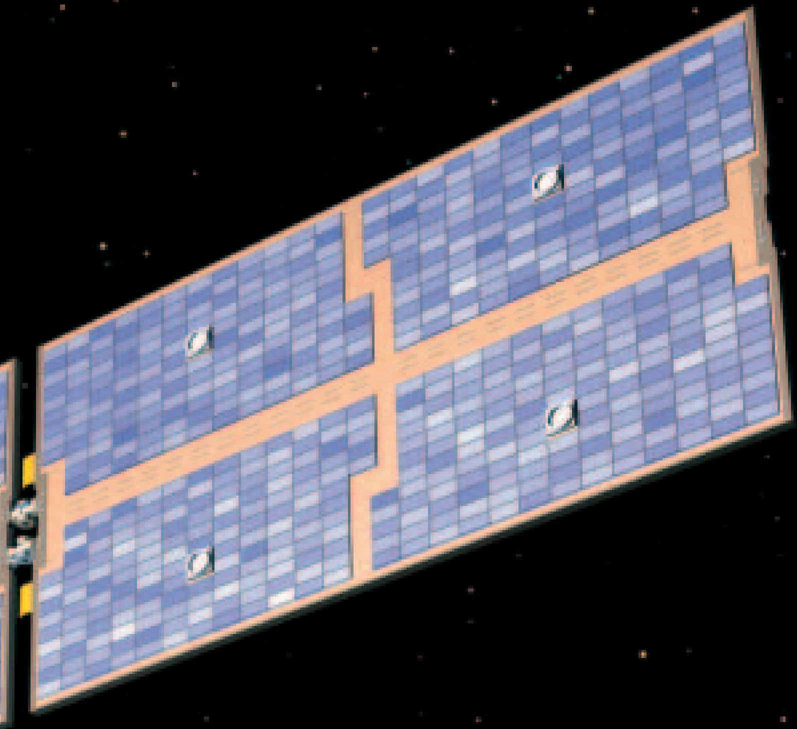
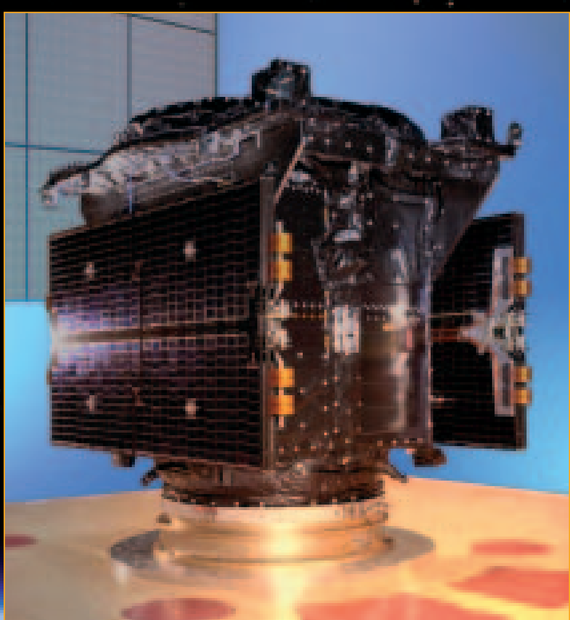
The Triumph of GIOVE-A



The First Galileo Satellite



Javier Benedicto, Giuliano Gatti & Antonio Garutti
Galileo Project, Directorate of European Union and Industrial Programmes, ESTEC, Noordwijk, The Netherlands

John Paffet, Andy Bradford, C. Jackson & E. Rooney
GIOVE-A Project, Surrey Space Technologies Ltd., Guildford, UK

Shortly before the end of 2005, the first Galileo experimental satellite was successfully launched. Two weeks later, GIOVE-A transmitted its first navigation signals from orbit, achieving a major milestone in the Galileo satellite navigation programme.

Introduction

Following the approval of Galileo in 1999 as a joint programme of the European Union and ESA, a demonstration element was added – the Galileo System Test Bed (GSTB) – to allow early experimentation with the navigation signals and services before committing to the final satellite design. GIOVE-A (Galileo In-Orbit Validation Element, formerly known as GSTB-V2/A) is the first of these two experimental satellites. The satellite's design and successes are described in this article. GIOVE-B is scheduled for launch in November or December 2006; an article is planned in the November *Bulletin* issue to cover that mission.

