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BREM-SAT - First Flight Results

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Abstract

On February 3, 1994, the small University satellite BREM-SAT was carried into orbit by the Space Shuttle Discovery. The spacecraft waited six days in its Get Away Special (GAS) Container before it was deployed in its initial 350 km high circular orbit. The orbit has 57° inclination, allowing operations from the ground station at the Drop Tower in Bremen

BREM-SAT carries six experiments with different scientific objectives. Experiments using the micro-g environment are operated as well as experiments investigating the low earth orbital environment. Two sensors measure the micrometeorite and dust flux and the atomic oxygen flux. In addition, re-entry experiments will be carried out during the last hours before re-entry, which is expected in January 1995. One of these experiments determines the gas/surface interaction, the other experiment uses deployable temperature and pressure sensors for measurements shortly before re-entry.

The experience of operating a small, but complex and versatile platform with ambitious objectives will be described in detail. First results of the spacecraft operations, especially the attitude control operations, are presented.
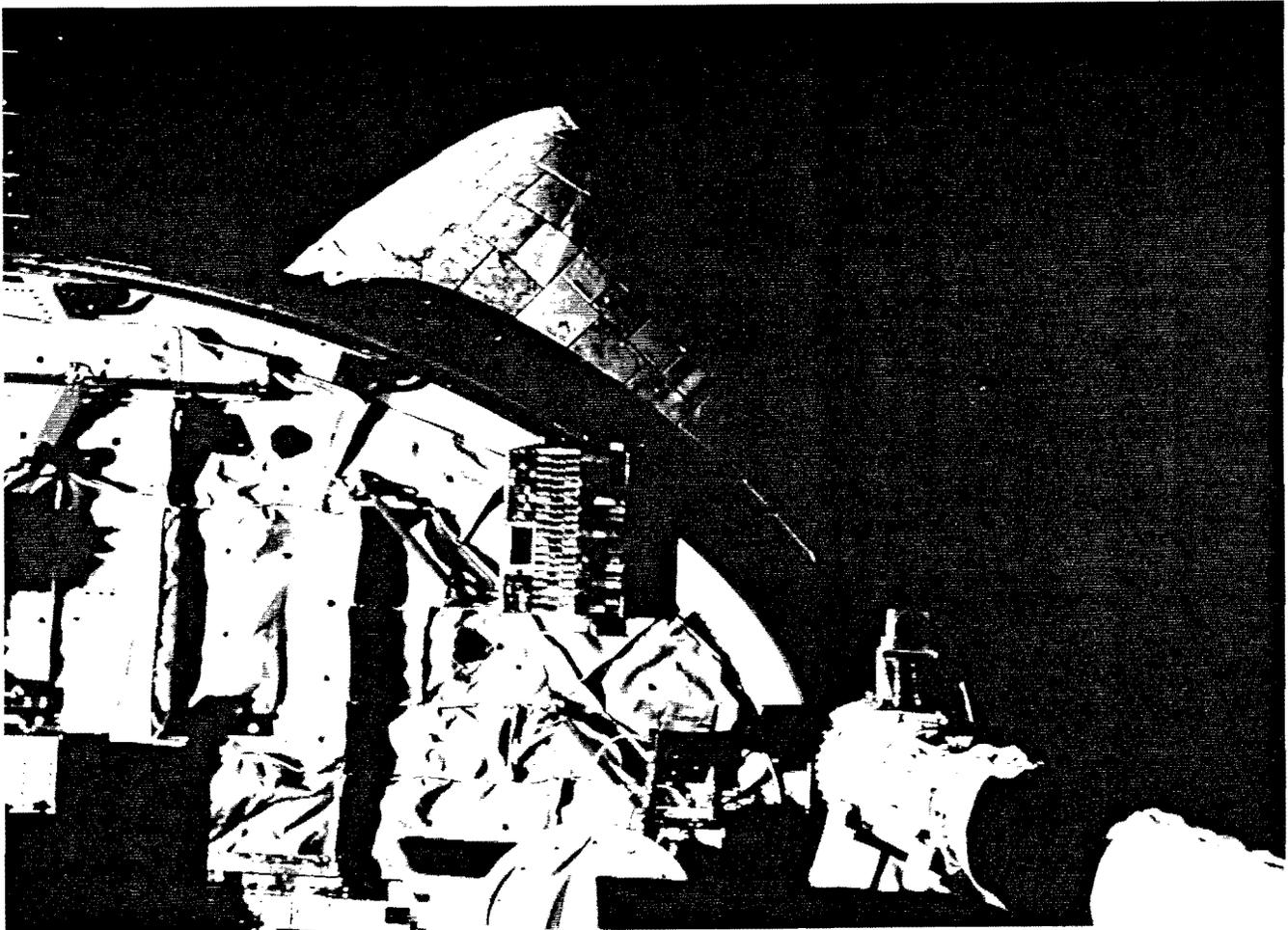
Photograph of BREM-SAT taken by the Space Shuttle STS-60 crew during deploy. The GAS-canister lid is visible at the lower part of the picture. The dust detector of BREM-SAT can be seen on the left side of the spacecraft with a small hole for the atomic oxygen sensor below it. Photograph : NASA

