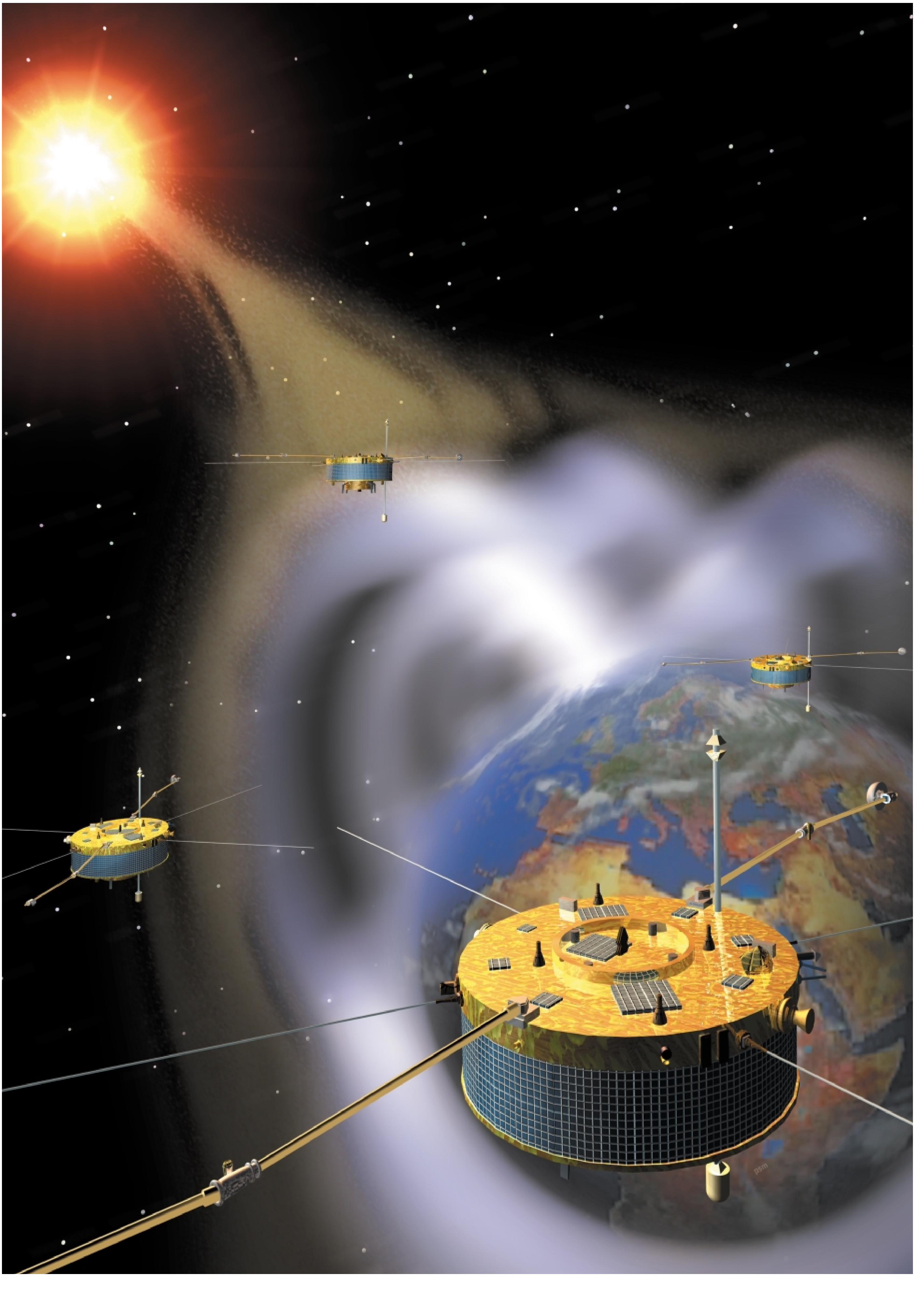

The Cluster-II Mission
– Rising from the Ashes

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Four years ago, the first Cluster mission was lost when the maiden flight of Ariane-5 came to a tragic end. Today, through the combined efforts of the ESA Project Team, its industrial partners and collaborating scientific institutions, the Cluster quartet has been born again. A two-year programme of investigation into the Sun-Earth connection will begin this summer when ESA's Cornerstone mission to the magnetosphere lifts off from Baikonur. Flying in formation over the Earth's polar regions, Cluster-II will carry out the first three-dimensional exploration of near-Earth space ever attempted.

In June and July of this year, four Cluster-II spacecraft will be launched in pairs from Baikonur Cosmodrome in Kazakhstan (Fig. 1). If all goes well, these launches will mark the culmination of a remarkable recovery from the tragic loss of the original Cluster mission.

In June 1996, an explosion of the first Ariane-5 launch vehicle shortly after lift-off destroyed the flotilla of Cluster spacecraft. Now, just four years later, this unique Cornerstone of ESA's Horizons 2000 Science Programme has been rebuilt and is ready to complete the mission to the magnetosphere planned for its predecessors.

