→ JULES VERNE'S JOURNEY FROM EARTH TO ISS

ESA's first space ferry

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With a perfectly controlled re-entry high above the Pacific Ocean on 29 September, ESA's *Jules Verne*, the first of five Automated Transfer Vehicles (ATVs), successfully completed its six-month inaugural mission – proving itself as Europe's space supply vessel.

Launched on 9 March 2008 on a modified Ariane-5, the most challenging and complex space vehicle ever developed by ESA has met all its objectives, with flying colours. Named after the visionary French author, ESA's first space ferry has ushered in a new era for European space transportation, achieving a milestone for human spaceflight and space exploration.

Together with Russia's Progress and the NASA Space Shuttle, the ATV has become the third spacecraft type with the capability to resupply the International Space Station (ISS) on a regular basis. The ATV cargo capacity is about three times that of Progress.

On 3 April, ATV *Jules Verne* became the first spacecraft ever to self-navigate in orbit and control its own rendezvous with a manned space station, based solely on the use of relative GPS and optical sensors. This unique capability of autonomous rendezvous is the main difference between ATV and Russian Soyuz and Progress spacecraft; ATV relies solely on its on-board sensors for the final approach, the Russian vehicles need data provided by the ISS radar sensors in addition to their own sensors. All US rendezvous and dockings in space have been performed manually and visually by astronauts.

Jules Verne then completed all its resupply tasks for the ISS and also provided propulsion support to the Station, such as giving it regular reboosts and even an unexpected debris avoidance manoeuvre for the 300-tonne orbital outpost.

Looking beyond 2010, when Shuttle flights are scheduled to end, the ATV is poised to become an even more critical and indispensable contribution for the Station and for the ISS partners. Moreover, the ATV is currently the only space vehicle capable of deorbiting the ISS at the end of its life. Together with the launch of ESA's Columbus multi-purpose science laboratory earlier this year, the success of the ATV means that Europe becomes a fully fledged partner of the ISS.

The ATV enables Europe not only to transport its own payload to the ISS, but also to carry propellant, gases and other goods for use by the entire ISS and its partners. It also ensures the delivery of experiments and scientific equipment to Columbus.

The five ATV missions are intended to cover in kind the European share of the common operational costs of the ISS, in the same 8.3 % contribution Europe has in the ISS programme. In particular, they allow a European astronaut to live and work aboard the station for six months every two years without any exchange of funds.

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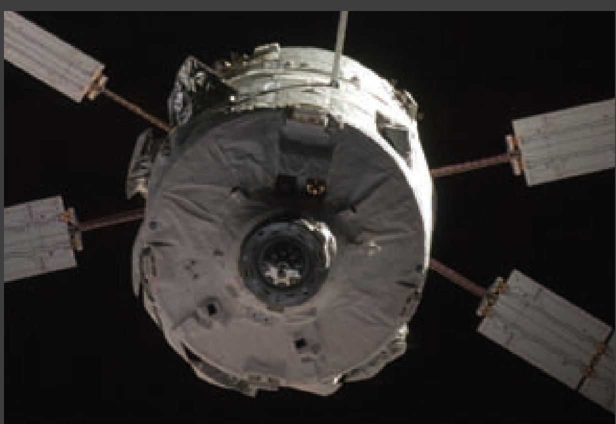
A close-up view of ATV taken from the ISS, with one of the partially detached thermal blankets visible on the left



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ESA's ATV compared to the Russian Progress Spacecraft

The mission

The first ATV rendezvous attempt with the ISS demanded strict safety protocols. Rendezvous operations were designed so that each critical step of the rendezvous would be demonstrated at a safe distance from the ISS before proceeding with the final approach. For each of these steps, the performance was reviewed by a dedicated team of NASA, RSC Energia and ESA experts.

The launch took place exactly as planned. Lifting twice its usual payload mass, the Ariane-5 upper stage performed an initial eight-minute burn over the Atlantic Ocean and entered a 45-minute coast phase, flying over Europe and Asia before reigniting for a 40-second circularisation burn over Australia. *Jules Verne* was delivered into the planned 260-km altitude orbit, and the critical early automatic operations to secure power autonomy (deployment and orientation of solar panels) were carried out as planned as the vehicle gently stabilised itself.

