

REXUS-4: VEHICLE AND SUBSYSTEM DESIGN, FLIGHT PERFORMANCE AND EXPERIMENTS

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ABSTRACT

On the 22nd of October 2008 EuroLaunch launched the REXUS-4 rocket at Esrange in Northern Sweden. EuroLaunch is a joint venture of the DLR Mobile Rocket Base and the SSC Esrange Space Center. The REXUS-4 payload was comprised of five technological experiments from German and Swedish Universities.

The REXUS-4 mission was also the maiden flight of a newly developed service system. After this successful demonstration, it has been implemented into the REXUS/BEXUS programme.

This paper gives a short overview on the development of the REXUS service system and points out the advantages of using standard interfaces for student experiments. Furthermore it will contain a description of the REXUS-4 vehicle, the mission, the campaign and the experiments.

1. INTRODUCTION

The development of REXUS-4 started with the Kick-Off Meeting in December 2006, held by EuroLaunch at DLR Mobile Rocket Base in Oberpfaffenhofen. Two major drivers have been influencing the time plan: The development of the new service system and the main scientific payload, the MIRIAM experiment. The MIRIAM experiment is a probe, located under the nosecone during the ascent phase and ejected exo-atmospherically. This re-entry experiment needed a higher altitude than a standard single-stage REXUS comprising an Improved Orion rocket motor can achieve. This was the reason to use a two-staged motor combination.

Even though the launch had to be postponed several times, the major requirement concerning the REXUS programme was to have a successful flight of the new service system with a large enough time gap before the REXUS-5 flight in March 2009. This was achieved by the launch in October 2008. Table 1 shows the critical time frame in overview.

Table 1. The REXUS-4 Schedule

| Milestones | Date |
|--------------------------------------|------------|
| Kick-Off Meeting | 2006-12 |
| REXUS SM Assembly | 2007-06 |
| MIRIAM Life Cycle Test | 2008-08-22 |
| REXUS SM Vibration Test | 2008-09-03 |
| MIRIAM Vibration Test | 2008-09-12 |
| Experiment Acceptance Tests | 2008-09-15 |
| Flight Simulation Test at DLR | 2008-09-18 |
| Transport of EGSE to Esrange | 2008-09-29 |
| Transport of PL to Stockholm | 2008-10-01 |
| Balance Test at Packforsk, Stockholm | 2008-10-07 |
| Beginning of Campaign at Esrange | 2008-10-13 |
| Practise Countdown | 2008-10-22 |
| Launch of REXUS-4 | 2008-10-22 |

2. VEHICLE DESIGN AND SUBSYSTEMS

REXUS-4 was a two-stage unguided solid propellant sounding rocket. The vehicle consisted of a Nike motor as 1st stage, an Improved Orion as 2nd stage, a motor adapter, a recovery system, a service system, two experiment modules, a nosecone adapter ring with the MIRIAM electronics and an ejectable ogive nosecone.

2.1. Lift-Off Configuration

The total lift-off mass of REXUS-4 was 1175 kg with the motor mass contributing more than 1000 kg.

Including both motors the REXUS-4 rocket had a length of 9.5 m. The payload mass was 152 kg including a scientific payload mass of 75 kg. The polar moment of inertia of the payload was measured to be 2.65 kgm².

Table 2. The REXUS-4 Mass Budget [9]

| 1 st Stage: | 598.5 kg |
|-------------------------------------|-----------|
| 2 nd Stage | 424.5 kg |
| Payload | 152.3 kg |
| Motor adapter + Balancing Mass 1 | 11.9 kg |
| Recovery System | 19.9 kg |
| IGAS Module | 10.7 kg |
| Service System | 18.9 kg |
| Extension Ring | 2.3 kg |
| Experiment Module 1 | 10.7 kg |
| Exp. Mod. 2 + Ballast + Bal. Mass 2 | 23.3 kg |
| MIRIAM Camera Module | 8.9 kg |
| MIRIAM + Pod | 31.7 kg |
| Nosecone | 13.9 kg |
| Total | 1175.3 kg |

Two requirements on the payload configuration are important to ensure a safe flight of a sounding rocket. The first requirement is the center of gravity during lift-off that has to be ahead of the center of pressure. The center of gravity for the lift-off configuration referenced to the aft plane of the motor adapter was measured at 1315 mm, 40.6 % of the payload length [6].