The GIOVE-A Mission

GIOVE-A's main objectives are to secure the frequencies allocated to the

Galileo programme, characterise the orbit's radiation environment, evaluate critical payload technologies and enable early signal experimentation. It has succeeded magnificently in all of these goals. Creating and flying the satellite have provided valuable lessons in manufacturing, assembly, integration, testing, mission analysis, launch, early operations and in-orbit testing. All of this priceless information is being used in developing the operational Galileo satellites.

Satisfying the frequency regulations was particularly demanding because the International Telecommunication Union required a satellite transmitting at the Galileo frequencies to be in orbit by June 2006.

No previous European satellite had flown in Galileo's planned orbit at around 24 000 km altitude, so it is important to map this difficult radiation environment using detectors on both GIOVE satellites. The results are being used to improve the existing models and to show how much shielding the operational Galileo satellites must carry to guarantee flawless performance over their 12-year lives.

GIOVE-A is also providing flight experience for equipment that has never flown in space before – particularly the rubidium atomic clocks and the navigation signal generators. Their good performance is the bedrock of the service quality from the operational constellation.

The behaviour of the realistic navigation signals from GIOVE-A is being measured comprehensively and is helping to develop early versions of receivers for testing. A broad range of experiments is being carried out thanks to the flexibility of the signal generators, which can be significantly modified in-orbit by uploading software patches.

Major Events and Mission Phasing

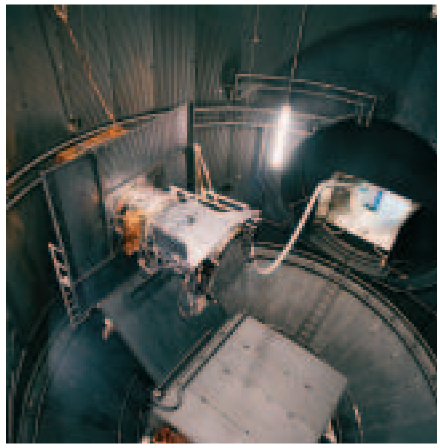
Following the GIOVE-A contract kick-off on 11 July 2003 with Surrey Satellite Technology Ltd. (SSTL), a Qualification Status review over the first month assessed which existing hardware could be reused and which units had to be freshly designed or at least modified.

Signature of the GIOVE-A contract on 11 July 2003 by Claudio Mastracci (left, former Director of EUI) and Martin Sweeting of SSTL

The overall mission was then reviewed at the Delta Preliminary Design Review 4 months after kick-off, when the emphasis was on the new or modified units and on approving their flight production.

As part of the satellite development philosophy, a structural model was built by SSTL and tested at ESTEC in mid-2004 to verify the new structure; previous SSTL satellites were about half the size of GIOVE-A.

The results of the structural testing, the final design and the readiness for the final satellite integration and testing passed the Critical Design Review in March 2005. The Flight Model was completed in July 2005, when the satellite was transported to ESTEC for environmental testing.



GIOVE-A in the Large Space Simulator at ESTEC for thermal and vacuum testing

The results of the campaign were scrutinised at the Flight Readiness Review a month before launch, to authorise shipment to the Baikonur Cosmodrome and the start of the launch campaign. The satellite's review process was completed at the Qualification Readiness Review, passed in early December 2005. The Launcher Readiness Review took place 3 days before the perfect launch of 28 December 2005.

Following commissioning, the first Galileo signal was transmitted by GIOVE-A on 12 January 2006. Payload commissioning was completed by the end of February 2006. The In-Orbit Test Review was organised in March 2006, followed by the Frequency Filings Review in April 2006; both were successful.

