

The Unsung Heroes of Space Missions

From the day a new space mission is conceived, it involves many people in different roles and an incredible array of hardware and software, resources, innovation and technology. Here we celebrate a few of the behind-the-scenes contributions that typically get little, if any, time in the spotlight. This includes tools essential for performing planetary flybys and the data archives that are the foundation of many of the important discoveries from the European Space Agency's (ESA's) science missions.

Think of any space mission and what comes to mind? Most likely it will be fiery launches, rockets arcing into space and celebrations in the mission operations room. Or maybe it's the incredible images of other planets, stars and distant galaxies. Behind the scenes, though, there are numerous individuals and brilliant technologies that rarely, if ever, get mentioned.

Many ESA science missions are one-off designs, which, when measured from initial idea to end of life, have lifespans sometimes of decades and involve hundreds of people and many companies. They rely on special software to support activities such as project management, system engineering, mission planning and operations, and for accessing and analysing the data the missions produce. All of this requires exceptional expertise on the part of the scientists and engineers who nevertheless may never appear in the coverage of a successful launch or during a mission.

The following are just a few examples of these unsung technological and human heroes that make space missions possible.

1 Ground segment

Underpinning every satellite mission is the ground segment – the Earth-based infrastructure that supports the operation, control and data handling of the satellite, ensuring the mission runs smoothly from launch to end-of-life. The large antennas and mission control rooms are familiar to all of us, but before these come into play, a team of specialist software engineers will have been working for many months or years to prepare the software that will eventually be used by the mission operations team to 'drive' the satellite. This includes planning the activities, sending commands and analysing the satellite's responses, enabling it to fulfil the mission's aims and sometimes even helping to rescue a mission when something goes wrong.





Image © Argotec

Teodoro Bonariol, Flight Operations Engineer at Argotec, which designs, manufactures and operates small satellites globally, says: “Our involvement as ground software engineers can begin months or even years before launch, sometimes as early as the mission proposal phase. At this stage, we help define the high-level architecture for ground tools and networks, ensuring that the future system will be flexible, robust and mission ready. This early engagement is crucial: it allows us to shape solutions that are tailored to the mission’s unique operational needs right from the early design phases.

“As the mission moves into design and development, we develop, test and validate the tools that will monitor, control and support mission operations. Our responsibility doesn’t end with the software delivery. Once the system is operational, we often become ground controllers ourselves, ensuring real-time software performance, reacting to anomalies, coordinating with external entities and maintaining the infrastructure that keeps the mission running smoothly.”

Ground segment software for satellite operations is not ‘plug and play’ because each mission or constellation

is different. “It needs to be adapted to the mission and the satellite, so the engineers will work in tandem with the mission development team to understand the needs and the requirements for the ground segment. This includes aspects such as which onboard software will be employed and which standards will be used on the satellite,” explains Pablo Beltrami, Programme Manager and Ground Segment Competence Lead at Starion. “Given that the ground segment software needs to be able to communicate with the onboard software, it’s typical that one or other will need to be adapted.”

Constellations and automation

The growth of satellite constellations adds another dimension, as does the drive towards increased automation. In terms of ground segment software, each mission may have its own instance. “But when you are operating many satellites at the same time, you don’t want to have to manually run the procedures for each one individually,” continues Pablo Beltrami.

“Automation is key and modern control systems are designed specifically to work with constellations, simplifying the operators’ tasks.” End-to-end

automation means that procedures can be prepared in advance, planned and commands sent automatically without the need for manual intervention during nominal operations.

“When dealing with satellite constellations, the operational complexity increases significantly,” explains Teodoro Bonariol from Argotec, whose Hawk for Earth Observation (HEO) constellation is using Starion’s Astral ground segment solution as part of its flight operations system.

“Supporting multiple spacecraft simultaneously requires robust, flexible and scalable tools. That’s why the selection and design of the ground segment software is a central focus from the very early phases of mission planning, continuing through development and testing. Our software must be able to adapt quickly to evolving needs, handle large volumes of data and support parallel operations across multiple satellites.