1. Introduction

The BREM-SAT satellite was launched successfully with the STS-60 Shuttle mission on February 3, 1994. Six days later, the small university satellite was deployed into a 350 km circular orbit.

BREM-SAT (fig.1) was carried in a GAS (Get-Away-Special) canister, which permits a 520 mm height and a diameter of 480 mm. 68 kg mass are admissible for a deployable satellite, and BREM-SAT reached only 63 kg. In spite of the mass and volume restrictions, six scientific experiments have been integrated on the spacecraft, which became a small multi-purpose experimental carrier.

The BREM-SAT launch was the second attempt after the satellite was removed from the D-2 mission (STS-55) early 1993. The ejection pedestal, which is necessary to deploy a satellite from the GAS-container, had a malfunction on an earlier mission and was therefore modified by safety considerations. This led to a different orbit, with 57° inclination (instead of 28°) and lifetime of 11 months, 8 months more than originally planned. The satellite itself was adapted to that specific mission mainly by software changes.
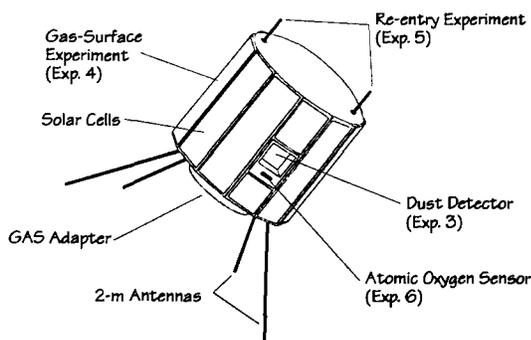

Fig. 1) BREM-SAT

2. The Mission Phases

Small satellites without deployable solar arrays typically have a small power budget. To overcome some restrictions, the mission was divided into three phases: the *microgravity (µg)*, the *orbital* and the *re-*

entry phase. The µg-phase started right after launch for 48 hours, until the satellite was ready for deploy. The time from deploy to re-entry is the standard orbital period. At lower altitudes, when operation is usually stopped, BREM-SAT performs two experiments for the re-entry phase, which lasts about 1-2 days[1]. All mission phases have specific requirements for telemetry, power and attitude subsystems. The comparably short µg-phase has been extended into the orbital phase to allow more measurements.

3. The Scientific Payload

The six experiments have numbers, which do not represent their order of operation, but formally acceptance as payload.

Microgravity Phase

- Experiment-1, Determination of thermal conductivity of fluid mixtures
- Experiment-2, Measurement of residual accelerations

Experiment-1 is needed for the precise measurement of the heat conductivity of low-viscosity fluid mixtures [1,2]. The measurements under microgravity, without the interference of thermal convection, provide reference data for the estimation of errors inherent to terrestrial measurements. The instationary hot-wire method used here is based on the measurements of transient temperatures and requires less measurement duration than stationary methods like the two plate method. A thin hot wire is mounted in the center of the cylindrical measurement cell. The temperature of the wire increases if heated with constant power, producing a constant heat flux per unit length. A small portion of it heats the wire itself, whereas the main part heats the surrounding fluid mixture. The variation of the wire temperature depends on the heat conductivity of the media and the supplied heat flux. It is

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[1]This phase is finished when blackout at the antenna occurs

measured with the change in electrical resistance of the heatwire.