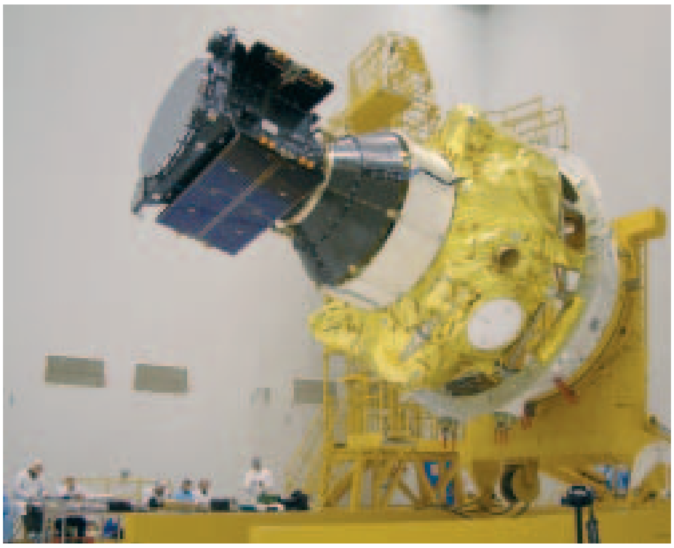
Operation Reviews are being conducted every 3 months during the 27-month life of the satellite.

GIOVE-A Characteristics

Orbit: 23 260 km circular, 56°
Launch mass: 602 kg
Lifetime: 27 months
Power supply: 700 W beginning-of-life, 600 W end-of-life
Stowed envelope: 1.3 x 1.8 x 1.65 m
Propulsion: 2 sets of 5x50 mN thrusters, fed from 25 kg of liquid butane in each of 2 tanks
Power system: 50 V regulated bus for high-power load, 28±6 V unregulated bus for payload/platform
Solar array: 2 wings of 2 panels each (0.98 x 1.74 m) Si cells, SEPTA 31E drive, 60 Ah Li-ion battery
Payload: rubidium atomic clock reference, dual-signal simultaneous transmission, CEDEX and MERLIN radiation sensors, one GPS receiver

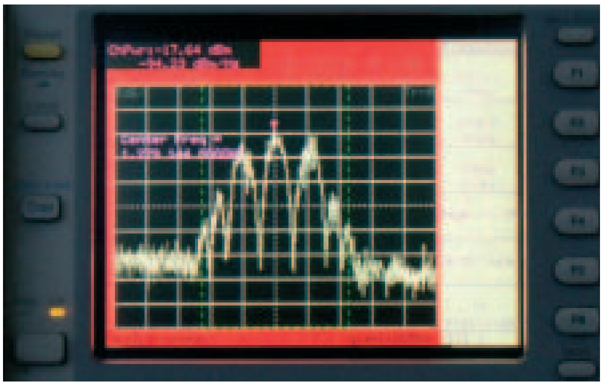
The Satellite

All the 21 SSTL satellites after UoSAT-2 in 1984 were based on their predecessors; each mission took an evolutionary step. The 23rd satellite, GIOVE-A, is an enlarged version of the

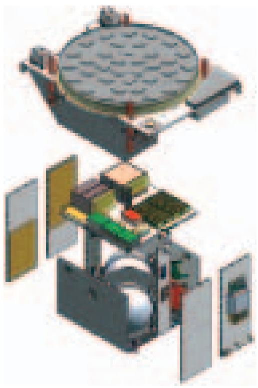


GIOVE-A is mated with its Fregat upper stage at Baikonur

The Soyuz launcher is poised for departure, 28 December 2005



A momentous achievement: the first Galileo navigation signal is received



The GIOVE-A basic structure

microsatellite platform used for the ALSAT-1, BILSAT, NigeriaSAT-1 and UK-Disaster Monitoring Constellation missions. GIOVE-A also makes extensive use of subsystems developed for the Gemini small geostationary communications satellite.

The platform is, wherever possible, dually redundant, or allows for gradual degradation, and minimises the number of single-point failures. The communications system, based on an existing design, provides 9.6 kbit/s telecommand and telemetry and payload telemetry at S-band via SSTL's station in Guildford (UK). The inherited onboard computer is cold-redundant, and provides 32 Mbytes of RAM disk. A dual-redundant Controller Area Network (CAN) bus runs around all the subsystems, providing communication and data-handling functions.

The mission lifetime and this new orbit's radiation environment dictated the strategy for selecting and shielding component. Units that have flown before are shielded such that they suffer the same total radiation dose as they did during their low-orbit missions. This means that the experience built up with them over multiple missions is still valid, providing confidence in their robustness. For modified or new units, radiation-tolerant devices were selected that can handle at least 50 krads, and preferably 100krads.