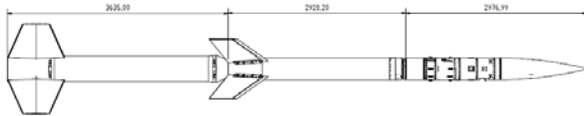


Figure 1. REXUS-4 two-stage unguided solid propellant sounding rocket [9]

2.2. Re-entry Configuration

For the re-entry a center of gravity close to 50 % of the payload length is necessary to avoid a stable attitude of the vehicle during the descent and prevent the recovery system from too much heating. Since the main experiment MIRIAM was ejected during the ballistic flight it was necessary to integrate 12 kg of ballast mass into the nosecone adapter.

The center of gravity for the re-entry configuration was measured at 780 mm (50.1 %) which ensured near perfect re-entry conditions. The re-entry payload mass was 95 kg.

3. THE NEW SERVICE SYSTEM

The newly developed REXUS service system has the capability to provide five experiments with 1 ampere at 28 volts and a serial data interface for up- and downlink. The service system provides GPS position and velocity data, 3-axis acceleration data and rotation rates from 3-axis rate gyros. A standard TV channel can be used by

one experiment. More information on the REXUS service system can be found in [3].

4. EXPERIMENTS

The REXUS-4 payload comprised of five university experiments and one DLR Mobile Rocket Base experiment in an extra module.

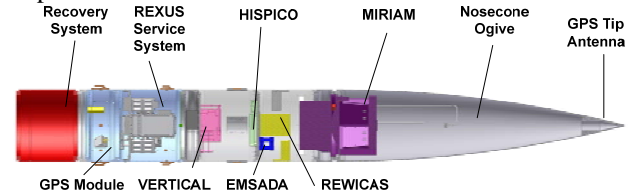


Figure 2. REXUS-4 experiment configuration [9]

During the ballistic flight the MIRIAM experiment of the Universität der Bundeswehr München and the Mars Society Germany was separated from the main payload to test a balloon system that will be used for the entry of a probe in the Martian atmosphere in the future. Several cameras on the REXUS-4 payload as well as cameras and telemetry on the MIRIAM flight system monitored the separation and inflation during the ballistic flight phase.

The VERTICAL experiment from the Technische Universität München verified the startup procedures of the CubeSat MOVE and its solar panel deployment under real spaceflight conditions.

The HISPICO experiment of the Technische Universität Berlin tested a high-integrated S-Band transmitter. The REWICAS of the Technical University of Luleå consisted of three cameras. The EMSADA experiment from the same university is a multiple sensor and data acquisition unit [9].

4.1. MIRIAM

The MIRIAM Experiment (Main Inflated Reentry Into the Atmosphere Mission test for ARCHIMEDES) is placed under the nosecone. It was the spaceflight test for the ARCHIMEDES project. ARCHIMEDES is an effort to probe the atmosphere of planet Mars by means of a hypersonic drag balloon, a device known as a "ballute" (a term coined by the Goodyear Corporation in 1959 by combining the terms "balloon" and "parachute"). The project is currently under study, proposed and supported by the Mars Society Germany, the Universität der Bundeswehr München, the AMSAT-DL e.V. organization and several other research institutions and industrial companies.

4.1.1. MIRIAM Experiment Design

The most important step in the development of ARCHIMEDES so far was the spaceflight test MIRIAM. MIRIAM was to test the deployment mechanism, the inflation process, the ballute behaviour

during inflation and the high speed entry into the atmosphere on a ballistic trajectory. This is important to validate trajectory- and CFD analyses [4].

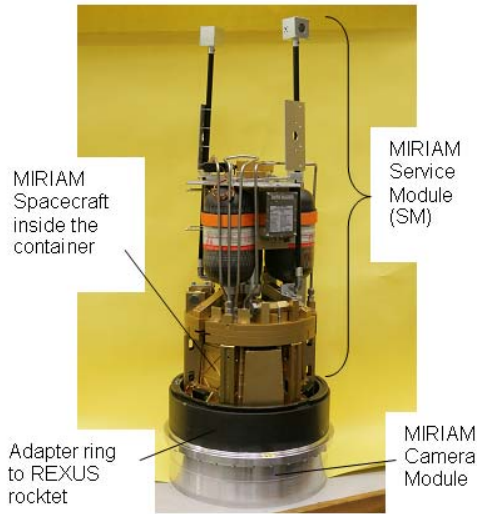


Figure 3. MIRIAM flight system stack

The spaceflight system consisted of 3 major elements:

- The MIRIAM ballute spacecraft which comprises an instrumented pod and the helium-filled hypersonic drag balloon (ballute). As stated above, MIRIAM's pod instrumentation already closely resembled that of ARCHIMEDES, but purely for flight analysis purposes. The FMI-provided ATMOS-B pressure sensor was installed inside the balloon. The magnetometer for MIRIAM (MiriMag) was contributed by the IGEP institute and MAGSON. Paired with an optical still image camera it provided attitude information. The still image camera though is a commercially available low resolution unit which can be integrated cheaply and easily and is sufficient for an occasional attitude fix in combination with the other sensors. A suite of two different sets of accelerometers built by the ARCHIMEDES team and universities in Iasi and Pitesti, Romania gave deceleration and roll rate information. The Miriam Ballute was 4m in diameter and made of UPILEX 25 RN. The ballute had 32 segments which were bonded with a high-temperature high strength UPILEX-RN tape specially manufactured to MIRIAM mission specifications by Lohmann Tapes of Neuwied.
- The Service Module (SM, see Figure 4) contained the inflation system, structural box, release mechanism, a telemetry and a life television subsystem. It also contained a set of cold gas thrusters. These thrusters were used to pull the Service Module away from MIRIAM after inflation.
- The Camera Module which remained attached to the rocket. It documented the release and operation of

the SM/Miriam system, as well as providing the structural interface between the MIRIAM flight system stack and the REXUS payload section. The camera module also contained the release mechanism for the Service Module / Miriam combined system.

All three elements combined formed the MIRIAM Flight System Stack (see Figure 3).

Due to strong cost requirements in the development of MIRIAM's structure, special emphasis had to be put on commercially available and reliable components which are suitable for use in a zero-g and vacuum environment. All components have to also withstand the loads occurring during the launch and the ascent on top of a ballistic rocket.

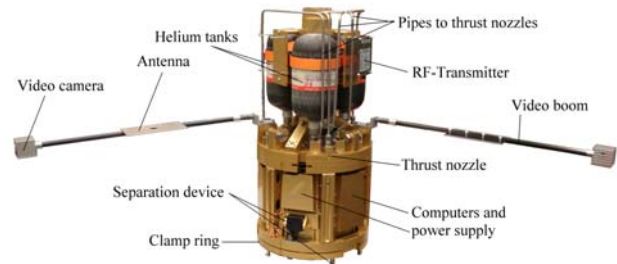


Figure 4. MIRIAM Service Module

The Helium gas was stored in three CFRP pressure tanks at 200 bars (see Figure 4). These tanks are carbon-fibre wound low cost tanks normally used for paintball games. It was found that these components fulfil the MIRIAM requirements very well. To reduce the piping between the tanks and the valves, most of the piping was integrated into the base plate of the inflation systems deck. This plate is divided horizontally into two parts and the plumbing is milled directly into the aluminium plates. Sealing is done by conventional O-rings. Tests have shown that leakage is not a problem. The valves were connected directly to the channels in the base plate via special adapters with integrated gas channels. The only pipes necessary are those for connecting the channels with the thrust nozzles. One more is used to connect the main inflation control valve (ICV) to the central expansion chamber assembly.

Due to weight and volume limitations, no conventional pressure regulator could be used. Two chambers of expansion volumes together with specially designed throttles and an inflation control valve (ICV) were used instead. The ICV was a high pressure injector valve and is controlled dynamically at a high frequency, thereby controlling the inflation hose pressure through pulse width modulation.

The Instrument Pod was directly attached to the ballute. It consisted of a hexagonal shaped thin-walled container, completely milled out of aluminium. It contained all the sensors, camera, transmitter and

computer as well as the batteries of the ballute spacecraft. It was located mainly inside the balloon. The ballute envelope thin film was clamped between the container and the circular cover. This cover had the same curvature as the ballute itself to give the spacecraft a perfectly spherical shape. All communication between the Instrument Pod and the Camera Module (CM) was done via an infra-red link through the camera window.