“Software specifically designed for constellations provides major advantages. It enables automation, efficient resource allocation and streamlined operations at scale. Most importantly, it allows us to manage multiple spacecraft with the same level of

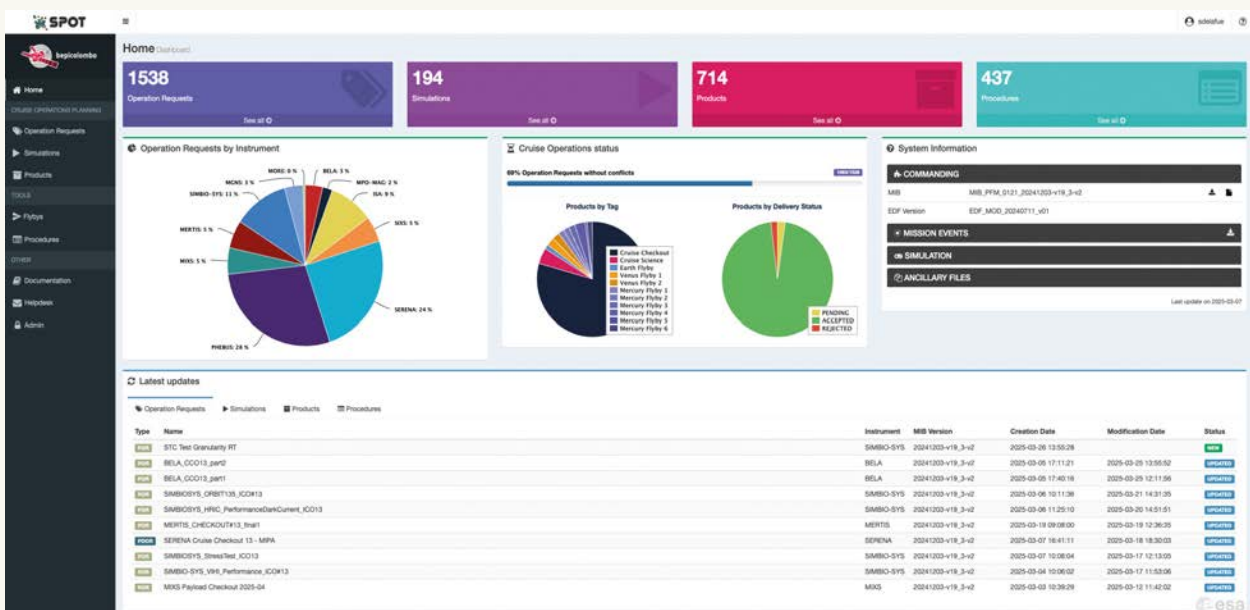
confidence and responsiveness as a single satellite – ensuring mission success, reducing operational overhead and increasing overall reliability.”

Even when the ground segment software is handed over to the mission operations team months before launch for preparing the mission and training, the software engineers remain involved to support and maintain it.

Teodoro Bonariol says: “Our work continues for the entire duration of the mission – this can mean many years of commitment, long after the initial excitement of launch. And even as we support current operations, we are already thinking ahead, creating new solutions for future missions.”

2 Supporting scientific payloads

Preparing and delivering commands to the science instruments (the payload) on board spacecraft is another fundamental part of ground segment mission planning. At ESA’s European Space Operations Centre (ESOC), these payload operations requests are part of a broader concept known as command request files



The Science Planning Operational Tool (SPOT) was created for the BepiColombo mission and has since been adapted for Juice.

(CRFs), which encapsulate various operational requests including telecommands, sequences, automation procedures and mission-critical events.

Starion's team of space science experts based at ESA's European Space Astronomy Centre (ESAC) in Spain developed a web-based framework to support payload operations teams for the generation and delivery of payload operations requests, which are a specific subtype of CRF: in this case for science activities during the mission's cruise phase. The CRF tool's design ensures seamless alignment with the mission's information database, which is integrated into the ESOC ground-based data systems.

The Science Planning Operational Tool (SPOT) Cruise was initially created for the BepiColombo mission, which is on its way to a final orbit around Mercury, the closest planet to the Sun in our solar system. It has subsequently been adapted for use with the Juice mission (under the name SPOT Juice), which is travelling in the opposite direction to study Jupiter and some of its icy moons.