The deployed silicon-cell panels were sized to provide more than 600 W by the end of the mission, allowing the output to degrade gracefully.

The structure

The basic structure is an aluminium box. The main antenna is on the +Z face, facing Earth. Deployable Sun-tracking solar wings are mounted via drive mechanisms in the middle of the +Y and –Y faces, with the rotation axis in the Y-axis. The +Y and –Y faces are primary radiators; the +X face is a secondary radiator. At launch, the –Z side was attached to the Soyuz-Fregat and the solar wings covered the +Y and –Y radiators. The outer walls form a square load-bearing thrust tube supporting two equipment-carrying panels (the Earth face and the internal avionics panel).

The structure is mainly machined aluminium and aluminium sandwich panels, bolted together in preference to bonding in order to simplify the design and handling. The structure is configured into three bays: propulsion, avionics and payload.

Propulsion features

The propulsion system is based around butane and had already flown on several

SSTL missions. It meets the delta-V requirements and offers significantly lower cost and risk than using hydrazine.

Two redundant controller modules drive the propulsion system, each responsible for half of the 10 thrusters and four tank-isolation valves. In the event of either controller failing, the other can feed five thrusters from either tank and complete the mission. The tanks, from PSI of the US, were derived from an hydrazine tank by removing the elastomeric diaphragm. Existing 50 mN thrusters with heaters are used.

Power system

The power system uses the 'GMP-D' design developed for SSTL's Gemini geostationary platform. It provides a dual-voltage (27 V & 50 V) bus and its modular design makes it scalable from about 400 W to 2 kW.

The Power Control and Distribution System is fully autonomous and fault-tolerant. The 50 V is regulated from the solar arrays during sunlit operation and from redundant regulators on the 60 Ah lithium-ion battery during eclipses. The solar array drive mechanism allows the wings to track the Sun while the antenna remains fixed on its Earth target.

Avionics

The data-handling system architecture is divided into three sections: the redundant CAN bus; two cold-redundant OBC386 computers; attitude safety module.

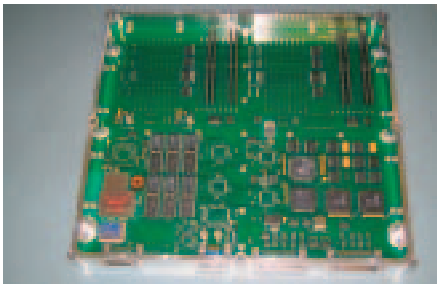
The CAN bus has been used by SSTL in several previous missions. Typical modules in the bus system could be the power system or the propulsion controller. Telemetry and telecommand nodes can autonomously switch between primary and secondary busses if a lockup condition is detected. All SSTL satellites have 'back-door connections' between the receivers and the power system, allowing a ground station to turn units on or off directly without going via the CAN bus.

The CAN bus links each OBC386 to sensor data (Sun sensors, gyro, Earth-horizon sensors), formatted and generated by the attitude and orbit-control module, and routes the actuator (magnetorquer, wheel, propulsion) commands. Again, most of these sensors and actuators were based on SSTL flight-proven units or standard space-qualified units.

As with all SSTL satellites, GIOVE-A was launched inert and activated by separation from the launcher. The onboard software was then loaded by the ground station.

The non-redundant attitude safety module provides GIOVE's highest level of control. After launch, it managed the de-tumble and Sun-acquisition. During the operational phase, it acts as a watchdog over the primary units, switching to secondaries in the case of failure. It also contains simple attitude-control algorithms using Sun-sensors, gyros and thrusters to maintain Sun-pointing in the case of OBC386 failure.

The OBC386 onboard computer had already proved itself on earlier missions



The Payload

The GIOVE-A payload comprises three main sections: navigation, radiation monitoring and experimental. The navigation section contains all the elements generating the navigation signals in the E5a, E5b, E6, E2, L1 & E1 Galileo frequency bands. The elements include the Rubidium Atomic Frequency Standard (Temex Neuchatel Time, CH), the Clock Monitoring and Control Unit (Alcatel Espacio, E), the Frequency Generation and Upconverter Unit (Norspace, N), the Navigation Signal Generation Unit (Laben, I) and the Navigation Antenna (Alenia Spazio, I).