From concept to reality

The Cluster mission was first proposed in November 1982 in response to an ESA Call for Proposals for the next series of science missions. It grew out of an original idea from a group of European scientists to carry out a detailed study of the Earth's magnetotail in the equatorial plane. This idea was then developed into a proposal to study the 'cusp' regions of the magnetosphere with a polar orbiting mission.

The Assessment Study ran from February to August 1983 and was followed by a Phase-A definition study, which was presented to the scientific community in late 1985. At this time, the proposal included one 270 kg 'mother' spacecraft, carrying 46 kg of scientific payload, together with three smaller companions, each weighing 217 kg and carrying a payload of

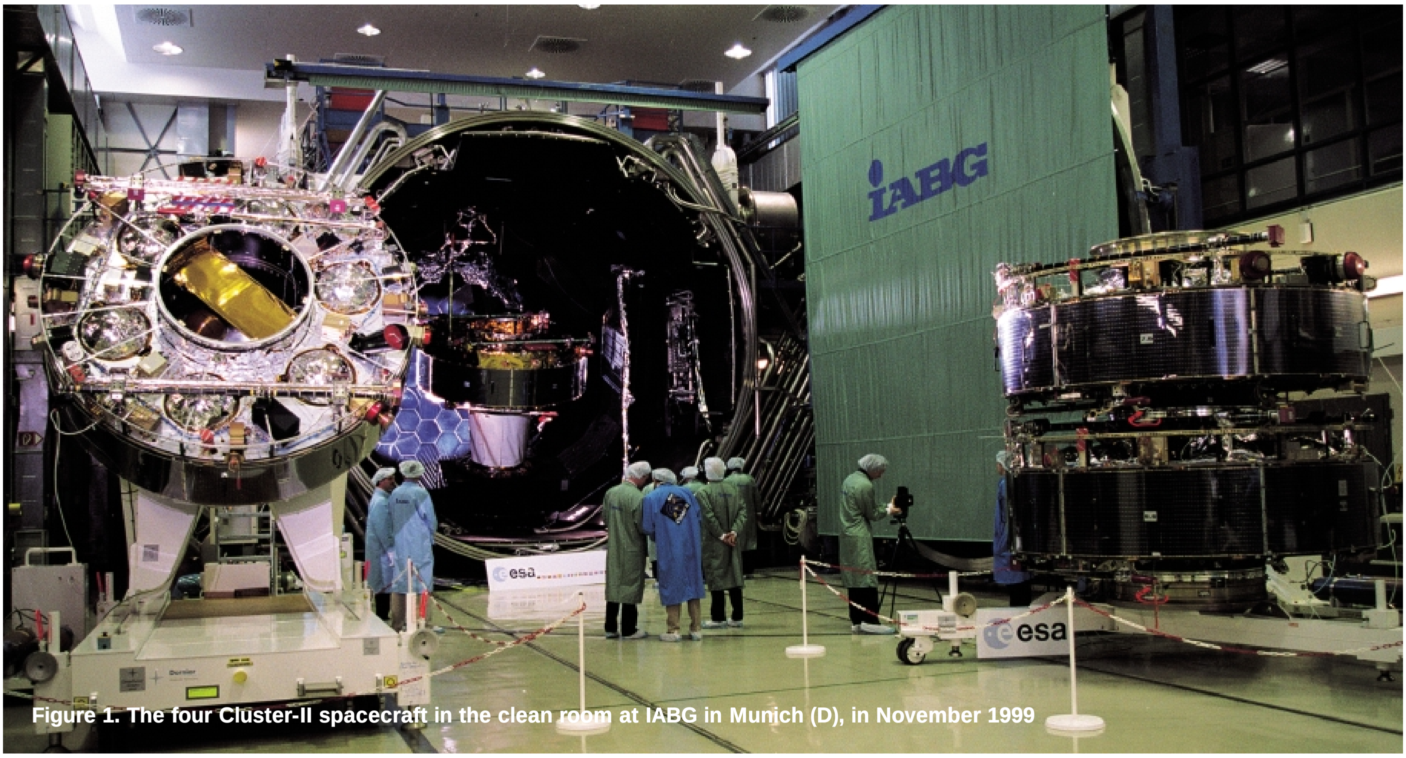

Figure 1. The four Cluster-II spacecraft in the clean room at IABG in Munich (D), in November 1999

26 kg. This quartet would be launched into an elliptical polar orbit of 4 x 22 R_E (Earth radii)*.

At the same time, a parallel Phase-A study was also undertaken for the Solar and Heliospheric Observatory (SOHO) mission to study the Sun and solar wind. After the ESA Science Programme Committee (SPC) approved the Agency's Horizon 2000 long-term science plan, the combined Cluster and SOHO missions were selected as the Solar-Terrestrial Physics (STP) Cornerstone, the first major science project of the new programme.

Figure 2. Debris from the Cluster spacecraft being collected after the Ariane-501 launch failure

Prior to the final definition of the Cluster mission, a proposal was made to use the first Cluster spacecraft in place of a planned NASA satellite called Equator. This would have involved a launch into an equatorial orbit by a US launch vehicle for an initial one-year mission. The remaining three Cluster spacecraft would then have been launched by ESA into polar orbits, where they would later be joined by the original 'equatorial' spacecraft. This concept was eventually abandoned after consideration of expected payload degradation during one year in equatorial orbit and difficulties in inter-calibration of the four sets of scientific instruments after launch.

