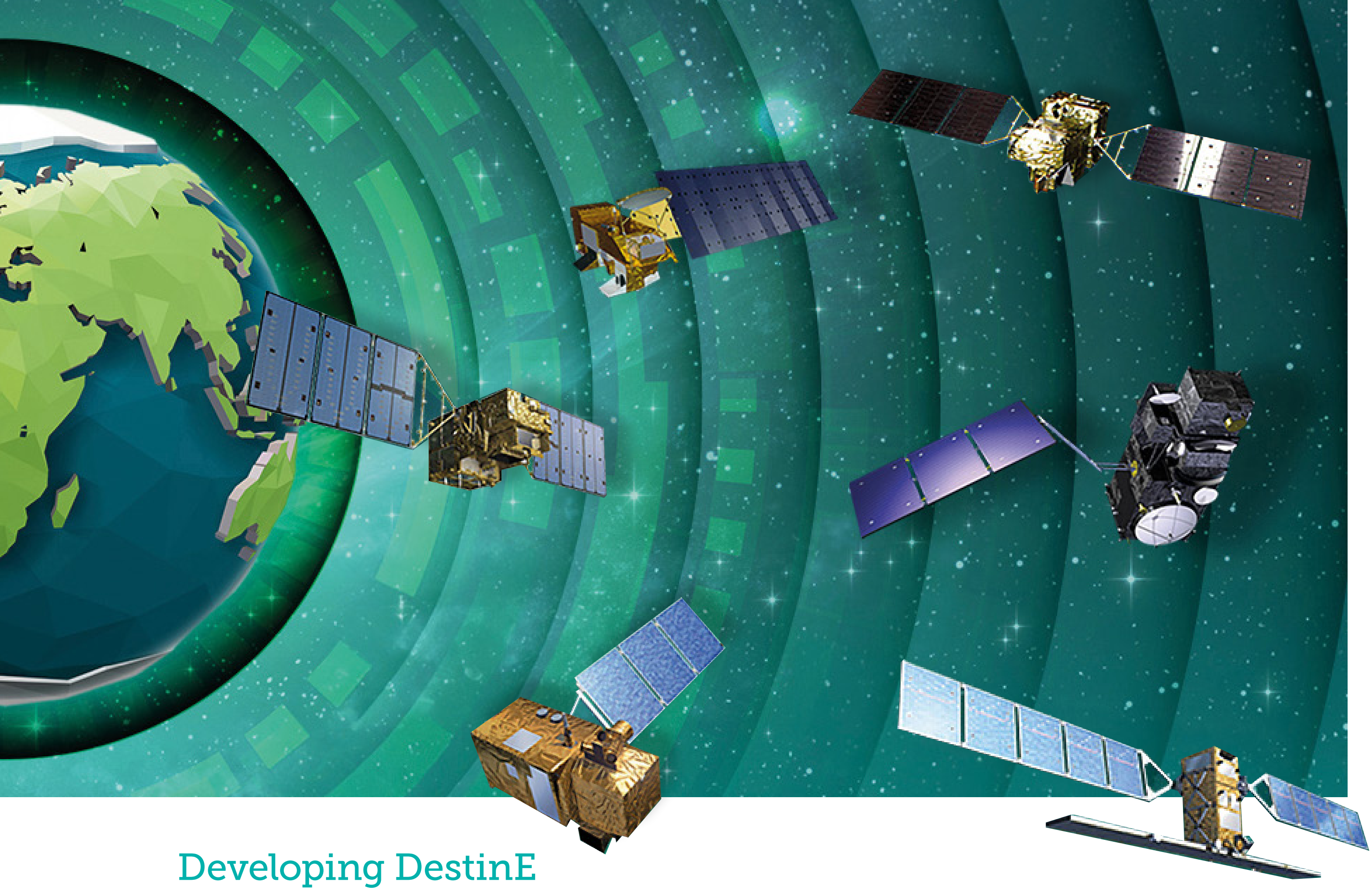
In cybersecurity for space, digital twins are used to create safe, simulated environments for real-time training and testing, as well as emulating functionalities that allows organisations to strengthen their defences without risking operational systems.