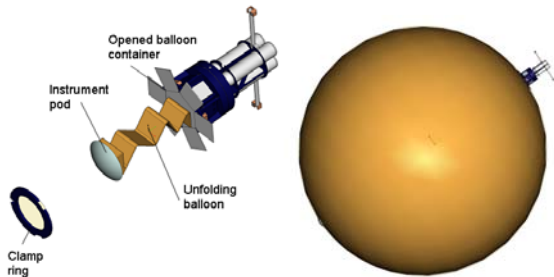


Figure 5. MIRIAM Mission Sequence and Elements: The Deployment (left) and the inflation of the Miriam spacecraft (right). Note size ratio of balloon / service module, which dictates the necessary packaging efficiency

The folded ballute spacecraft was held down inside the spring-loaded deployment container by a clamp ring.

4.1.2. MIRIAM Mission Results

MIRIAM unfortunately did not meet all of its mission goals after one of the three main interlock bolts failed to properly separate the spacecraft from the rocket. As a result the MIRIAM ballute spacecraft was not fully deployed. However, the deployment and inflation control systems functioned as planned, as well as the observation platform, validating the method and yielding important data and experience based upon which an improved system can be designed.

The next step in the development of ARCHIMEDES would therefore be the flight test of an improved version of MIRIAM. Based on the architecture of MIRIAM, its successor would feature not only a different separation mechanism, but also an improved ballute, an improved spacecraft bus and an improved observation system. However, funding for this mission remains to be raised.

4.2. VERTICAL

VERTICAL (VERification and Test of the Initiation of CubeSats After Launch) is a mission of the Institute of Astronautics (LRT) of the TU-München for verification of critical components for the pico-satellite First-MOVE (Munich Orbital Verification Experiment) [2], which will be launched in late 2009.

4.2.1. VERTICAL Mission Objectives

As the purpose of VERTICAL is to verify components which are used very closely after separation of a satellite from a launch vehicle, sounding rockets are a

particularly suitable option for verification of these operations, as mission characteristics are very similar to those of an orbital mission in such an early phase. A flight on a sounding rocket closely simulates the following conditions to those on a CubeSat orbital launcher:

- Load characteristics during ascent phase
- Decrease of pressure to vacuum during ascent phase
- Vacuum environment in high altitudes beyond Earth atmosphere during experiment operations
- Reduced gravity environment during experiment operations

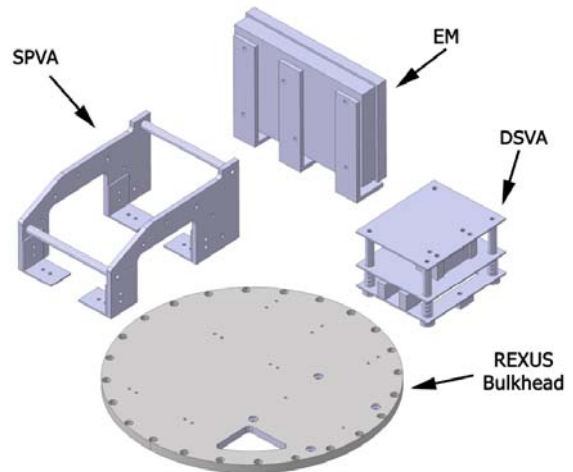


Figure 6. The VERTICAL experiment consists of the Solar Panel Verification Assembly (SPVA), the Deployment Switch Verification Assembly (DSVA) and the Electronics Module (EM) [8]

Verification Items (VI) have been phrased which shall define how those critical systems can be efficiently verified using the flight opportunity on Rexus-4.

- Deployment Switches (DS): Launch service providers require CubeSats to be powered off during launch until deployment. Normally micro switches are used for deployment detection, which detect the loss of contact to the launch vehicle. All following operations, including power up, require feedback from these switches to be initiated. On VERTICAL, a total of 16 commercial switches are verified to cover a broad spectrum of manufacturers, the CubeSat standard only requires one switch on-board.
- VI2 Solar Array Deployment Mechanism (SADM): MOVE's solar panels have to be stowed during launch and cannot be deployed before or during the ejection of the CubeSat from the launch vehicle. The SADM, consisting of a set of springs and a Hold Down Release Mechanism (HDRM) was newly developed at TUM and has no space heritage. The HDRM is activated by melting a nylon wire and the solar panel is deployed by a set of springs.