About two hours into the flight, a problem in the pressurisation of the propellant lines triggered the ATV on-board Failure Detection, Isolation and Recovery system. This failure management software executed its job correctly, switching to a back-up pressurisation device and shutting down one of the four propulsion chains after detecting a temporary discrepancy in pressure between the system's fuel lines and its oxidiser lines. An engineering investigation confirmed immediately that this problem would not affect the *Jules Verne* mission: it would be fixed for future ATVs.

During the free-flight phase, telemetry data indicated a thermal anomaly on the Integrated Cargo Carrier (ICC) shell and much higher than normal activity with some shell heaters. Engineers quickly concluded that several heat leaks existed on the ICC shell. The suspected cause was a partial detachment of the multi-layer insulation thermal blankets around the ICC cylinder. Because the thermal and power situation remained acceptable, this was not considered to be a problem and the mission continued normally.

→ History of ATV

For more than a decade, ATV has involved thousands of high-tech workers in dozens of companies from ten European nations under the prime contractor EADS Astrium. The top contractor companies include Thales Alenia Spazio, Contraves Space, Dutch Space, Snecma, Alcatel Espacio, Crisa and MAN. Eight Russian companies were also involved, with the main contractor, RSC Energia, in charge of providing 10% of the ATV development (docking and refueling systems and assorted electronics).

For the first time, the new ATV Control Centre (ATV-CC) in Toulouse acted as the lead Mission Control Centre in charge of man-rated operations for the ATV, while the Mission Control Centres in Moscow and Houston supported and authorised the rendezvous to the ISS. From 2008, a team of 80 people from the French space agency CNES, Astrium and ESA based in Toulouse will now coordinate all ATV operations on behalf of ESA for the next four ATVs planned until 2015.

1994 - 111th ESA Council in Paris agreed to the Manned Space Transportation Programme, including ATV.

1995 - The Ministerial Council in Toulouse formally approved full programme development.
Ten countries (France, Germany, Italy, Switzerland, Spain, Belgium, Netherlands, Sweden, Denmark, and Norway) commit to developing the Columbus laboratory and ATV, a new generation of spacecraft combining the fully automatic capabilities of an unmanned vehicle with human spacecraft safety requirements.

1998 - Full development contract signed with Aerospatiale, now EADS Astrium. Europe and Russia reach a general agreement on the integration of ATV into the Russian segment.

2000 - Manufacturing starts for the first ATV hardware, and a full structural mock-up is put through its paces at ESTEC, Noordwijk, The Netherlands.

2002 - ATV Service Module integrated with the Avionics and Propulsion module at Astrium in Bremen, Germany. The pressurised Cargo Carrier module, the ATV's forward half that provides cargo storage and a workplace for the astronauts, is built at Thales Alenia Spazio, Turin.

2003 - The Service Module and Cargo Carrier are first integrated in Bremen. The project passes the Critical Design Review, in which some 140 international space experts analyse 55,000 pages of technical documentation before announcing their full confidence in the vehicle design. This review certifies that the ATV design and operations concept meet requirements for performance, reliability, and safety. The Functional Simulation Facility (FSF) starts to test the ATV's electronic 'brain' and flight software in computer simulations at EADS Astrium, Les Mureaux.

2004 - ATV is transferred to ESTEC for extensive acoustic, thermal, electromagnetic and functional qualification tests.

2006 - Small technical problems occur in the processing of Jules Verne, including a minor fatigue failure on a propulsion valve and an anomaly on the drive mechanism of the solar arrays. In addition, the FSF testing does not progress as fast as planned. These discoveries had a cascade effect on the schedule, but other issues, especially after the Shuttle *Columbia* accident in 2003, add another year of delay. However, this is common in such ambitious and innovative projects.

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→ History of ATV

2007 – ATV is shipped to Europe's Spaceport, Kourou, French Guiana, ready for launch.

2008 – ATV is transported to the Final Assembly Building, where it is installed on top of the launcher on 13 February. On 25 February, the fairing is closed over *Jules Verne*, ready for launch.

Later, photos taken by the ISS crew confirmed the problem to be with the attachment of the external thermal blankets. Measurements of temperature inside the cargo carrier by the crew later confirmed the robustness of the system against any thermal problem such as condensation. Simple measures are underway to prevent similar problems on future ATVs.

Approach and docking

Five days after launch, and far away from the ISS, *Jules Verne* successfully demonstrated the Collision Avoidance Manoeuvre (CAM), which consisted of braking the orbital speed by 5 m/s, then stabilising the spacecraft in a safe orbit, in a minimal 'survival' mode pointing at the Sun, using a completely independent functional chain.

