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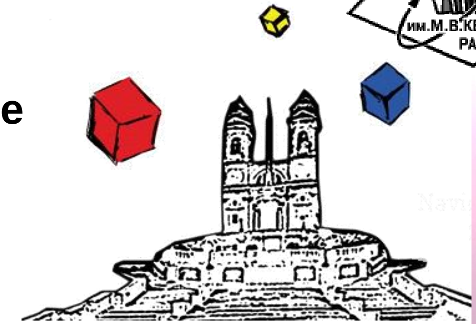

Flight Results From Passively Magnetic Stabilized Single Unit CubeSat

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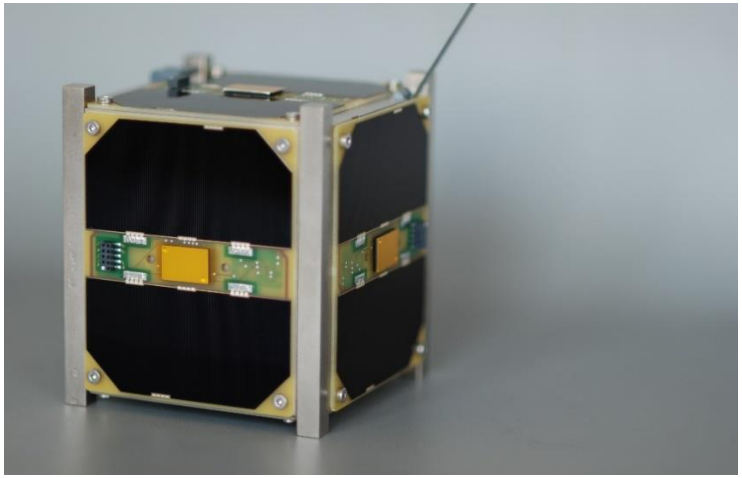
BEESAT-3 Nanosatellite

- **Mission goals:**
  - education of students of Technische Universität Berlin
  - orbit demonstration of a newly developed S-band transmitter
- **Attitude control system:**
  - passive magnetic:
    permanent magnet, hysteresis plate
- **Attitude sensors:**
  - six Sun sensors
- **Inertia tensor and mass:**

$$J=\begin{bmatrix}3 & 0 & 0\\ 0 & 2.5 & 0\\ 0 & 0 & 2.5\end{bmatrix}\cdot 10^{-3}\,\mathrm{kg}\cdot\mathrm{m}^2;\quad m=973\ \mathrm{g}$$



Picture of the BEESAT-3 flight model in the laboratory during testing

- **Launch date:**
  - April 19, 2013
- **Orbit:**
  - 575 km
  - Inclination 64 deg

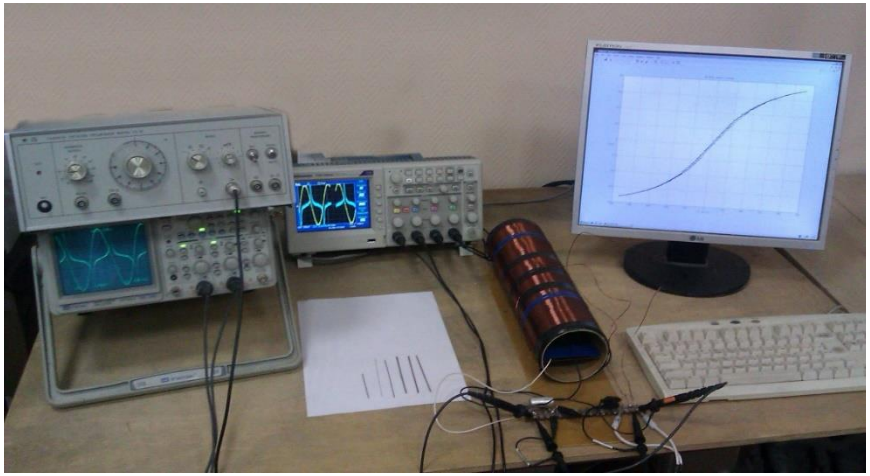
ACS parameters

- Permanent magnet magnetic moment $m = 0.126\ \mathrm{A \cdot m^2}$
- Magnetic parameter of BEESAT-3