Destination Earth

In 2021, the European Commission (EC) launched a flagship programme called Destination Earth (DestinE), which is being delivered through a collaboration between EUMETSAT, ESA and the European Centre for Medium-Range Weather Forecasts (ECMWF). DestinE offers a highly accurate digital twin of the Earth to model and monitor the effects of natural and human activity on Earth. It enables users to anticipate extreme events and test and adapt policies addressing climate-related challenges. DestinE utilises an unprecedented amount of data, innovative Earth system models, AI, cloud computing, high-speed connectivity networks and data from multiple existing and new sources.

DestinE is designed to help scientists and policymakers understand the complex interactions that the environment and humans will play in shaping the Earth's future. It also forms a baseline for effective adaptation strategies in support of the green transition, helping the European Union (EU) reach its carbon neutral goal by 2050.

The DestinE core platform – the Data Lake – and the first digital twins have been made operational as part of the EC's Digital Europe Programme. Horizon Europe provides research and innovation opportunities that support the further development of DestinE. There are synergies with other relevant EU entities and programmes, such as the EuroHPC Joint Undertaking and the European Space Programme, as well as related national initiatives.



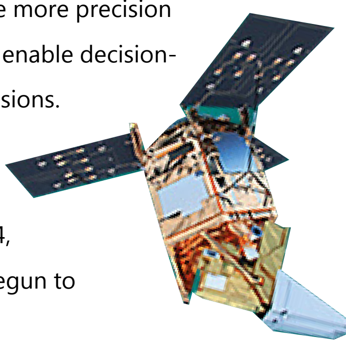
Developing DestinE

The main components of the DestinE system are:

- **DestinE platform**: evidence-based decision-making tools, applications and services, based on an open, flexible and secure cloud-based computing infrastructure.
- **Data Lake**: designed to enable efficient access and high-performance processing capabilities (including AI workflows) for a vast and diverse number of datasets. It allows discovery and data access as well as big data processing in the cloud.
- **Digital twins and digital twin engine**: digital replicas of the Earth system, using advanced simulations and real-world data. These models focus on different aspects of the planet to support better decision-making. At the centre is the digital twin engine – a powerful platform enabling high-resolution, data-driven simulations.

“I worked on the first ESA DestinE project, which started before the DestinE platform was available,” comments Starion’s Antonio Romeo, Project Manager for the DestinE Platform Use Cases project. “Starion was establishing the communication and stakeholder engagement for the whole DestinE initiative for ESA, although we were in contact with the organisations working on other parts of the programme. We also created the initial website for the DestinE portal, which switched to the main website platform in February 2025.

“Initially we had to identify a set of use cases that could show how DestinE worked in terms of technology, new datasets and how they could be used. We went through a procurement process following ESA’s procurement rules and ended up with five diverse use cases: two looking at urban resilience planning, one related to the polar regions and polar navigation, another referencing renewable energy and the last looking at sustainable fisheries. The commonalities are that they are all integrated into the DestinE platform, leveraging the technology in the Data Lake, maximising the use of digital twin data to provide more precision forecasting and ‘what if’ scenarios to enable decision-makers to make better informed decisions.



“Since the DestinE platform was opened to the public in October 2024, a growing community of users has begun to

form. User numbers are expected to rise significantly thanks to a set of general-purpose services that enable data visualisation, access and interactive exploration to test 'what if' scenarios. The first two available digital twins focus on enhancing our understanding and response to climate and weather-related challenges. One supports long-term climate change adaptation through climate simulations, while the other provides detailed forecasts and on-demand simulations of weather-induced extremes."

Antonio Romeo continues: "As more advanced services are integrated into the Data Lake platform, users will be able to generate more impactful predictions that bring real benefits to society. Take air quality, for example: by combining historical and real-time data with policy information, AI modelling and powerful computing resources, we can better understand both environmental and social impacts. The digital twin enables us to simulate different scenarios, helping us determine whether we're on the right path.

"Looking to the future, I believe digital twins could play an important role in simulating and supporting broader space missions. For instance, with innovative sensors, having accurate models of both the sensor and the Earth would allow us to virtually test their performance in space and identify potential issues before launch. An accurate model will enable us to simulate what could happen in orbit and how the sensors would work. Similarly, digital twins could be invaluable for future missions to Mars, allowing key aspects to be simulated on Earth, saving significant time, resources and budget. The potential for digital twins is truly exciting!"