Additional heating elements allow to vary the initial temperature of the measurement cell to determine the relation between thermal conductivity and temperature. With a piston system, the concentration of the two test fluids is changed during the measurements. The design of the experiment allows autonomous operations. A microcomputer performs the heating and mixing, and stores the data for the next ground station contact. The experiment needs one of four compartments of the spacecraft and has a mass of 5.1 kg. The measurements of experiment-1 are supported by an acceleration sensor package, listed as experiment-2. This package provides further support during the re-entry experiments. Without a dedicated micro-controller, its data can only be accessed via the experiment-1 or -4/5 microcontrollers.

Orbital Phase

- Experiment 3, Measurements of micrometeorites and dust distribution in low Earth orbit
- Experiment 6, Atomic Oxygen Sensor

The dust detector is used to provide impact data of micrometeorites as well as data of man-made debris at the lower mass scale. Particles from 10^{-10} to 10^{-18} kg and with velocities between 1 and 70 km/s are investigated [3,4]. Dust particles impacting on a target are ionised and separated by high voltage collectors. Two charge-sensitive amplifiers record the signal of an ion and an electron channel. To overcome the disturbing noise level, the experiment is designed to store the whole charge signal and transmit it to the ground station. The complete signal shape can be inspected then and valuable information about the noise environment in space can be obtained. The sensor with complete data measurement electronics and microcontroller weighs only 650 gr. and consumes about 2 W. With its modest dimensions of app. $160 \times 100 \times 100$ mm it fits perfectly into a small satellite. The target area of the experiment can be seen on the photograph of the satellite deploy on the abstract page. The experiment was started on Feb. 17., 1994 and recorded already hundreds of impacts.

Although the energy of atomic oxygen is low (<0.1eV thermal energy), the high relative velocity results in erosion and degradation of most organic and a few metallic materials. In some cases, this can change surface characteristics significantly. Quantitative evaluations of these effects require a reliable prediction of the atomic oxygen distribution. Two piezo-crystals, coated with carbon, are exposed to the flow, and their eigenfrequencies and temperatures are measured periodically. The temperature measurement is necessary to compensate temperature effects (drift) on the frequency. With erosion of the carbon layer, the eigenfrequency changes. This frequency data need to be correlated with actual position and attitude data for further processing. Up to now, several ten thousands of measurements have been made. This experiment is a contribution of ESA/ESTEC [5].

Re-entry Phase

- Experiment 4, Measurement of the gas-surface interaction
- Experiment 5, Re-entry flow experiment

The interaction between the gas particles of the atmosphere and the satellite surface determines the spacecraft aerodynamic characteristics. Theoretical models which allow practical usage can not describe this phenomena, and semi-empirical models are widely used. Input data are provided by gas-surface experiments which measure either the spatial distribution of the reflected molecular flux or the resulting forces on the surface [2]. For BREM-SAT, one panel of the solar array is connected to a two-component micro-balance. During launch and the orbital phase this panel is

locked, and shortly before the measurement starts, it will be released. For a clear experiment signal a minimum force is necessary, or a minimum atmospheric density. On the other hand, a stable attitude is necessary, which defines the lower limit of the experiment-4 operation [6].

As planned now, this experiment will be activated in 180 km altitude and run for 3-4 hours.

Although BREM-SAT is not a re-entry capsule, we want to use the first re-entry phase for important measurements [6, 8]. Two free molecular sensors, mounted on deployable devices, measure the free molecular particle and heat flux. The corresponding quantities on the surface are measured by similar sensors, fig. 2. Opposite to the deployed sensors, the surface quantities are influenced by first collision phenomena. Comparison of the two measurements, one in undisturbed flow and one in the satellite flow field, is valuable for Monte-Carlo simulation methods of real orbital conditions.