The final baseline Cornerstone, renamed the Solar-Terrestrial Science Programme (STSP), was defined as a two-thirds/one-third co-operative endeavour between ESA and NASA, with most of the American participation allocated to SOHO. Cluster was expected to benefit from a 'free' launch on the first test flight (V501) of the newly developed Ariane-5 booster.

After several minor delays, Ariane-501 lifted off from Kourou on 4 June 1996, carrying its payload of four Cluster satellites. Unfortunately, the launcher's maiden flight lasted just 37 seconds before intense aerodynamic loads resulted in its break up and initiation of the automatic destruct system. Debris from the Cluster spacecraft was scattered across the mangrove swamps near the launch site (Fig. 2).

The phoenix rises from the ashes

It seemed to all concerned that 10 years of work had come to naught. However, in July 1996, after considering possible ways of recovering at least some of the unique science from the mission, ESA, with the approval of its Science Programme Committee, decided to build a fifth Cluster satellite.

Appropriately named 'Phoenix', after a mythical Arabian bird that was burnt on a funeral pyre and then was reborn by rising from the ashes, this spacecraft was to be identical to the original Cluster spacecraft. It would be based on the Cluster structural model and equipped with flight spares of the experiments and subsystems prepared for the Cluster mission. New equipment, such as the harness, wire booms and radial booms, would only be manufactured when necessary. By taking advantage of the existing hardware, together with the knowledge and experience gained in the original programme, Phoenix was expected to be fully integrated and tested by mid-1997, opening the way for a launch later that year.

This rapid response to the launch failure soon gave way to a longer term strategy. An awareness that the scientific objectives of the Cluster mission could not be met by a single spacecraft led to proposals to rebuild three or four full-size Cluster spacecraft, or to launch three smaller satellites alongside Phoenix.

Although these proposals had significant implications for an ESA science budget that was already fully committed, it was accepted that the costs of a full rebuilding programme would be much lower, since the spacecraft had already been through a complete cycle of design, development and testing. In addition, designing and developing completely new, albeit smaller, spacecraft, would jeopardise the objective of constructing the new satellites as soon as possible, so that they would be available to study the Sun during the peak of the solar cycle, which was expected in the year 2000.

On 3 April 1997, the SPC agreed that the potential science return from a full Cluster re-flight was so important that a further three near-replicas of the original spacecraft would be built, in addition to Phoenix (Fig. 3).