Digital twins in cyber

Within cybersecurity, digital twins provide a different service. They offer a high-fidelity virtual/hybrid replica that can mirror both a system and the processes it supports, from information technology (IT) networks to operating technology (OT) assets, radio frequency (RF) links and mission flows. This offers a comprehensive system and process emulation, enabling the user to replay real-time telemetry, control logic and business workflows to produce a 'what if' analysis for training and testing purposes.

In cybersecurity, digital twins are used in three main ways: to train personnel in an ultra-realistic environment; to test systems safely, so failures don't compromise data or operations; and to emulate functions and behaviours to support research and development and study behaviour in operational contexts.

Simone Urbano, System Simulation Engineer – Security Services at Nexova, is working on a cybersecurity for space (CSS) project utilising digital twin technology. "Digital twins are used in the 'cybersecurity in space' domain to increase the resilience of space systems. We are currently working on a cooperative finance research project in Toulouse, France, to build a simulator of a constellation of CubeSats. The 3-year programme has several streams, and we are involved in the definition of the space system simulation, cyber threat intelligence and verification, and testing work packages.

"We started the project in 2023 and presented an initial simulation demonstration during the CYSAT 2025 conference in Paris. This project's environment is hosted on Nexova's Cyber Integration, Test and Evaluation Field (CITEF) platform, where we have uploaded a lot of different attack scenarios. We are also using open-source software, specifically NASA's NOS3, which is an operational simulator for SmallSats, and CryptoLib for the encryption layer.

"For the satellite, we are considering using specific data from a CubeSat mission – STF-1 – which was deorbited in February 2024. We aim to simulate all the Consultative Committee for Space Data Systems (CCSDS) standards for space communications, representing all the layers of communications between the ground and the satellite. The only aspect that is not represented is the radio frequency layer, which can be added at a later date.

In cybersecurity, digital twins offer a high-fidelity virtual/hybrid replica that can mirror a system and the processes it supports

"The CSS project aims to enhance the resilience of space systems against threats from the space environment. Our goal is to develop a simulation for a constellation of CubeSats, through which we can analyse and test potential vulnerabilities. We're building a library of attack scenarios and designing complex attack simulations to support this work. These efforts allow us to explore and develop innovative mitigation strategies that can be applied to real systems using the same architecture. Examples include a customised on-board intrusion prevention system or a hybrid approach that combines ground-based and space-based data to detect and counter emerging threats."