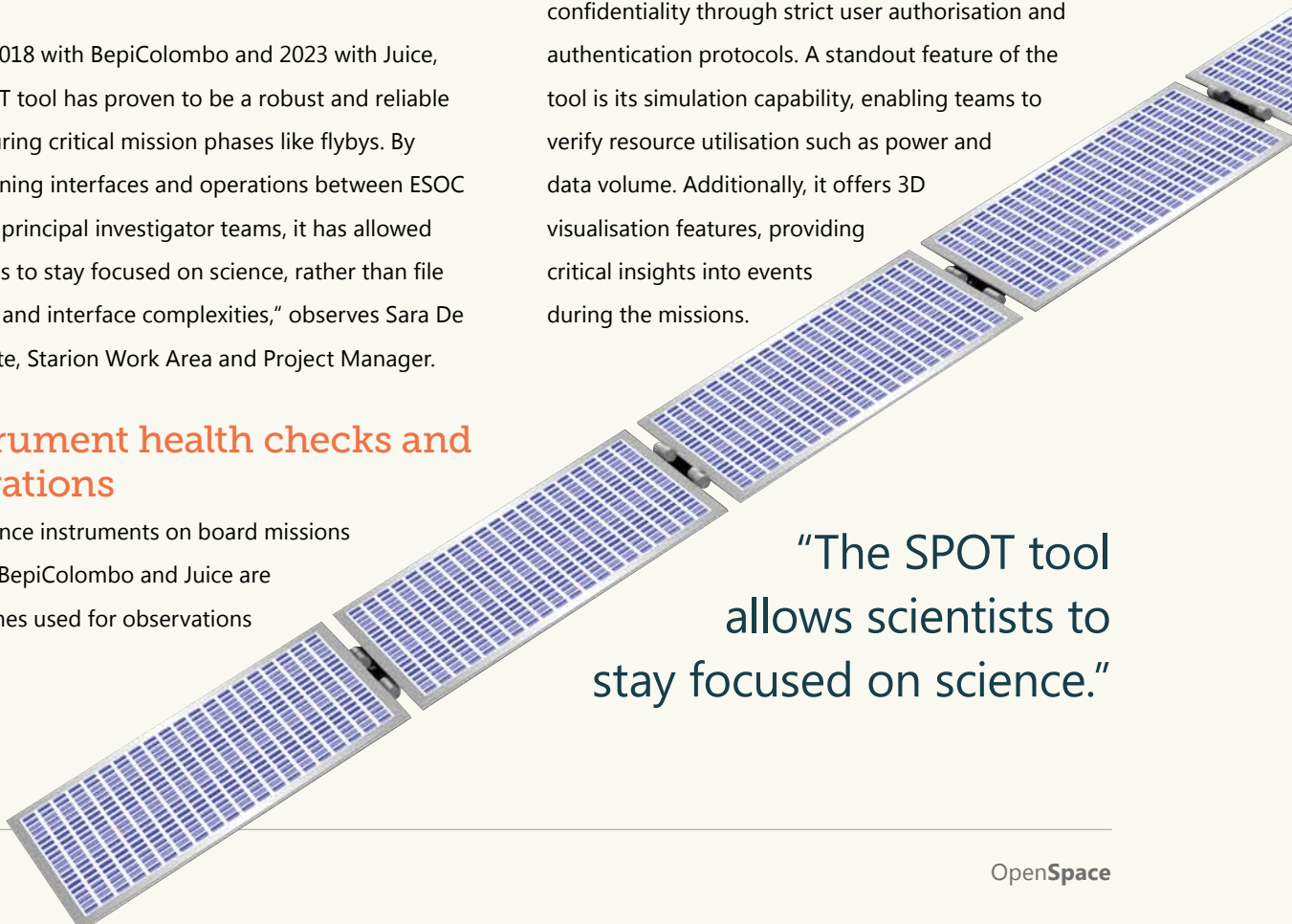
"Since 2018 with BepiColombo and 2023 with Juice, the SPOT tool has proven to be a robust and reliable asset during critical mission phases like flybys. By streamlining interfaces and operations between ESOC and the principal investigator teams, it has allowed scientists to stay focused on science, rather than file formats and interface complexities," observes Sara De La Fuente, Starion Work Area and Project Manager.

Instrument health checks and operations

The science instruments on board missions such as BepiColombo and Juice are sometimes used for observations

during the long cruise phase, for example during planetary flybys that adjust the spacecraft's trajectories to help them arrive at their final target, and SPOT is used to ensure the instruments are used to best effect during such flybys. But for the rest of the time they remain inactive, except for checkouts and dedicated cruise science activities. For space missions that have a long cruise phase, like Juice, which is due to take 8 years to reach Jupiter, it's important that the payload teams can be confident the instruments will work when a spacecraft reaches its final destination. Periodically, the instruments are checked using SPOT to make sure everything is working well. These payload checks typically take 3 to 4 days and are carried out approximately every 6 months.