The CAM demonstration was necessary to prove, before the first approach to the Station, that the spacecraft could reliably move away from the ISS in case of major system problems during the final rendezvous. In case of safety-critical situation, which could not be handled by the nominal

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Volkov and Kononenko transferred 1150kg of dry cargo from *Jules Verne* to the ISS

two-failure control system, the spacecraft's Monitoring and Safing Unit is designed to isolate the ATV's nominal systems and initiate this manoeuvre.

Due to other traffic to and from the ISS, the free-flight phase was extended from 10 to 25 days before docking. This allowed NASA to launch the Shuttle *Endeavour* on a 16-day mission carrying the first element of the Japanese Kibo science lab and demonstrated the flexibility of the complete system. For future ATV missions, docking with the ISS will happen much earlier.

The mission plan then called for three successive approaches. A more elaborate 'escape' manoeuvre, than the CAM test, was planned for each of the first two approaches. These manoeuvres were to demonstrate that the ATV could safely back away from the Station during the rendezvous if it could not be completed, but with a still controllable vehicle without going into 'survival' mode.

The first approach (called Demo Day 1) on 29 March, demonstrated that the ATV could automatically calculate its position and manoeuvre with respect to the ISS using relative GPS navigation. It performed the 'escape' manoeuvre some 3500 m behind the ISS. Two days later, on Demo Day 2, the second approach tested close-proximity manoeuvring and control, including contingency manoeuvres for both the ATV Control Centre and the crew aboard the ISS. This required that the ATV first approached within 20 m of the ISS using its innovative optical proximity sensors, retreated, and then reapproached to only 12 m from the docking port of the ISS Russian module before again backing off to a safe 20 m. This last approach provided ultimate proof that Europe's resupply vessel was ready for final and safe rendezvous and docking.

During the third approach, leading to the first planned docking attempt, *Jules Verne* paused as planned at 250 m, 20 m and 12 m guided solely by its on-board high-precision optical navigation system. Jules Verne closed in with the ISS at a relative speed of 1.4 km/h, slowing to 0.2 km/h while both spacecraft were flying in close formation at an absolute speed of 28 000 km/h. It successfully docked with the ISS on 3 April at 16:41 CEST (14:41 UT), 341 km above the southern Atlantic Ocean, just south of the equator and east of South America.

The final phases of approach and docking were monitored under the watchful eyes of ISS Commander Peggy Whitson and Flight Engineer Yuri Malenchenko. "Right now the vehicle can be seen clearly. It's lit by the Sun," said Malenchenko, just before the two spacecraft docked. With *Jules Verne* securely attached, the ISS crew entered the pressurised cargo section and started to remove the payload.

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Expedition 17 crew Greg Chamitoff, Oleg Kononenko and Sergei Volkov retrieve original 19th century Jules Verne manuscripts. Because of its comfortable size, ATV was used by two of the crew as a new area to sleep and wash