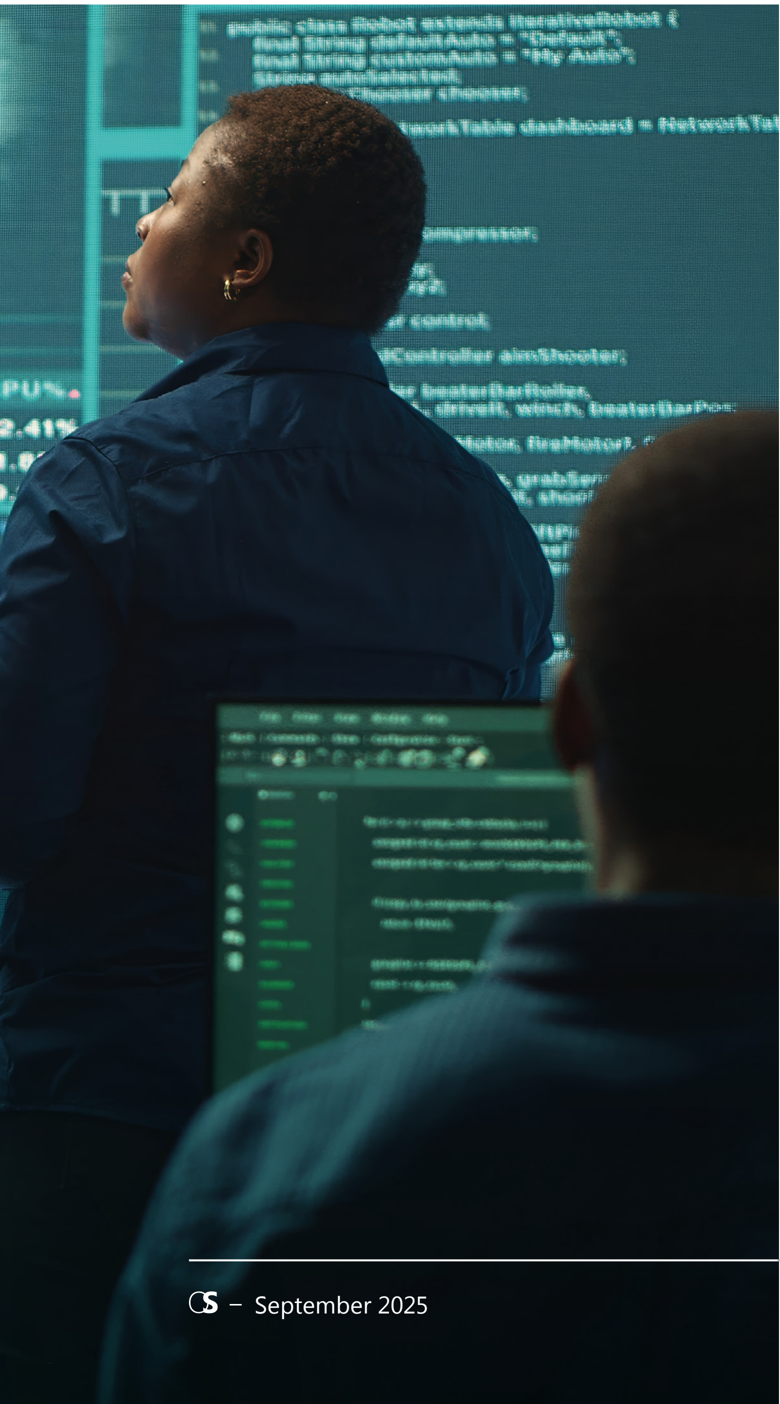
Protecting ESA's systems

Matteo Merialdo, Cybersecurity Principal at Nexova, has been working with ESA on several projects, and directly on ESA's cyber resilience for the past 4 years.

"We are investigating with ESA how to best use digital twin technologies to enhance cybersecurity. This could be to deploy a replica of a security operations centre [SOC] into a digital twin environment: for example, ESA's Security Cyber Centre of Excellence [SCCoE] cyber-range is based on Nexova's CITEF. Real data from the SOC is mirrored into the twin; this type of capability helps to predict the behaviours of the original system. It can enable operators to train, test

new features and systems, and support effective alert handling and threat investigation without affecting live operations.

"This is the one difference between an emulation and a digital twin. In the cybersecurity sense, using an emulation of Windows, Linux or other platforms, you can perfectly emulate a one-to-one scenario. By enhancing this with the original traffic copied and uploaded into the digital twin, the fidelity and representation of the live system is more realistic. The level of emulation can be tailored based on complexity, cost and schedule, demonstrating that the most important features and characteristics can be performed efficiently, while helping to provide hands-on, real-life testing and training facilities. Our target is to put in place a first proof of concept during 2026."



Where next?

Federico Antonello comments: "For ESA, the use of digital twins is expanding beyond operations to support pre-launch phases, providing users with realistic system representations, advanced simulations and predictive insights. In operational contexts, digital twins serve as a valuable tool for mission operators, enhancing situational awareness, validating procedures and supporting decision-making. A digital twin can also be an enabler for embedding AI tools that will leverage quality data and simulation models to provide precise predictions, improving prognostics, health management and assessment of the remaining life of a spacecraft.

"Digital twins strengthen digital continuity by enabling more automated and data-driven workflows. They also contribute to mission planning, testing and troubleshooting by offering high-fidelity virtual models that help reduce risks and improve autonomy."

For ESA and many other organisations across Europe, digital twins are proving to be essential tools for enhancing cybersecurity compliance. When applied to specific critical processes, they offer efficient testing, validation and training capabilities by replicating real-world conditions. They also play a key role in enabling detailed cybersecurity reviews and supporting conformity assessments across supply chains. As European cybersecurity regulations continue to evolve, these technologies will be increasingly vital in ensuring compliance and resilience.