SPOT was designed to streamline and centralise the workflow for scientific instrument teams. Users can efficiently manage operations requests by creating, cloning, editing, deleting and delivering them, all within a centralised, version-controlled environment. This approach not only enhances operational efficiency, but also ensures robust data privacy and confidentiality through strict user authorisation and authentication protocols. A standout feature of the tool is its simulation capability, enabling teams to verify resource utilisation such as power and data volume. Additionally, it offers 3D visualisation features, providing critical insights into events during the missions.



"The SPOT tool allows scientists to stay focused on science."



Sara De La Fuente summarises the advantages of using SPOT for payload operations: "SPOT significantly enhances efficiency and reliability by eliminating manual data handling, ensuring seamless integration with ESOC systems, and centralising data for secure, real-time access. With robust web-based monitoring and full compatibility with TM/TC Operational Database management, it streamlines operations and reduces both time and cost."

BepiColombo exploring Mercury. Image © ESA



3 Pointing in the right direction

During the nominal mission and special observation opportunities like flybys, the instruments don't only need to be operational and receiving commands, they also need to know where to look!

To support this, careful planning is vital to allow scientists to understand in advance what will be in the view of each instrument at any time. For ESA's planetary missions, this is handled by a team based at ESAC, who support planning for the flybys through their work on the operations of the SPICE geometry system software. The team receives an array of mission-related data, such as trajectory and attitude predictions, in different formats from multiple sources. These are converted into the SPICE format and distributed for use in tools used to prepare flyby operations and observations.

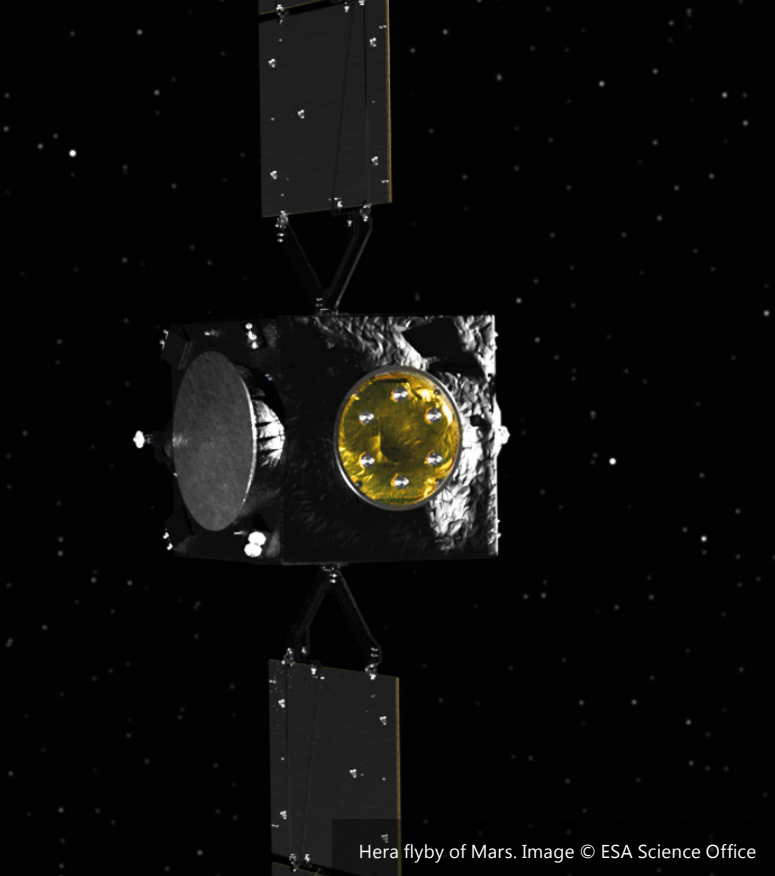
SPICE was originally developed in the 1990s by the Navigation and Ancillary Information Facility (NAIF) at NASA's Jet Propulsion Laboratory (JPL). Led by the Starion team, SPICE now provides the core of planning tools used for all ESA's planetary missions,

including the Cosmographia visualisation tool, which also originated from JPL's NAIF. The SPICE team is responsible for keeping both SPICE data and planning tools such as Cosmographia up to date and making geometry data for planning and analysing operations available to the science community.

"Cosmographia provides a powerful visual way to view the geometry data for missions such as Solar Orbiter as it holds both 'flown' telemetry data downloaded from the spacecraft and 'planning' or 'predicted' data," explains Starion's Alfredo Escalante Lopez, who is the Spice Work Package Manager at ESA. "This lets users see how the spacecraft's trajectory will change over time. More importantly, they can also use it to display the field of view of each instrument. For Solar Orbiter, for example, it enables them to plan an observation of a specific region of the Sun. It can also be used to see the position of spacecraft components, such as solar arrays and antennas, at any time."