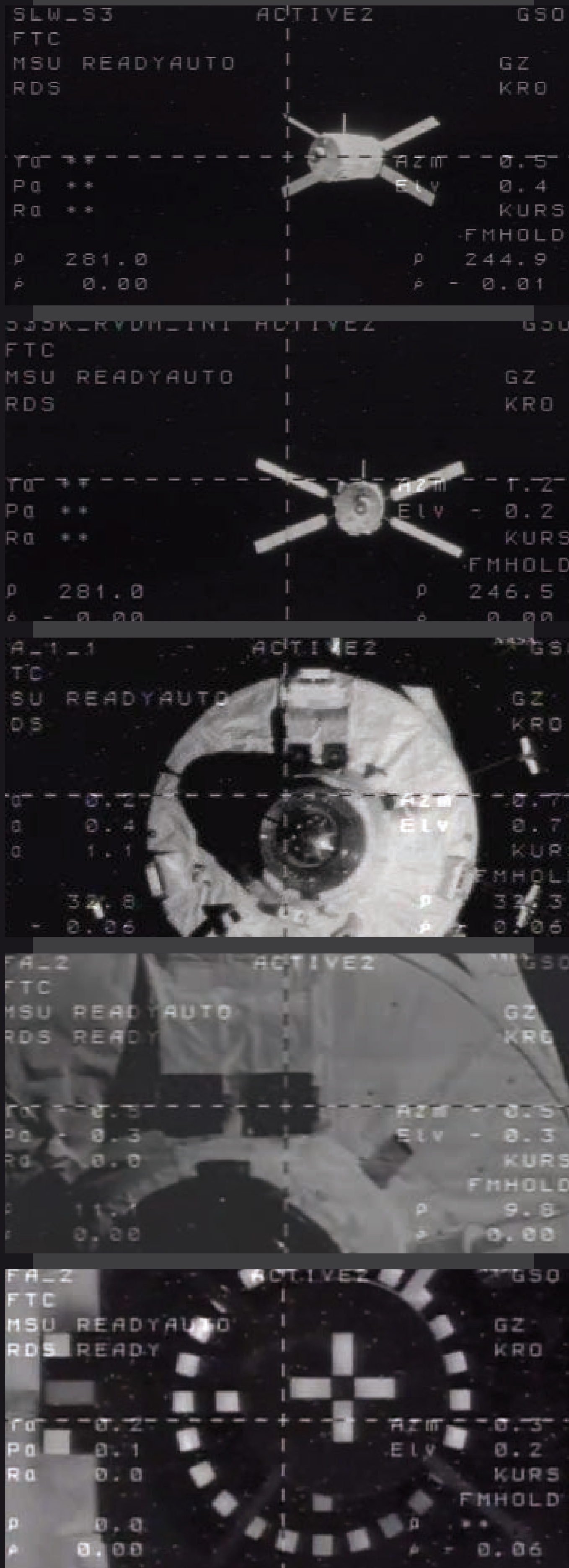
→ Docking in detail

For the first time, a supply vessel navigated as if it was 'on rails', flying straight to its moving target with an amazing accuracy superior to any manual piloting by astronauts. The position of the ideal centreline of the docking probe at the moment of docking has been estimated from telemetry to have been within 1–2 cm.

With its on-board capability to handle any combination of two failures and its one million lines of software code, Jules Verne used two types of optical sensors to guide this precise trajectory. The ATV videometer sensor analysed images of its emitted laser beam, reflected by passive reflectors located on the ISS near the Russian docking port reserved for the ATV. During the last 250 m of final approach, the videometer automatically recognised the reflector's target patterns and measured distance, position and closing rate, and finally the relative orientation of ATV to the ISS. As an extra precaution, distance and direction to the docking port were monitored based on another independent optical sensor, the telegoniometer.

During this 'clockwork' approach, Jules Verne stopped as planned at four holding points, waiting each time for a 'go' from the ground controllers to move to the next step. The automatic pilot had to respect the strict rendezvous safety corridors. These consist of a narrow virtual 'funnel' within which the ATV must stay or else an automatic escape manoeuvre would be triggered to prevent any risk of uncontrolled collision with the ISS.

In the highly unlikely case of multiple failures, exceeding the design requirements (i.e. more than two major failures), the ISS crew could also activate four types of pre-programmed actions to interrupt the ATV's approach.



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A sequence of images taken from the ISS TV camera monitoring the docking of ATV on 3 April, showing the spacecraft approaching the ISS

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Expedition 16 and 17 crew members inside ATV: Garrett Reisman, Peggy Whitson, Yuri Malenchenko, Sergei Volkov and Oleg Kononenko

The ATV's fuel tanks were connected to the plumbing system of the ISS, and the three ISS crew members, Sergei Volkov, Oleg Kononenko and Greg Chamitoff, manually transferred 269 litres of water and released 21 kg of oxygen directly into the ISS.

In June, the entire 811 kg cargo of refuelling propellant was automatically transferred to ISS. In August, the crew moved dozens of white cargo bags from the ATV, as well as two original manuscripts handwritten by author Jules Verne and a 19th century illustrated edition of his novel *From the Earth to the Moon*.

The crew also worked hard carrying items in the opposite direction, loading waste and excess equipment from the ISS into the racks and spaces left empty inside *Jules Verne*. The total dry cargo waste loaded into ATV represents 900 kg of material no longer needed on the ISS. On top of that, 264 kg of liquid waste was transferred from the ISS to the ATV in foldable plastic containers.

For five months, *Jules Verne* was a 48 m³ pressurised and integral part of the ISS, and had boosted the ISS orbit to overcome the effects of residual atmospheric drag four times.