The function of the DSVA is to verify the deployment switches. A total of 16 micro switches are mounted on two brackets. During the launch the switches have to be depressed. This is accomplished by a so-called retraction plate which is actively pushed towards the switches by an actuator. After launch the switches have to be triggered, then the actuator is commanded to unlock the plate, which is pushed away from the switches by four springs. The retraction plate retracts with 0.2 m/s, which is slower than an actual CubeSat deployment [5].

The SPVA achieves two objectives, it detects the deployment of the solar panel, confirming the HDRM's function and it also measures the panel's motion during deployment. To accomplish this, photo diodes and LEDs are mounted opposite each other on two plates located on both sides of the solar panel. When the panel deploys, the sensors are shaded for a very short time.

4.2.2. VERTICAL Mission Results

Out of the 16 deployment switches, 15 worked as expected. All working switches remained open during the ascent. When the retraction plate was commanded to retract, all switches closed within 73 ms of each other. This was consistent with ground test results and is due to the mechanical configuration of the individual switches.

The HDRM released the solar panel 1.48 s after the melting wire was activated. This was the same duration as observed during ground tests. The maximum panel velocity observed was 1.66 m/s, this is also consistent with ground test results. The EM performed as expected and did not show any anomalous behavior. More detailed results can be found in a paper concerning the performance of the experiment [8].

4.3. HISPICO

One of the main focuses of the technology research at the Chair of Astronautics of the TU Berlin is the development of pico-satellites and their subsystems by involving students. A High Integrated S-Band Transmitter for Pico-Satellites (HISPICO) was developed by TU Berlin and the company IQ wireless GmbH.

4.3.1. HISPICO Experiment Design

HISPICO achieves 1 Mbps data rate with a transmission power of 27 dBm and power consumption of 5 W. These technical parameters can only be reached by the use of modern channel coding algorithms – especially Turbo-code. Turbo-code is typically used in deep-space and large satellite missions. The innovation of HISPICO lies in adoption of turbo-coding for pico-satellite applications. The communication of nearly all launched pico-satellites is UHF based [1]. During the REXUS-4 flight the HISPICO system were mounted on a bulkhead as shown in Figure 7.

4.3.2. HISPICO Mission Results

During 10 minutes rocket flight to an altitude of 175 km the HISPICO got data from PCDH by SPI and transmitted these images' data to the ground station via four S-band patch antennas, that were mounted axial symmetry to the rocket. Also after landing HISPICO operated faultlessly. With this experiment the technical parameters of HISPICO were proved. The expected bit error rate of approximately 10^{-5} was verified. A periodic decrease in signal to interference ratio could be detected during flight. This depends on the interferences of the patch antennas and the remaining rotation of the rocket. At a realistic satellite communication link these interferences do not appear. The successful data link demonstrated the resistance of HISPICO against launch loads and high relative motion, caused by the rocket.



Figure 7. HISPICO system mounted on bulkhead (from top left to bottom right): HISPICO with power splitter, power control and data handling unit (PCDH), camera

4.4. EMSADA

The EMSADA Experiment (Experimental Multiple Sensors And Data Acquisition) of the Luleå University of Technology was mounted in the experiment module. It measured acceleration, pressure and temperature in the experiment.

4.5. REWICAS

The final version of the REWICAS system of the Technical University Luleå consisted of 3 cameras, all placed inside their own box containing individual controlling electronics and a 9V battery. These 3 camera boxes were then connected to the main box where the video was to be stored. All the other components of REWICAS (such as a video receiver, channel chooser, analog-digital recorder, IR-controller, microcontroller and a switching regulator power supply) were mounted inside the main box.

4.5.1. REWICAS Mission Objectives

REWICAS's primary objective was to visually present a sounding rocket's flight path from 3 different angles. Starting from lift-off, the smooth 25 pictures per second video would contain rocket separations, parachute release and later on touch-down. The secondary objective was to test and promote the use of COTS equipment on sounding rockets.

4.5.2. REWICAS Mission Results

Due to an electrical leakage from the batteries of the camera boxes. No video was unfortunately captured from space. This leakage was known and some electrical adjustments were made pre launch. Even so, a slow degradation of the batteries power supply took place during the 24 hour rocket assembly and lift-off preparation, together with the night in storage waiting for launch. Thus, already by lift-off, the batteries were depleted and could not provide any power to the cameras. All other functions operated nominally.