Providing SPICE for the Hera flyby

Earlier this year, the SPICE team supported the Hera mission gravity-assist flyby of Mars, because scientists



Hera flyby of Mars. Image © ESA Science Office

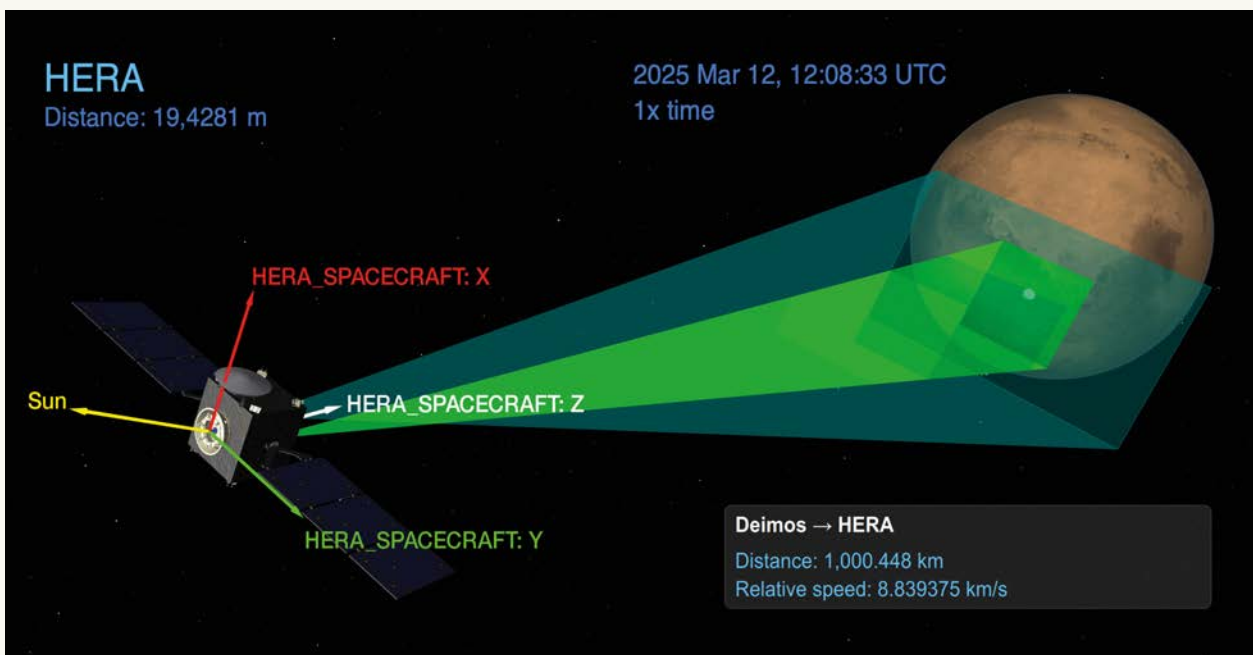
wanted to use the opportunity to study Mars' moon Deimos from close range and use that to calibrate Hera's instruments before it reaches its final target of the Didymos binary asteroid system.

In advance of the flyby, the SPICE software operations team took predictions of the spacecraft's trajectory and attitude from the mission's flight dynamics team and converted these into the SPICE format. This was

then made available to the spacecraft's instrument teams to help them plan an observation timeline for Hera's Asteroid Framing Camera (AFC), Thermal Infrared Imager (TIRI) and Hyperscout hyperspectral imager.

Alfredo Escalante Lopez recounts: "As the flyby happened, we analysed the images in real time, using telemetry and trajectory data given to us by the flight dynamics team, to support calibration of the instruments. By comparing the images with our original simulations made using the Cosmographia tool, we then provided SPICE data kernels to let the instrument teams correct issues such as misalignment or optical distortions that may have been caused by factors such as vibrations during launch, and optimise aspects like the image exposure times. Calibrating the instruments this way before Hera reaches Didymos will let scientists start making observations straight away when they reach the asteroids, saving precious time."

The use of SPICE is not limited to ESA missions. The SPICE service team has also been using it for constellation mission analysis prior to the launch of any of the satellites.



Cosmographia tool visualisation of Hera's flyby of Deimos showing the field of view of onboard instruments.