* The Earth's equatorial radius R_E = 6378 km

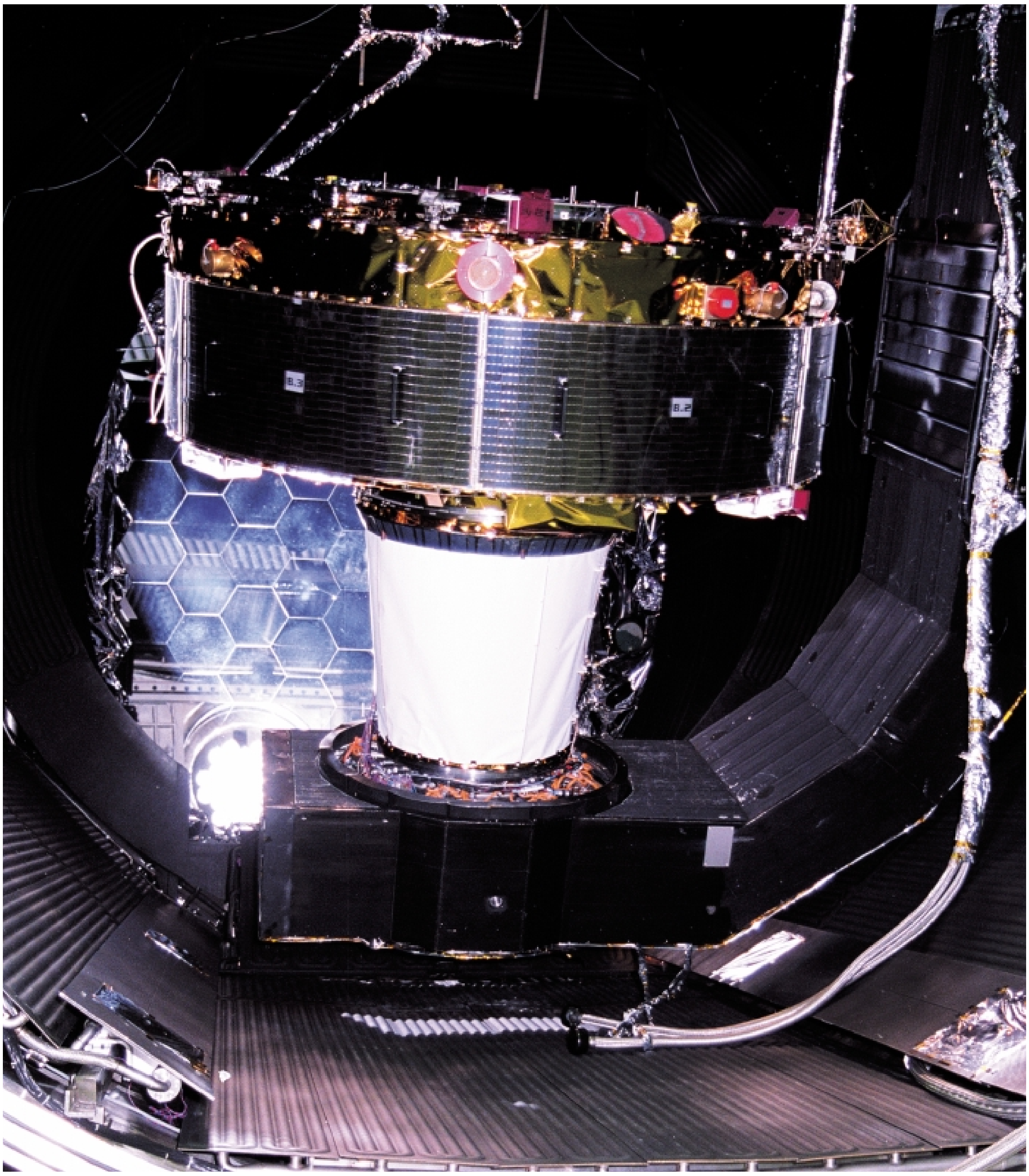

Figure 3. Phoenix (FM 5) on the test stand at IABG in Munich (D)

Dubbed flight models (FM) 5 to 8, these spacecraft have now completed their assembly and integration test programme, and were transported to Baikonur Cosmodrome in April of this year.

Anatomy of a Cluster-II spacecraft

Construction of the Cluster and Cluster-II spacecraft has been a major enterprise for European industry. Manufacturing companies in almost all of the 15 ESA Member States, and in the United States, have provided hardware for these projects. The prime contractor is the German company Dornier Satellitensysteme, but many other companies have also participated (Fig. 4).

All of the spacecraft have been assembled in the giant clean room at Dornier's Friedrichshafen plant, and then sent to IABG in Ottobrunn, near Munich, for intensive acoustic, thermal-vacuum and magnetic testing.

The first spacecraft to be completed by Dornier was FM 6, which was then transported to IABG in March 1999. It was followed at regular intervals by FM 7, then FM 8 and FM 5. All four spacecraft were briefly brought together for a press briefing at IABG in November 1999, and the test programme for the final satellite, FM 5, was completed in March 2000.

The spacecraft have been assembled by hand from thousands of individual parts. Built into each 550 kg satellite are six propellant tanks, two pressure tanks, eight thrusters, 80 m of pipework, about 5 km of wiring, 380 connectors and more than 14 000 electrical contacts.

When fully loaded with fuel, a Cluster-II spacecraft weighs approximately 1.2 tonnes. Each spacecraft is shaped like a large drum, 1.3 m high and 2.9 m in diameter (Fig. 5). In the centre is a cylinder with an aluminium honeycomb structure covered with a skin of