The re-entry experiment requires special operations of the satellite attitude control and the ground station teams. After experiment 4 is finished, aerodynamic stabilisation is necessary. The momentum wheel, which gave stability during the orbital phase, is ejected and four flaps at the spacecraft bottom are then deployed for better aerodynamic stability. Mobile groundstations are distributed around the world at predetermined locations. At higher north and south geographic latitudes the probability to receive the satellite's last signal is comparably higher than at lower latitudes. The locations of the mobile stations are co-ordinated from the Technical University of Brunswick, responsible for orbit and re-entry prediction [7].
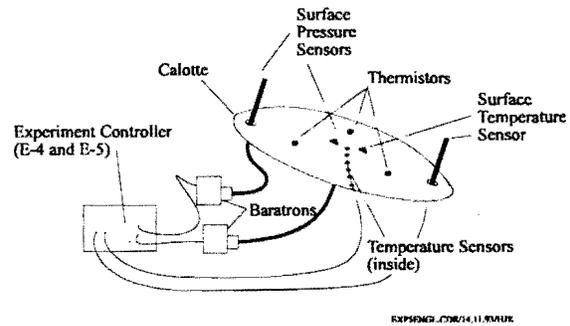

Fig. 2) Re-entry experiment sensors

4. Flight Data

The flight data contain experiment data, during the orbital phase mainly dust detector data and atomic oxygen measurements, and housekeeping data. The dust detector transmits 64 KByte of recorded impact data every day, which must be correlated with position and attitude data. The atomic oxygen sensor transmits about 10 KByte daily, but these data contain also history data from the magnetometer and the batteries. The data are distributed via mailbox and ftp-server to the experimenters (fig. 4).

4.1 Orbit

As stated above, the initial orbit was higher than originally expected. With 350 km altitude and an almost circular orbit, the lifetime is expected to be little less than a year. The actual re-entry date is important for the last two experiments and moved from January 5th to January 23th during the first five months of the mission, mainly due to actual lower solar activity than predicted. The daily decrease in semimajor axis is 150 to 200 m (average value 180 m), resulting in a decrease as shown in fig. 3. For comparison, an analytical solution for lifetime estimation of low earth orbiting satellites is given.
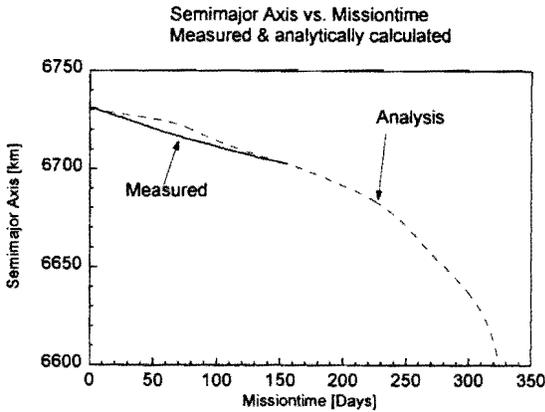
Fig. 3 Semimajor Axis BREM-SAT

4.2 Telemetry/Telecommand

The first days after deploy were necessary to adjust the main ground station at the ZARM Drop Tower in Bremen to our (real) needs. Filters were needed to de-