4 Exploring the archives

The ultimate goal of any space mission is to gather data that can be analysed and turned into useful information. To enable that process, the data needs to be stored and made accessible in useful formats. For ESA's space science missions, this takes place at the ESAC Science Data Centre (ESDC) in Spain, where a team of 50 scientists and engineers manage an exponentially growing volume of data.

"There's a lot of focus on the very visible rockets and the hardware flying in space, which are technological marvels. But there are also technological marvels that we build and manage quietly on the ground – essential to the success of science missions – that might be less known because of their behind-the-scenes nature," says ESA's Bruno Merín, Head of the ESDC.

"Our overall remit is software development, operations and maintenance of the science data archives. We start by gathering the scientific community's requirements and then implement them, but this isn't as simple as it may sound because from a scientific point of view, different scientific communities use data very differently, with their own standards and tools, and the types of data analysis they do. It's a lot more complex than people think."

The Archive team supports four scientific domains: astronomy, heliophysics (the study of the Sun, its influence on the solar system, and the space environment it creates), planetary science and, since 2018, human and robotic exploration. The latter includes aspects such as medicine and human biology on the International Space Station and material physics in low gravity. Each domain contains multiple individual archives.

"We have data from missions from the 1970s onwards and are preparing archives for missions to be launched in 10 or 20 years' time."

Digital Library of the Universe

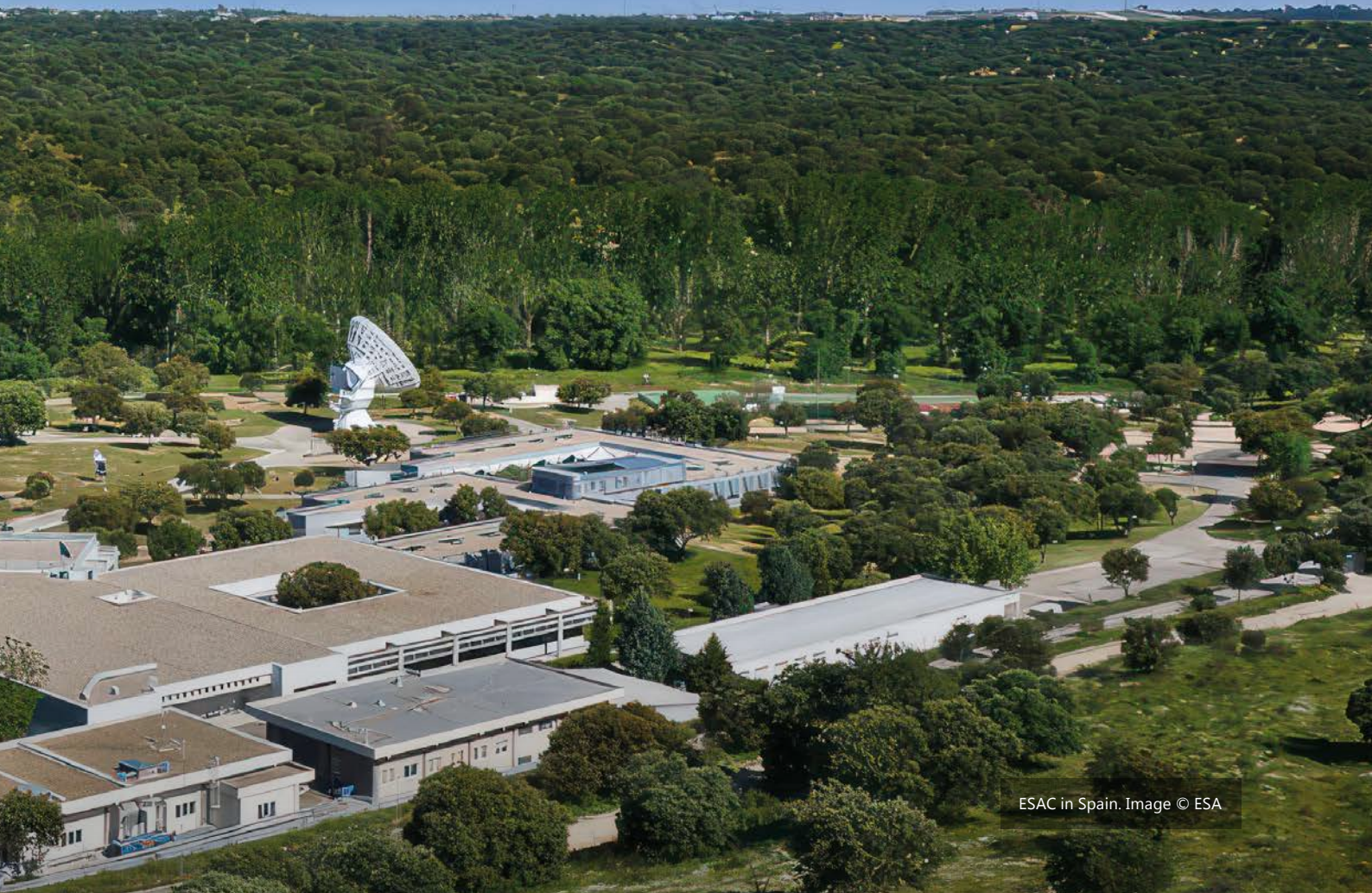
"We call the archive ecosystem the 'Digital Library of the Universe' because it contains data of many varied missions and scientific domains all in one place," adds Starion's Héctor Pérez, Archives and SPICE Software Development and Operations Work Area Manager. Starion leads the development, operations and maintenance of the archives. "With these different domains, the team here needs to have a lot of technical knowledge to understand the data and process it, and make it available in a way that scientists can easily find and exploit it. There's a huge effort going on to homogenise the look and feel of all the archives and web applications."