The navigation antenna (Alenia Spazio)

The Environmental Monitoring Section includes two monitors – CEDEX (SSTL) and Merlin (Qinetiq, UK) – to characterise the orbit's radiation and charging environment.

The Experimental Section includes SSTL's GPS receiver and a laser reflector. The receiver is a 24-channel GPS receiver developed by SSTL assisted by British National Space Centre and ESA ARTES-4 funding.

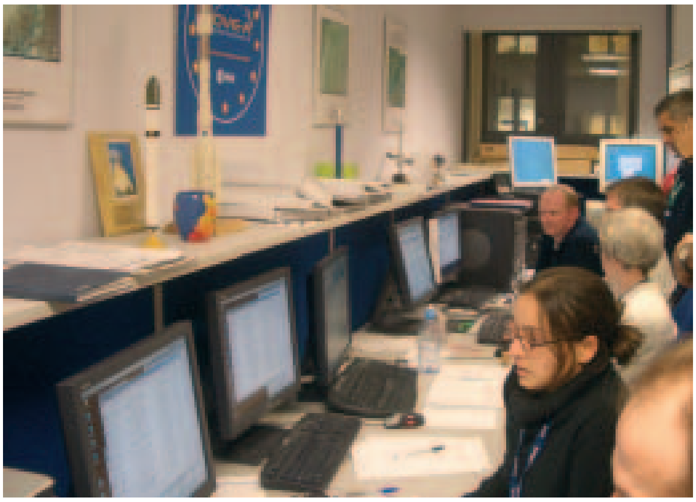
The Ground Segment

Mission control uses an existing network of ground stations connected via the Internet to the Surrey Operations Control Centre:

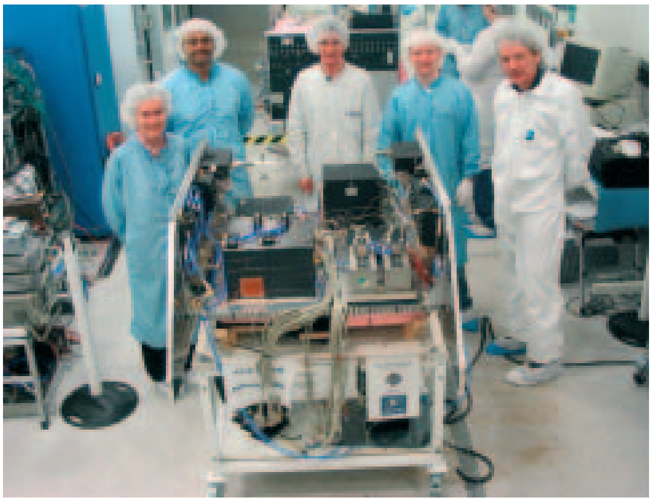
- Mission Operations Control Centre at SSTL;
- Guildford ground station for early-orbit and nominal operations;
- Malaysian ground station for early-orbit operations;
- Rutherford & Appleton Laboratory (RAL, Oxford, UK) ground station for early-orbit and nominal operations (backup);
- Bangalore (India) ground station;
- Chilbolton (UK) in-orbit testing station.

ESA's Redu (B) station was used as a complementary/backup in-orbit testing station. It will become the main station for commissioning GIOVE-B at the end of 2006.

All routine mission operations are automated, allowing SSTL personnel to staff the control centre during normal



The SSTL control centre in Guildford



Payload bay integration

working hours only. While it is not uncommon to find the centre unmanned, the satellite is automatically monitored and staff are contacted via email or paging systems in case of alert. Automatic data processing allows staff to spend their working time operating the satellite.

Integration and Testing

The integration of the satellite began in February 2005 and was completed in a record time by the following June. GIOVE-A was then delivered to ESTEC's Test Centre for a wide range of tests: thermal-vacuum and thermal balance, vibration, mass properties and balancing, acoustic, solar array deployment, electromagnetic compatibility, clamp-band integration and release, and system end-to-end. Ground system validation tests were run through a network connection to the Guildford mission operations control centre.