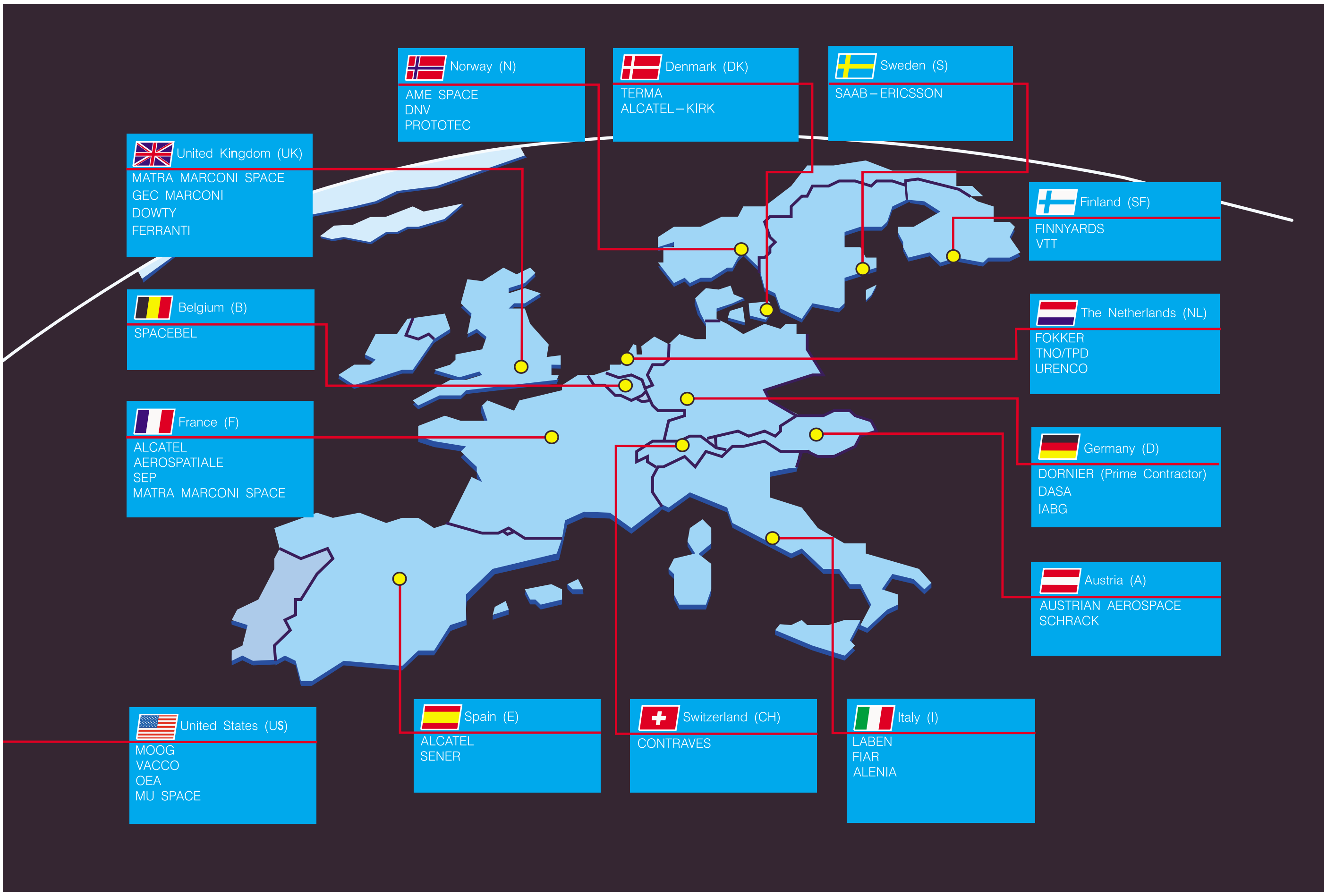

Figure 4. Major industrial contractors involved in Cluster

carbon-fibre-reinforced plastic. The equipment panel inside this cylinder supports the main engine, two high-pressure tanks and other parts of the propulsion system.

Six spherical fuel tanks made from titanium are attached to the outside of this central cylinder. The fuel they carry (MMH and MON1) accounts for more than half the launch weight of each spacecraft. Most of this fuel will be consumed soon after their launch, during the complex manoeuvres required to reach their operational orbits. Each spacecraft also carries eight 10 N thrusters – four radial and four axial – for smaller changes of orbit.

Table 1. Spacecraft vital statistics

Diameter	2.9 m
Height	1.3 m
Mass	1200 kg
Propellant	650 kg
Scientific payload	71 kg
Solar-array power	224 W
Battery capacity	80 Ah
Power to payload	47 W
Spin rate	15 rpm
Operational mission	2 yr
Telemetry downlink	2–262 kbit/s

Around the central cylinder is the main equipment platform. It consists of an aluminium-skinned honeycomb panel, which is reinforced by an outer aluminium ring. Most of the subsystems, such as the power and computer processing hardware, are attached to its lower surface, while the science experiments are placed on top. Electrical power is provided by six curved solar panels attached around the outside of the platform. Five silver-cadmium batteries supply power during the four-hour-long eclipses when the spacecraft enter Earth's shadow.

Various rod-shaped booms open out once the satellite reaches orbit. They include two single-hinged antennas for communications and two 5 m, double-hinged booms on the satellite's upper surface which carry sensors that would otherwise be disturbed by the spacecraft. There are also four 50 m-long wire booms, which deploy horizontally when the spacecraft begins to spin. These measure the changing electrical fields around each spacecraft.

Although all of the Cluster-II spacecraft are outwardly similar in appearance, the present-day Phoenix is an unusual combination of the old and the new. At its heart is the first spacecraft structure ever manufactured during the original Cluster programme back in 1992.