4.6. IGAS (Intelligent GPS Antenna System)

The IGAS experiment was developed at the DLR Mobile Rocket Base and consisted of an intelligent antenna and a standard antenna system with the appropriate GPS receivers. Additionally, a new type of command antenna for P-Band (450 MHz) was qualified. More information can be found in [7].

5. FLIGHT RESULTS

REXUS-4 was launched from Esrange, Sweden on the 22nd of October 2008 at 12:30 UTC. The maximum acceleration of 20.3 g was reached after 2.5 s and the burn-out of the 1st stage was 3.4 s. The rocket was spin-stabilized during the ascent. After the burn-out of the 2nd stage a yoyo system de-spun the rocket at an altitude of 66 km to a rate of only a few degrees per second. At an altitude of 71 km the nosecone was jettisoned. The MIRIAM release was initiated at 76 s but a fully separation of the experiment occurred 13 s later at an altitude of 109 km. The 2nd stage motor was separated from the payload at 112 s in an altitude of 132 km. Because of the late MIRIAM release and impulse of the separating motor on the main payload it approached towards the MIRIAM probe and collided at an altitude of 135 km. Both, the main payload and MIRIAM reached its apogee in 175 km.

The vehicle reached the lower atmosphere at altitudes of <100 km and by definition started the re-entry at 335 s. The maximum deceleration during the descent phase occurred 53 seconds later at 26 km altitude.

The heat shield, stab-chute and beacon of the recovery system were activated at 4.5 km altitude. The stab-chute was de-reefed 5 seconds later and the main chute released at 3.1 km altitude. The payload landed safely on ground and was recovered by the helicopter and

brought back to Esrange one hour later in excellent condition.

6. THE REXUS/BEXUS PROGRAM

The REXUS-4 mission was the maiden flight of a newly developed Service System. After the successful demonstration, it has been implemented into the REXUS/BEXUS programme. This German-Swedish programme allows students from universities and higher education colleges across Europe to carry out scientific and technological experiments on research rockets and balloons. Each year, two rockets and two balloons are launched, carrying up to 20 experiments designed and built by student teams.

The REXUS / BEXUS programme is realised under a Bilateral Agency Agreement between the German Aerospace Center (DLR) and the Swedish National Space Board (SNSB). The Swedish share of the payload has been made available to students from other European countries through a collaboration with the European Space Agency (ESA). EuroLaunch is responsible for the campaign management and operations of the launch vehicles.

Experts from ESA, SSC and DLR provide technical support to the student teams throughout the project. For further information visit www.rexusbexus.net.

7. REFERENCES

1. Alavi R. / Brieß K. / Jäckel K. / Podolski H., *S-Band-Sender für Nano- und Pico-Satelliten*, Deutscher Luft- und Raumfahrtkongress 2008, Darmstadt, Sep. 2008.
2. Czech M., *First-Move in Satellite Development at the TU-München*, 7th IAA Symposium on Small Satellites For Earth Observation, 2009.
3. Ettl J. / Pinzer M., *Principle Design of the Service Module of REXUS*, 19th ESA PAC Symposium, Bad Reichenhall, 2009.
4. Griebel H., *MIRIAM Spaceflight Test Mission Definition*, Version 2R1, The Mars Society Deutschland e.V., March 2007.
5. Lan W, *Poly Picosatellite Orbital Deployer Mk III IC*, California Polytechnic State University, 2007.
6. Löfgen O., *Inertia and balancing report REXUS-4*, SRI10-S2, SSC Esrange, 2008-10-13.
7. Markgraf M. / Ettl. J. / Hassenpflug F. / Turner P., *IGAS – A Novel GPS Antenna Concept for Spin-stabilized Sounding Rockets*, 19th ESA PAC Symposium, Bad Reichenhall, 2009.
8. Olthoff C. / Purschke R. / Winklmeier R., *Testing of Critical Pico-Satellite Systems on the Sounding Rocket REXUS-4*, 7th IAA Symposium on Small Satellites for Earth Observation, 2009.
9. Stamminger A., *REXUS-4 Campaign Report*, EuroLaunch, 2009.