crease the environmental noise in the 2 m frequency, which is used for up- and down-link. Downlink data rate is 9600 baud, uplink data rate is 1200 baud. The spacecraft does not transmit data automatically, only if requested by the ground station. One exception is the "pre-programmed" data transmission, which has been implemented for mobile ground stations without telecommand capabilities. The configuration of the main ground station which is used now is shown in fig. 4. Every day, 5-6 successive contacts with BREM-SAT are possible, before the satellite is unreachable for about 16 hours again.
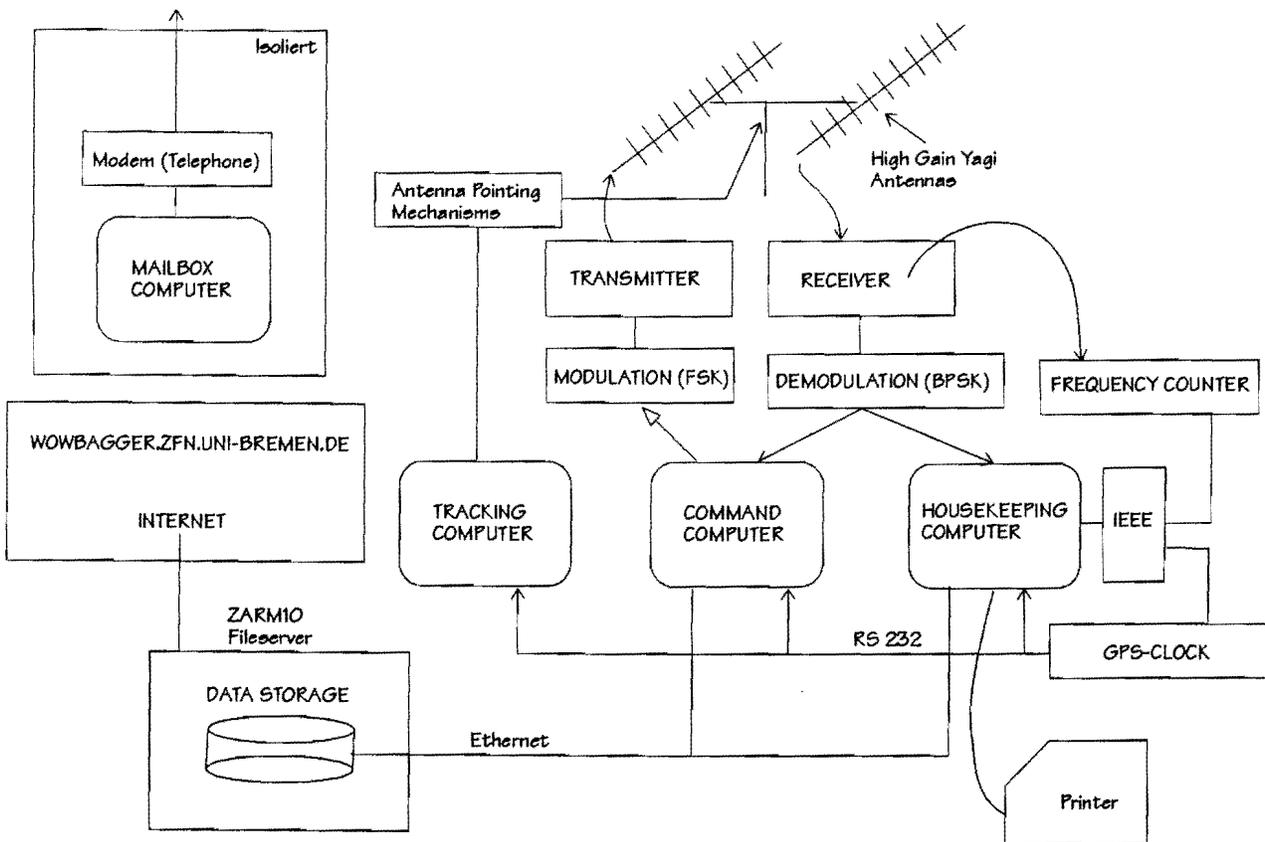

Fig. 4) The BREM-SAT groundstation configuration at the Drop Tower, Bremen, Germany

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4.2 Thermal

Due to the higher inclination and higher altitude, the eclipse phases are shorter than expected earlier. This results in higher temperatures than determined for the 28° inclination orbit. Fig. 5 shows the eclipse time calculated analytically and the time measured with the onboard clock. It is interesting to see that there are periods of 4-5 days without any shadow. The solar generator data show that partial shadowing does occur during that times.