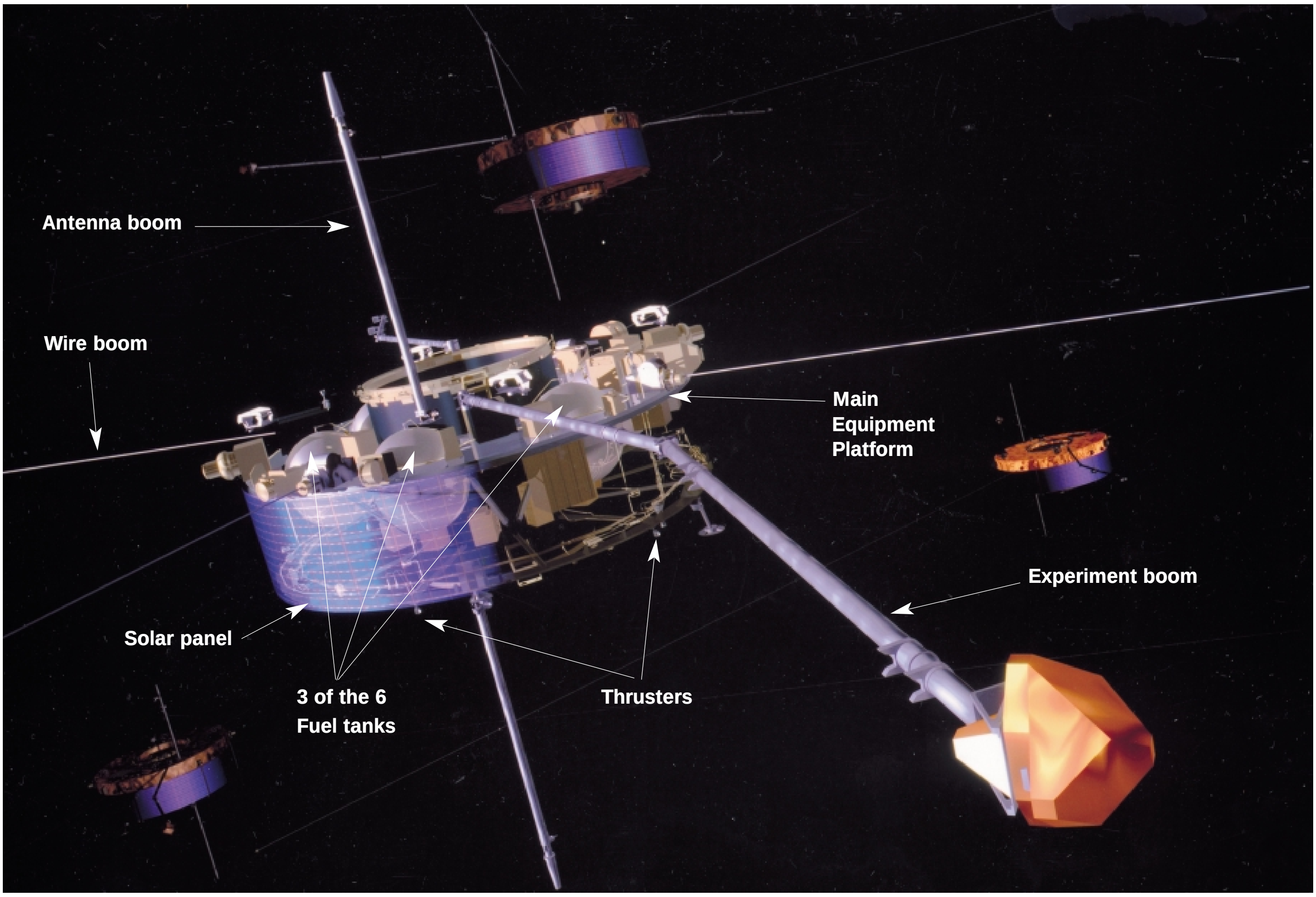

Figure 5. Cut-away view of the Cluster spacecraft

Never intended to fly in space, this main body was used for a variety of shock tests and eventually grabbed some limelight at the 1995 Paris Air Show.

Phoenix also differs slightly from its companions by having the original Cluster analogue transponder and signal amplifier. However, no hardware from the four Clusters that were lost has been used again. To all intents and purposes, Phoenix can be considered to be a new spacecraft.

The other three Cluster-II spacecraft are identical, but even they differ slightly from the original satellites. Significant modifications made to the overall design include the addition of a solid-state data recorder with a larger memory; two new computer boxes, a new high-power digital transponder, and experiment booms which have been slightly shortened to fit inside the protective fairing on the Soyuz rocket. Various other components that are no longer manufactured have also been replaced.

The same applies to the scientific payload. Under the first Cluster revival plan, Phoenix was to have carried spare experiments, but most of its science instruments have now been completely rebuilt. It was decided that, since it was necessary to make three new units for each experiment, it would be just as easy to make four.

One unusual addition to FM 5 and FM 7 (the upper spacecraft on each stack) is a small Visual Monitoring Camera, with which it is hoped to capture views of the lower spacecraft and its Fregat stage shortly after each pair separate in orbit.

Dual launches from Kazakhstan

The Cluster-II spacecraft are scheduled to be flown to Baikonur Cosmodrome, Kazakhstan on board two Antonov aircraft in early April. There, they will spend the next few months in the various launch-preparation and launcher-integration facilities, undergoing final checks and fuelling. The spacecraft will then be integrated to the launch vehicle, after which the entire assembly will be transported to the launch pad by rail car, in a horizontal position. The Soyuz is then lifted upright, ready for fuelling and lift-off. Launch will take place from Pad 6, which has been specially modified to handle a Soyuz with a Fregat upper stage.

The four satellites will be put into orbit, in pairs, by two Soyuz rockets provided by the Russian-French Starsem company (Fig. 6). The Soyuz is a more powerful version of the Semyorka rockets, which launched the world's first

Figure 6. Soyuz-Fregat lifts off from Baikonur at the start of its first qualification flight on 9 February 2000 (courtesy of Starsem)

satellite in 1957 (Sputnik) and the first spaceman in 1961 (Yuri Gagarin). Between them, the various versions of the booster have successfully completed more than 1650 launches. Although the Soyuz first flew in 1963, it is still used to orbit both manned and unmanned spacecraft. Upgraded versions of the booster are in the pipeline, ensuring its continued service well into the new century, and its future operations will include delivering crews and cargo to the International Space Station.