Not only does the Archive contain data from a broad variety of missions, but it also keeps data for every single science mission ever launched by ESA. "We have data from missions from the 1970s onwards and in

parallel we are preparing archives for missions that will be launched 10 or 20 years in the future," ESA's Bruno Merín notes.

This leads to one of the biggest challenges that the team faces, which is the ever-growing volume of data: partly because of additional missions and also because satellite downlinks are improving, gradually removing a traditional limit on the data that can be captured from a spacecraft. One mission in particular is starting to make a huge difference in this respect. The archives currently hold around 1100 terabytes (1.1 petabytes) of data, whereas over the next 5 years, the Euclid mission will boost that to over 20,000 terabytes (20 petabytes).

"This massive increase means we are having to completely redesign our systems, including our data centre," says ESA's Bruno Merín. "It's not just about storing all the extra data but designing it so that it



ESAC in Spain. Image © ESA

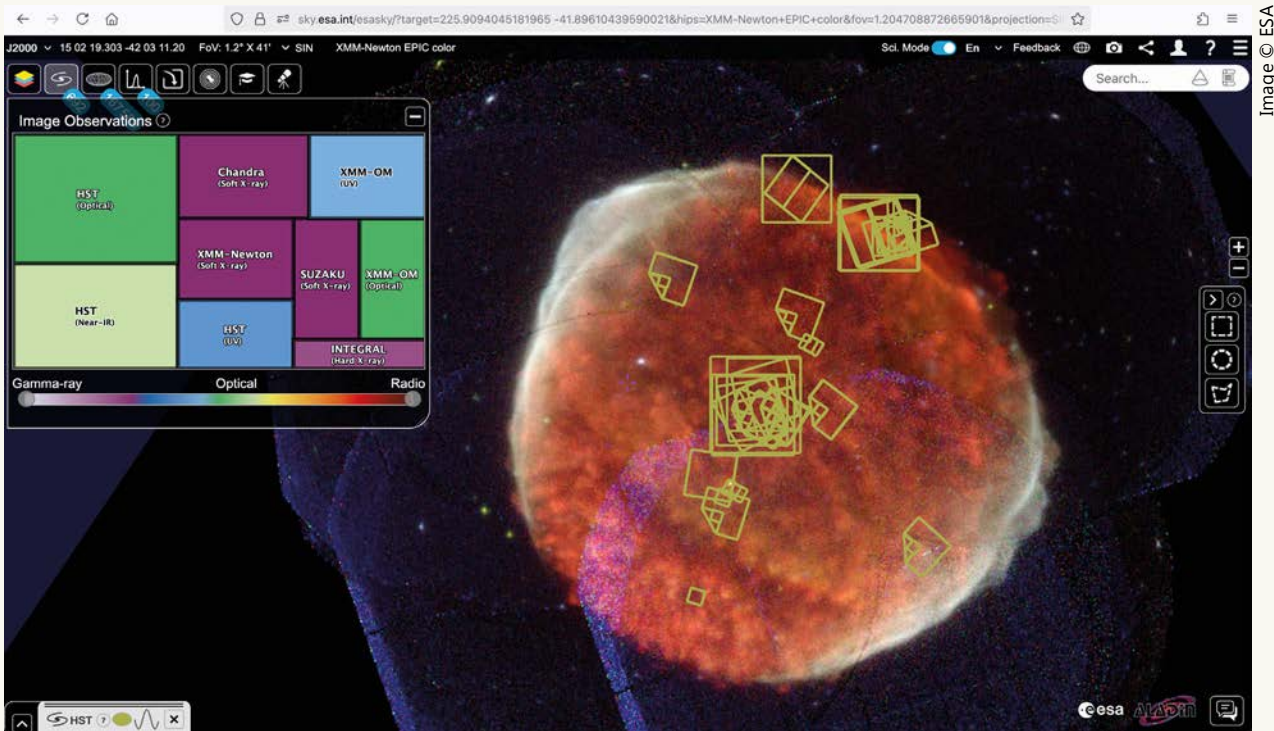


Image © ESA

Remnant of supernova SN 1006, believed to be the brightest stellar event in history, seen by XMM-Newton and viewed in ESASky.

is still failproof. We are about 80% of the way there, though there are still details to resolve.”

Starion’s Héctor Pérez adds: “Another issue is the amount of data that is going to be travelling across our network. Previously users would download a product from the archive and it may not even have been as big as 1 gigabyte. But if they want products for Euclid, they will be way bigger: too big to download to their machines. So it changes what we provide and means we have to change the mindset of users too, who will instead be able to analyse the data in cloud-based platforms.”

Viewing the universe through ESASky

What often goes unrecognised is that the archives are available for anyone to access, including via the graphical ESASky tool. And yet they lie behind an enormous number of scientific discoveries. A recent analysis showed that between half and three-quarters of the scientific knowledge from ESA’s space missions came not from those who built the instruments flying on individual spacecraft or who requested observations

or measurements, but from people accessing the archives, analysing the data and publishing papers showing their findings.¹ The analysis also shows that the archives remain highly scientifically productive for 20 or more years after the end of mission operations when the original instrument and science operations teams may no longer be operational.

“It’s important that people realise all this data that has been collected over decades is open for them



ESA’s XMM-Newton has been studying hot and extreme aspects of the universe using three x-ray telescopes since 1999. Image © ESA - D. Ducros