Calculated and MeasuredShadow Tims vs. Missiontime
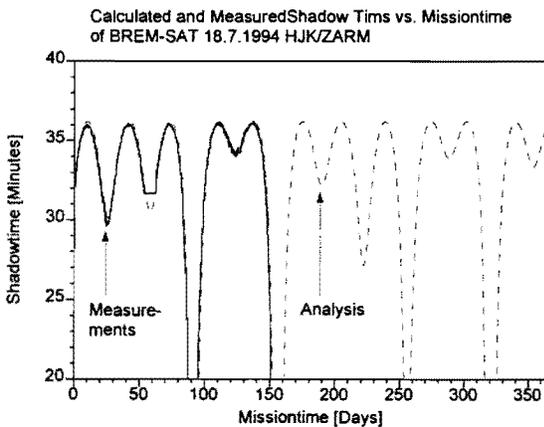of BREM-SAT 18.7.1994 HJK/ZARM

Fig. 5) Comparison of calculated and measured eclipse time

Shadowless periods increase the spacecraft temperature significantly. The average temperature of 28°C increases to 52°C during the first shadowless period on mission days 89 to 94. The temperature also varies with the sun angle, it is lower, if the black[2] cap of BREM-SAT points to the sun than if the spacecraft bottom (aludyne) is in sunlight. It should be noted, that due to an offset of the sun sensor[3] usually the spacecraft bottom is in sunlight at a low angle (~10°).

4.3 Power Subsystem

The average power available from the solar generator is between 25 and 30 Watts. Of course, all effects like temperature and atti-

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[2]The color is not a dull black but a little bright.
[3]To be precise, the offsets occurs at the signal conditioning and not at the sensor. The small offset is not a problem for the power supply and have therefore not been corrected.

tude must be considered to determine the performance of the generator. The flight data for input power and power required by the system are shown in fig. 6. These data include eclipse times (e.g. around day 20) where the input power is 0 during ground station contact. The power required by the system includes power for battery charging, which is also 0 at eclipse times. It should be noted, that all data are collected during ground station contact, when telemetry is switched on. The power required by the satellite without charging the batteries while transmitting data is around 22 Watts. For all satellites systems without telemetry, about 10 Watts must be subtracted. Large spikes on day 90 show the energy required by the µg experiment while heating the fluids. This overload needed substantial battery capacity although BREM-SAT was continuously in full sunlight. Fig. 7 shows the effect on the batteries, and the recovery of it after the experiment has been switched off.
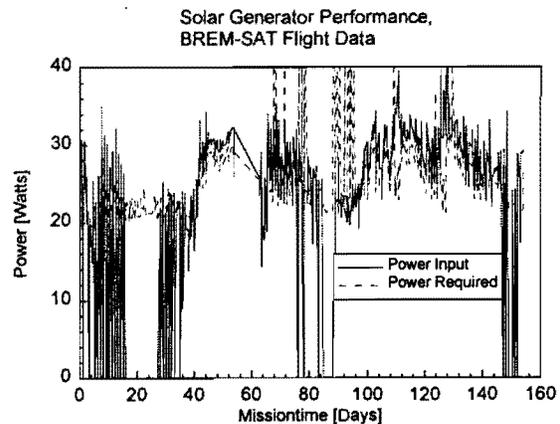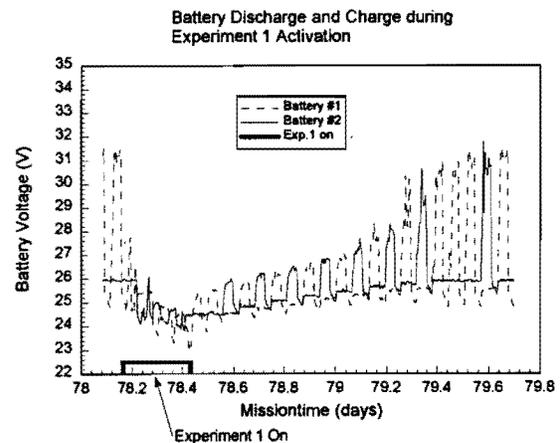
Solar Generator Performance,
BREM-SAT Flight Data