When the Cluster-II mission was approved by ESA's Science Programme Committee in April 1997, it appeared that a launch on a European Ariane rocket would be too expensive. The only feasible solution, bearing in mind the project's financial constraints, was to launch the spacecraft using two Soyuz launch vehicles, each equipped with a newly designed Fregat upper stage (Fig. 7). The contract for launch of the Cluster-II satellites was eventually signed on 24 July 1998 at ESA Headquarters in Paris.

Although a similar system has been fitted on nearly 30 interplanetary spacecraft, including the Phobos probes to Mars, the Fregat has not previously been flown on a Soyuz vehicle. Before finally committing itself to the dual Cluster-II launches, ESA has insisted on two qualification flights of the Soyuz-Fregat combination.

The first of these was successfully completed on 9 February 2000. The mission was performed according to the predefined schedule and Fregat performed the first two requested engine burns, placing its payload into the expected orbit. Preliminary analysis of the parameters received from the Fregat showed a very good accuracy, with values very close to the specification.

A second validation flight, involving a dummy satellite with the same mass as a pair of Cluster-II spacecraft, followed on 20 March. This also proved to be highly successful, clearing the way for the dual Cluster-II launches in June and July.

Built by the Russian Lavotchkin industrial complex, the Fregat has a single-chamber main engine, which can be restarted up to 20 times, and four groups of three 50 N hydrazine thrusters to provide attitude control.

Figure 7. Cutaway view of Soyuz-Fregat

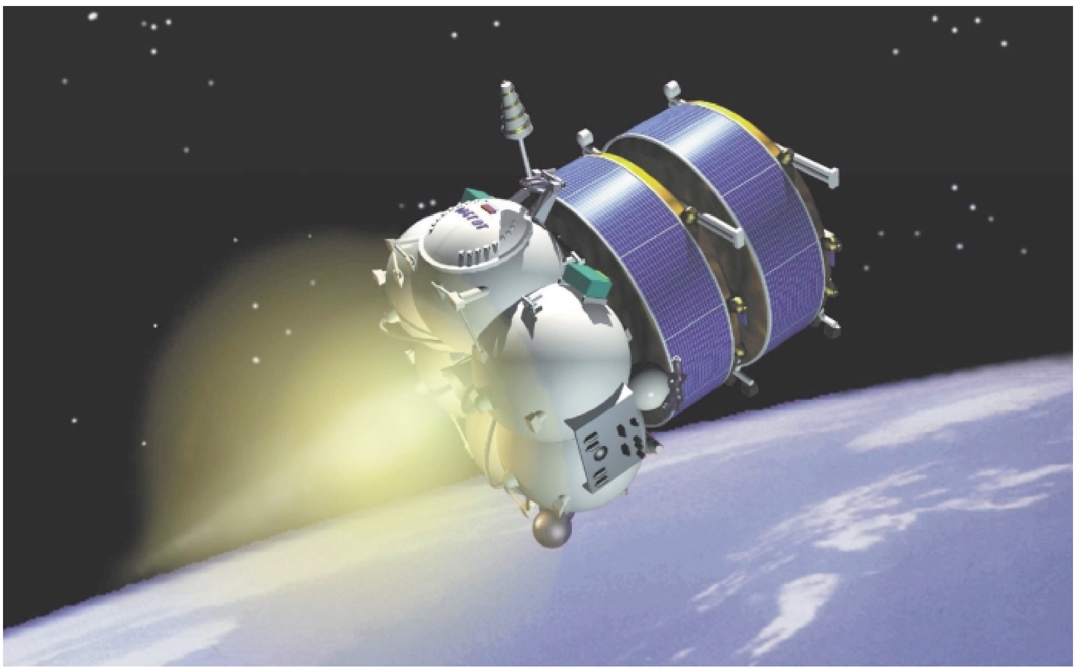

Figure 8. Artist's impression of Fregat with two Cluster spacecraft above the Earth (courtesy of NPO Lavotchkin)