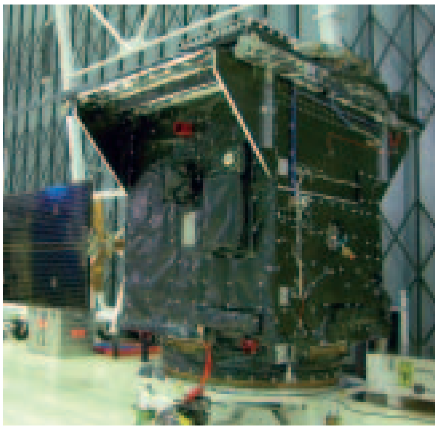
The final test campaign was completed by the end of November 2005 with the delivery of the satellite to the Baikonur Cosmodrome.

The launch campaign activities were simplified by the fact that the satellite was launched while inactive.

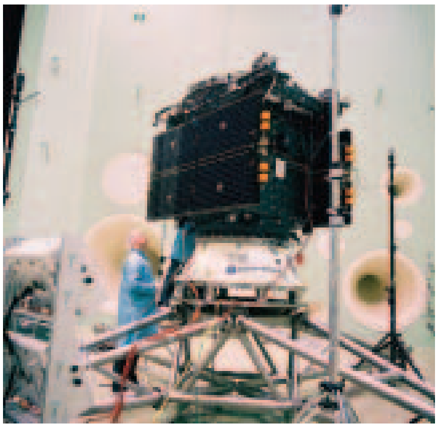
Launch and early operations

The 4-week launch campaign culminated in the successful ascent of the Soyuz-Fregat at 05:19 UT 28 December 2005. The Soyuz trajectory and burns were normal, leading to ejection of the satellite into its final orbit 222 minutes after lift-off.

Solar array deployment tests at ESTEC



Preparing GIOVE-A for acoustic tests at ESTEC



Two minutes after separation the 'TX1' command to turn on the first transmitter was sent from the control centre via the RAL station; the satellite responded immediately. A few seconds later, the control centre began receiving satellite telemetry and could see that GIOVE-A was healthy.

The attitude control system was activated and in a very short time the satellite was stable, with one of the stowed wings facing the Sun and so providing power. Immediately, ground controllers began uploading the software into the computer. Once initialised, the computer could begin to take full control of the satellite.

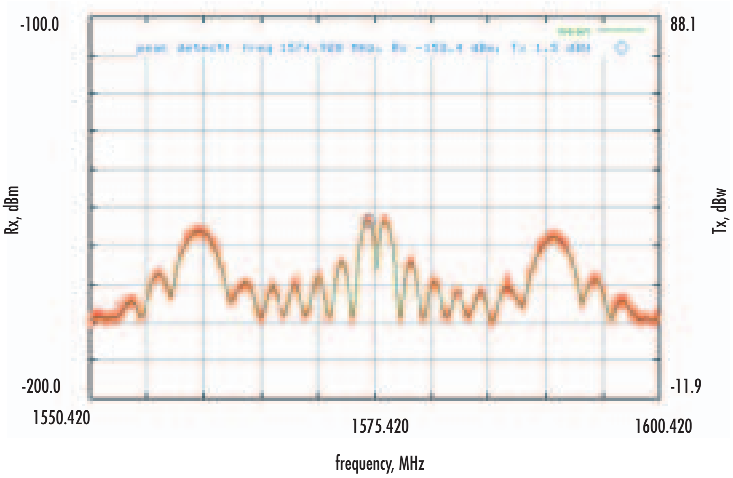
At 11:15 UT, deployment of the first solar wing began with the uploading of the command file. Wing 1 deployment was confirmed at 11:39 UT by a signal from the latch showing that it was locked. The satellite turned for the wing to generate power and to be checked out. After rotating 90º, the second wing was released and confirmed as latched in position at 12:14 UT.

The satellite then acquired its final orientation towards the Sun, and the launch and early operations phase was declared as successfully completed.

Commissioning and Early Experiments

Platform commissioning involved 13 sessions to assess the performances of all the equipment, including redundant

Encapsulation in the Soyuz fairing



The first navigation signal transmitted at L1 (1575.42 MHz)

units, and of the various software configurations and attitude-control modes. GIOVE-A was then commanded into its nominal mode: Earth-pointing maintained by its reaction wheels.