Fig. 6 Power Input/Output

Battery Discharge and Charge during
Experiment 1 Activation

Fig. 7 Battery Discharge/Charge

4.5 Attitude

Attitude control is the subsystem which requires most attention during the mission. BREM-SAT has a momentum wheel with the spin axis aligned to the spacecraft's Z-axis (the axis of symmetry, fig. 1), and is slowly spinning around this axis. The rotation rate can be controlled by the momentum wheel, and for attitude corrections a single magnetic torquer is used [8]. The attitude sensors consist of a slit sun sensor, a star sensor and a magnetometer. Technical problems with the star sensor hardware, mainly caused by thermal cycles and the camera sensitivity to temperature, forced the ground station team to develop other methods for finding the attitude history. We developed a magnetic attitude determination algorithm, based only upon magnetometer data. This algorithm uses the fact that the earth magnetic field changes comparably fast with respect to the satellite coordinate axis. The magnetometer output is measured every 5 minutes and stored with experiment 6 data. The mission time of each data set is correlated to the real time, including corrections for the onboard clock. The position of BREM-SAT is determined using high-accuracy orbit prediction software and state vectors determined by Doppler measurements [7] and radar measurements. For the position of the measurement, the Earth magnetic field is calculated with the IGRF model in inertial (M-50) coordinates.

The angle between the satellite's Z-axis and the measured magnetic field has been determined earlier. Then, a circle with that angle is drawn around the calculated magnetic field vector. The satellites Z-axis must be on that circle, if the measurement and the model would be perfect. A second measurement, recorded a few minutes later, gives a different circle around a different geomagnetic field vector and narrows the Z-axis attitude to only two positions in most cases. In the real application, 25 to 50 measurements are used, and the Z-axis can

be found where all circles meet. Fig. 8 shows an example of magnetometer measurements which has been processed as described and plotted on a unit sphere for better demonstration. The Z-axis attitude can be determined either visually or with the computer, basically counting points per sphere element. With more advanced evaluation, the attitude determination would be easier and more reliable.
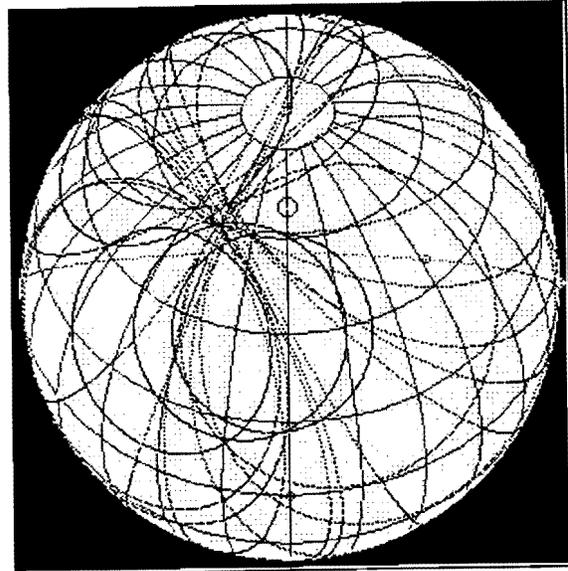

Fig. 8 Unit sphere with Z-axis circles from magnetometer measurements. +Z attitude is -120°/60° (the -Y axis points out of the paper).

The flight data were surprising from the first contact. When all control algorithms were switched off, the spin rate of BREM-SAT increased by 0.12 RPM per day, although the configuration gives no reason for a disturbance torque in Z-axis direction. The only explanation is a magnetic moment caused by the solar generator (i.e. with inertial fixed components), because a static magnetic moment would not have this effect. With active control loops, the momentum wheel compensates this effect, but charging and discharging the momentum wheel is frequently necessary. The allowable limits of the momentum wheel speed are set by telecommand, and most of the time during the mission the wheel speed is either at the lower or the upper limit - which can be seen in fig. 9.

During the period from day 70 to 110 both limits had been set to a lower value than usual. The behaviour of the momentum wheel demonstrates the function of the charge/discharge control mode, working only with a magnetometer and the magnetic torquer. The magnetometer data enable or disable this mode, allowing attitude control and charge/discharge depending on the magnetic field vector attitude with respect to the BREM-SAT coordinate system.
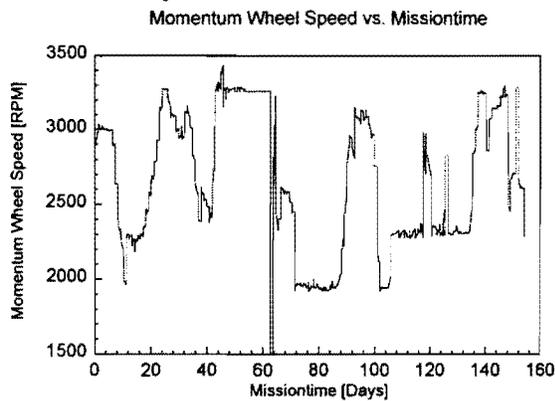