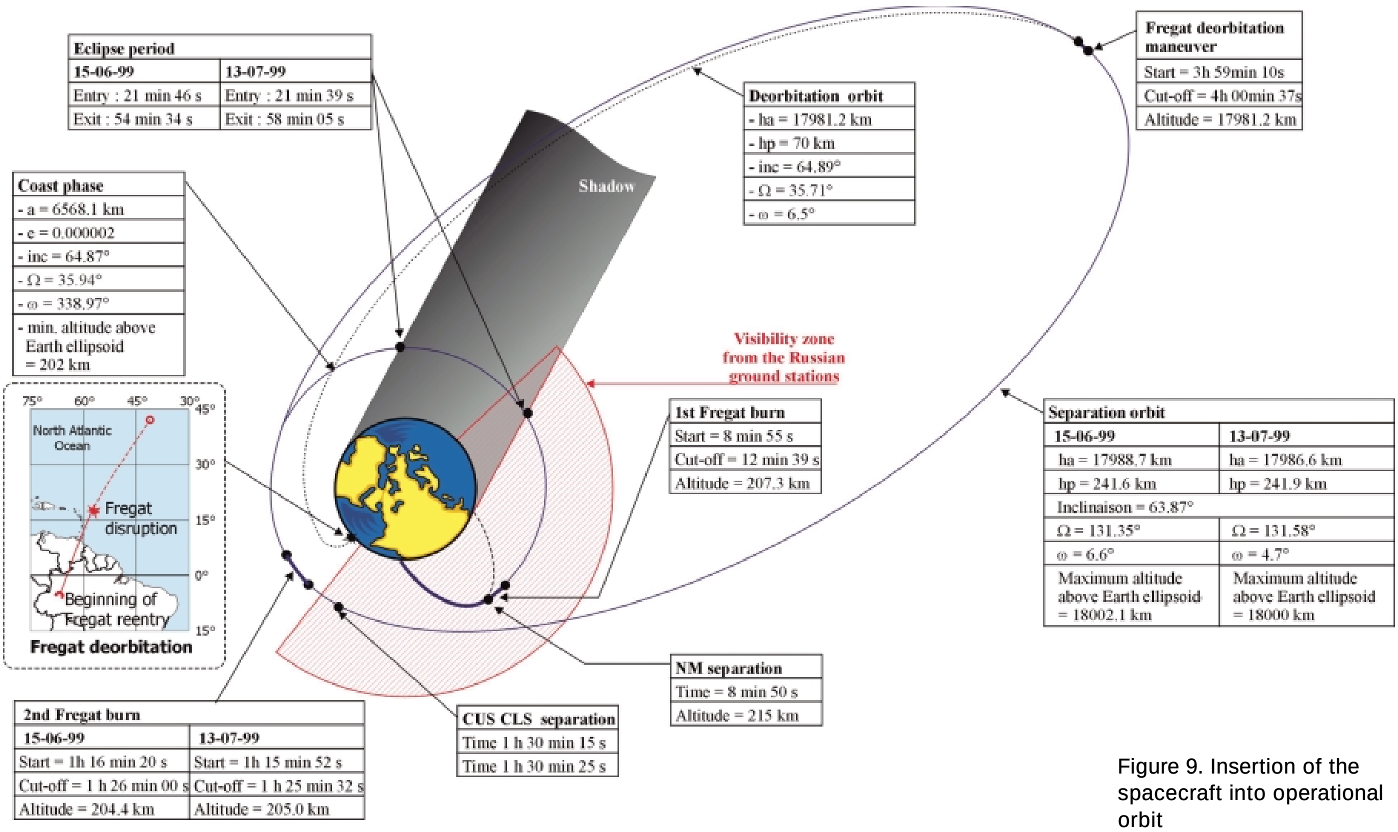

Figure 9. Insertion of the spacecraft into operational orbit

Into orbit

The first pair of Cluster-II satellites (FM 6 and 7) are currently set for launch in mid-June 2000, to be followed by the second pair one month later. The Soyuz launcher will place the upper stage and its Cluster-II payload into an orbit inclined at 64.8° to the equator. The fairing is jettisoned during operation of the Soyuz third stage. Once it reaches the correct altitude, 8 min 48 sec after lift-off, the Fregat payload assist module and its two Cluster-II spacecraft will separate from the booster (Fig. 8). The Fregat main engine will fire almost immediately to achieve a circular orbit of approximately 200 km altitude. About one hour later, the Fregat engine will fire again to inject the spacecraft into a 200 km x 18 000 km elliptical orbit (Fig. 9).

The two satellites will then be released, one after the other. They will use their own on-board propulsion systems to reach the final operational orbit. This involves changing their orbital inclination from 64.8° to 90°, while raising the highest point above the Earth (apogee) to 119 000 km and the lowest point (perigee) to 19 000 km. To do this, each Cluster-II spacecraft main engine will perform six major manoeuvres. These orbital changes are made possible by the large amount of onboard fuel, which makes up approximately half of each satellite's launch mass.

Once they reach their operational orbits, the spacecraft will fly in tetrahedral formation around the Earth. The relative distances between them may be adjusted from a minimum of 200 km to a maximum of 18 000 km by firing their onboard thrusters. Their separation will depend on the characteristics of the particular region of near-Earth space that is being studied and the spatial resolution that the scientists require.

The 57 h elliptical orbit has been selected so that the spacecraft will travel over the planet's polar regions and investigate all of the key near-Earth plasma regions within the magnetosphere (Fig. 10). Operations will begin several months after launch, when orbital checkout, commissioning and calibration of instruments are completed.
This means that, during the first part of the mission (in the northern hemisphere's winter), the spacecraft will pass over the polar cusp and spend a considerable amount of time during each orbit exposed to the solar wind when they venture beyond the magnetosphere. Six months later, when the Earth is on the opposite side of the Sun, the quartet will remain inside the Earth's magnetosphere and explore the electromagnetic environment more than 100 000 km down the magnetotail.

All regions of interest will be crossed again during the second year of operations, though, with the benefit of previous experience, the science team will have the option to investigate some of them more intensively by modifying the quartet's orbital configuration.