to inspect, download, analyse and play with, if they want. Anyone can use ESASky to see images from missions such as the Hubble and James Webb telescopes, and any other science mission,” says ESA’s Bruno Merín.

“There’s an important difference between hardware and software that most people don’t realise,” Bruno continues. “With hardware, once the human effort has been put in, the value really lies in the hardware itself. But the value of software lies with the people who made it and continue to support it, because the software evolves and grows almost like a living being. Rapid technological developments mean the way humans interact with information evolves quickly and we have to keep up with this. For example, 5 years ago, artificial intelligence [AI] was science fiction but now there’s a growing demand for us to understand and respond to the demand for scientists to use AI. And that’s just one example.”

Sources: See page 86



Here’s to the unsung heroes

These examples are just a small selection of the many people and technologies that lie behind orbiting satellites and successful science missions. But they serve to show how complicated space missions are and how important each piece of the jigsaw is – and the value of each person involved. Nothing is static, however, so these contributions will change over time, not least thanks to the value that will be added by AI. OpenSpace salutes the unsung heroes who are developing those new capabilities and who toil behind the scenes of each mission in so many ways. 

What’s in the ESAC Science Data Centre archives?

Astronomy observation and surveys

Astronomy observation missions typically point at a target in the far distant sky to capture specific images. Survey missions scan the sky to create a map of a certain feature, such as our universe, the Milky Way (Gaia) or all the features (Euclid).

Missions include: Cheops, Euclid, Gaia, Hubble Space Telescope, XMM-Newton, James Webb Space Telescope, Herschel, ISO, Planck, Exosat, Integral and LISA Pathfinder.

Planetary observation

Primarily missions studying planets, their moons and other solar system bodies such as comets.

Missions include: BepiColombo, Juice, ExoMars, Mars Express, Rosetta, Huygens, Venus Express.

Heliophysics

Any missions studying the Sun directly or related phenomena such as the solar wind.

Missions include: Solar Orbiter, SOHO, Ulysses, Cluster, Proba-2 and Double Star.

Human and robotics exploration

Investigations funded and co-funded by ESA’s Directorate for Human and Robotic Exploration performed on microgravity and ground-based facilities, plus a spectrometer on the International Space Station.

ESASky

A science-driven portal providing access to imagery observed by ESA’s space astronomy missions plus those of its partner agencies. Access ESASky at: sky.esa.int/esasky/