Fig. 9 Momentum wheel speed

Beside the large variation of the rotation rate we found a faster motion of the satellite than expected. The numerical analysis, which had been performed prior to launch, included mainly aerodynamic torques, which usually is the highest torque in a low Earth orbit. The motion had a large component in the orbital plane, which could not be explained with aerodynamic but with magnetic disturbance torque. Beside a small dipole moment created by the solar generator, the whole spacecraft has a large dipole moment causing comparably fast motion. This is shown in fig. 10 and 11, where measured data are compared to simulated data with an updated satellite model (0.8 Am^2 dipole moment in Z-axis, 0.04 Am^2 towards the sun). The measured data had been generated from magnetometer data. The attitude control was switched off during these two periods to determine the disturbance torques.
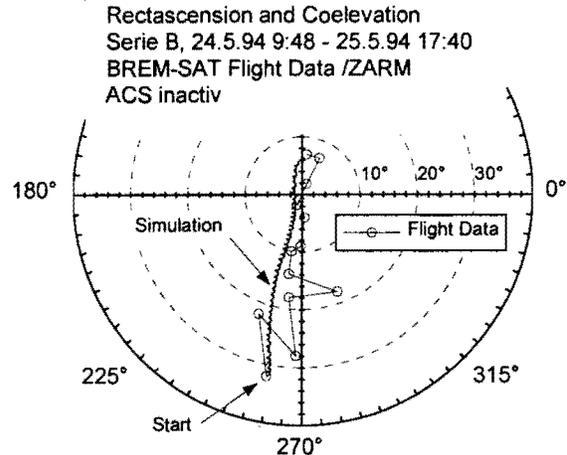

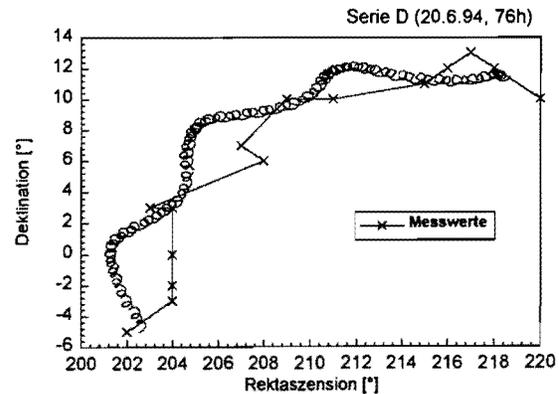Fig. 10 Attitude motion of the +Z-axis

Fig. 11 Attitude motion of the +Z-axis

4.6 Anomalies

BREM-SAT is a extremely reliable spacecraft, which originally was built for only 60-90 days. 55 days after launch contact was lost, but could be established again after a week. Later analysis of housekeeping data showed that there was no hardware damage or any hint of a malfunction. Because these anomaly occurred during a period of very high geomagnetic activity (ap-value more than 75), and during a pass over the geomagnetic South Atlantic Anomaly, we assume that a single event upset caused that telemetry was not switched on [9,10]. However, the true reason can never be verified. The recovery of the spacecraft demonstrated its flexibility. It was found to be in flat spin with the momentum wheel switched off. The rotation was fast (5 RPM measured by radar),

and housekeeping data were confusing due to the high spin rate. Because one of the solar panels was always in sunlight, the rotation axis could be determined. When the momentum wheel was switched on again and set to the predetermined speed, attitude was almost immediately recovered. Nutations were damped very fast within one orbit.

5. Conclusion

BREM-SAT has already successfully demonstrated the usage of small satellites for scientific research in different areas. Although the satellite does not have redundant components, its flexibility allows to work with unexpected anomalies. The longer lifetime increases the scientific output significantly and allows a careful planning of the important re-entry experiments, which would have been much more difficult with the originally planned lifetime.

Acknowledgements

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