Departure and reentry

The undocking of the ATV concluded the historic five-month attached phase of the Jules Verne mission. The ATV Control Centre sent the commands to open the hooks of the ATV, which then performed a fully automated undocking, on 5 September at 23:30 CEST.

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Image received from the DC-8 aircraft which observed the reentry of ATV over the Pacific Ocean

A few weeks later, on 29 September, *Jules Verne's* main engines used their remaining fuel in two separate deorbit boosts to terminate its three-week last solo flight. The 13.5-tonne spacecraft fell on a steep flight path, performing a controlled destructive reentry high above an uninhabited area of the South Pacific Ocean. Planning this event for the nighttime allowed the reentry to be observed by two aircraft equipped with a collection of NASA and ESA scientific experiments. The ISS crew was also able to observe the reentry with the Russian FIALKA ultraviolet and spectrometric instrument.

The success of *Jules Verne*

All *Jules Verne's* mission objectives were fulfilled, including all demonstration tasks specific to this first ATV flight. Preliminary post-flight assessment showed that *Jules Verne's* performance was well within predictions, and even better in certain cases, such as propellant consumption and the performance of the power system. After assessment of mission operations, very few design features have to be fine-tuned for future ATVs.

The ATV's pressurised cabin offered the crew a large space and a lot of additional privacy. Some crewmembers also enjoyed *Jules Verne* as their sleeping quarters or as a crew hygiene station to wash using their usual wet fabric towels and treated napkins. Last April, the ATV was also used by Yi So-Yeon, a nanotechnology engineer and the first South Korean astronaut, to perform experiments during her 11 days in space.

For the following ATVs, the capabilities will be slightly increased by improving the specifications for launch mass (20.7 tons) and cargo (7.5 tons). To ensure maximum flexibility for this demonstration flight, *Jules Verne* had carried more propellant and slightly less payload than on future ATV missions. In fact, future ATVs will carry at least one ton more than *Jules Verne*.

The future

With today's ATV technology, ESA has gained the capability for automatic rendezvous between spacecraft, which is crucial for future human planetary exploration, complex spacecraft assembly and robotic sample-return missions. The ATV is the largest automatic freighter ever built and, if future demands require, it could also evolve to carry tons of supplies into lunar or planetary orbit and beyond.

With the Space Shuttle retirement planned for 2010, the ISS partners will lose a major capability to transport crew into space and return experiments and equipment to Earth for exploitation or replacement. The next logical step for ATV would be to develop the capability to return payloads and goods from the ISS, with a final aim to develop a new crew space transportation system, based on an adaptation of the Ariane-5 launcher for manned spaceflight.

One possibility for cargo return could be to replace the pressurised ICC with a large cargo re-entry capsule with a thermal reentry shield, able to bring back hundreds of kilograms of cargo and valuable experiments. Such a project could use the flight-proven technologies of the ESA Atmospheric Reentry Demonstrator, which flew successfully in 1998.

The main advantage of such a vehicle is that its service module could be derived from the present ATV spacecraft, with the necessary adaptations. What remains is the development and qualification of the front part of the vehicle into a new reentry capsule.

Once the operational capability of bringing back cargo from space will have become routine, such a space freighter would boost confidence in continued ATV evolution. Its operational flights would also contribute to the flight qualification of a future European manned transportation system. The final step would then be a crew transportation system, which would require more complex modifications.

The upper part would be transformed into a manned reentry capsule with the addition of all the subsystems required for protection and support of a crew. This second-step vehicle would require additional developments in flight safety, especially for the launch (launch escape system) and life support. A significant difference with the cargo-only variant would be the presence of this Crew Escape System, consisting of booster rockets able to pull the crew capsule away from the launcher in the event of an emergency. The crew variant of the ATV could seat four crew members.

Today, the ATV is already the most powerful space tug ever built. If required, in future programmes the ATV spacecraft could also evolve to be used as a transfer vehicle, carrying infrastructure elements and tons of supplies into orbit, including crew habitats and orbital infrastructures for successive assembly in low Earth orbit, in preparation for missions to the Moon and beyond. ■

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Martial Vanhove, CNES Flight Director for undocking, Kris Capelle, ESA Mission Director for undocking, and Hervé Come, ESA ATV Mission Director, celebrate after a successful departure from the ISS (F. Castel)

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ATV *Jules Verne* seen from the ISS after undocking, beginning 23 days of rephasing manoeuvres to prepare for reentry