CEDEX and Merlin were turned on a day after launch and useful data have been returned continuously ever since.

The navigation payload went through a number of checkouts following platform commissioning. It was turned on for the first time at 17:30 UT on 12 January 2005. The first L1 and E5 signals were clearly received at Chibolton and Redu, and by other observers around the world. All the experiments at Chilbolton and Redu used receivers built in record time by Septentrio (B).

Since then, different signal modes and modulations have been broadcast and carefully measured at Chilbolton to show they satisfy the frequency filings documentation. The conditions were eventually met and the International Telecommunication Union (ITU) was informed at beginning of March 2006 that the frequencies for Galileo had been put into use.

The first laser-ranging test was successful at the beginning of April 2006, providing results well within expectation. This is being used to determine the orbit with cm-accuracy, which helps the removal of orbit errors and calibration of the clocks. The laser station is in China, in collaboration with the National Remote Sensing Center in China (NRSCC).

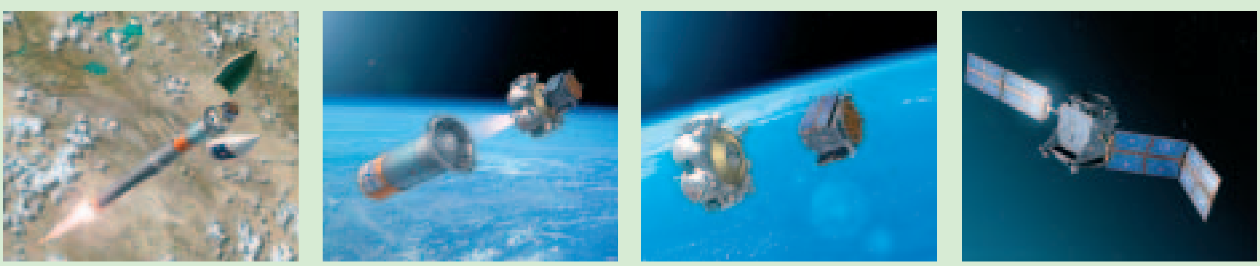
In June 2006 the first clock characterisation campaign was successfully carried out by Galileo Industries, who are building GIOVE-B and the first four operational satellites. The measurements showed that the rubidium clock is performing as expected.

Work still to be done includes full characterisation of signals in the different frequency bands and long-term characterisations of the clock and the radiation environment. Other experiments include the fine characterisation of the navigation payload performance in-orbit, which has never been done before by Europe. The overall mission duration is estimated to be 2 years. Completing the full experimental programme requires launch of GIOVE-B.

Conclusions

The GIOVE-A mission has already achieved its first, major objective: bringing the Galileo frequencies into use as required by the ITU. This major milestone for the Galileo Programme has been realised in a record time of

GIOVE-A launch and deployment sequence



30 months from kick-off, by taking advantage of the flexibility of SSTL and the pre-development of several payload units by the Agency.

Working with SSTL has been a challenging and enlightening experience for ESA as the Agency has been confronted with a significantly different working approach. This small, fully integrated space company has allowed a fast-paced development programme, supported by an enthusiastic, dedicated and professional team. The GIOVE-A experience is certainly a source of lessons for future experimental ESA missions.

The GIOVE-A ESA and SSTL teams

Acknowledgements

The GIOVE-A mission is a success based on the commitment, motivation and capabilities of the SSTL team, supported by the ESA team. In addition, the fundamental contributions of the following parties should also be acknowledged: SSTL subcontractors (Dutch Space, Comdev Europe, Galileo Avionica, Thales GmbH, RAL, Qinetiq); unit suppliers (Temex Neuchatel Time, Alcatel Espacio, Norspace, Laben, Alenia Spazio); Galileo test receiver (Septentrio); launch (Starsem).

Detailed information on Galileo and GIOVE can be found at www.esa.int/galileo. 'The First Galileo Satellites' brochure can be ordered at a cost of €10 from ESA Publications using the form at the back of this issue and quoting BR-251; a French edition is also available.