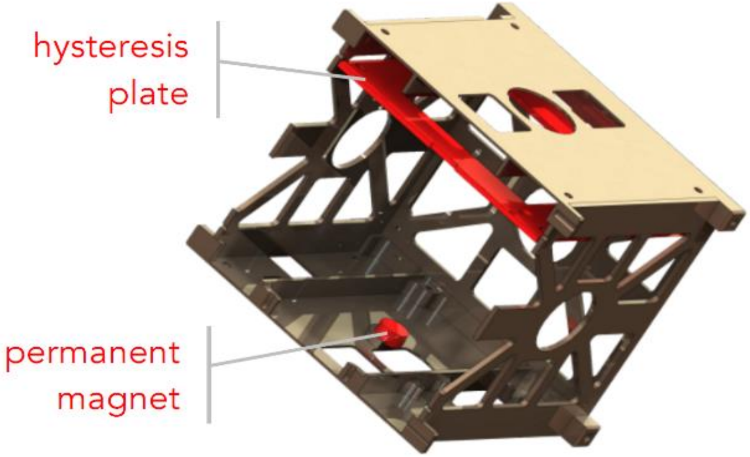
$$\eta = mB_0 / \left(A\omega_0^2 \right) = 1085$$

is far from the resonance effect

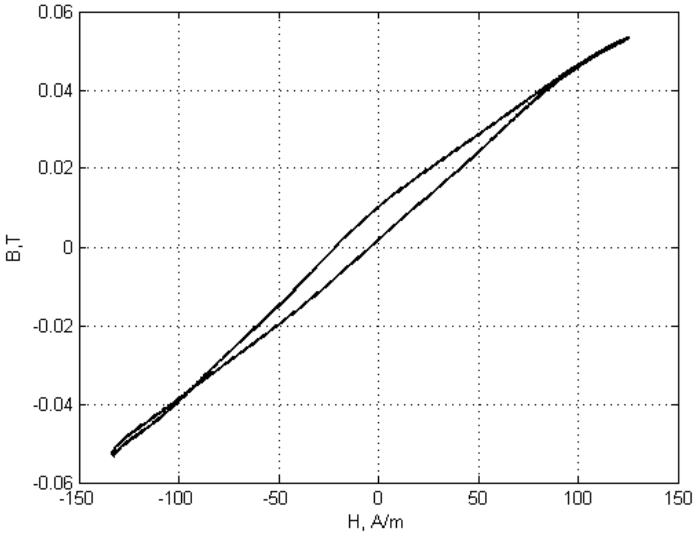
- Hysteresis loop of the plate is obtained using the laboratory facility



Laboratory facility for the hysteresis damper parameters determination



Elements of the passive magnetic attitude control system



Hysteresis plate curve

Magnetic attitude and communication

- BEESAT-3 is to be stabilized relative to the local geomagnetic field
- The angle between the magnetic field lines and the Earth's surface is approximately 67 degrees at the location of the ground station in Berlin
- Off-nadir angle of 23 degrees is expected during passes
- 85 degrees opening angle of the S-band patch antenna allows for sufficiently long contact times

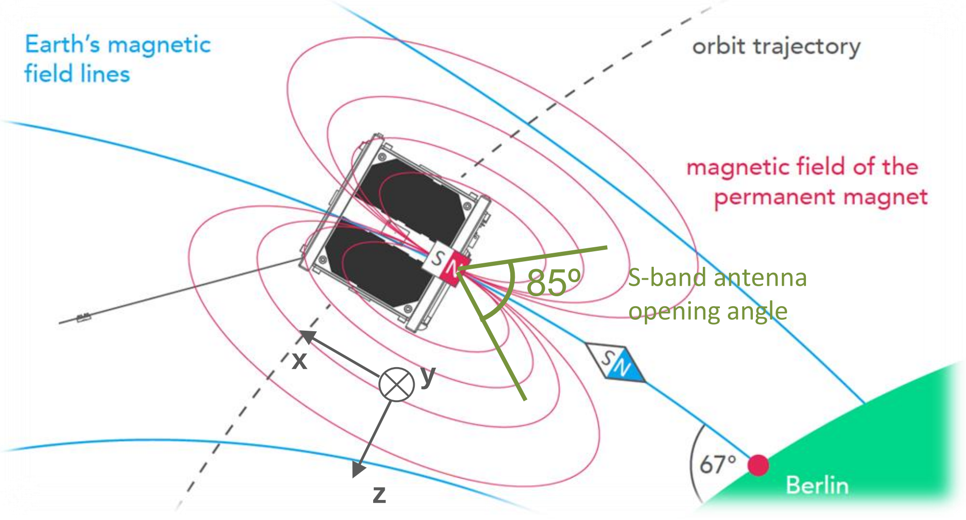
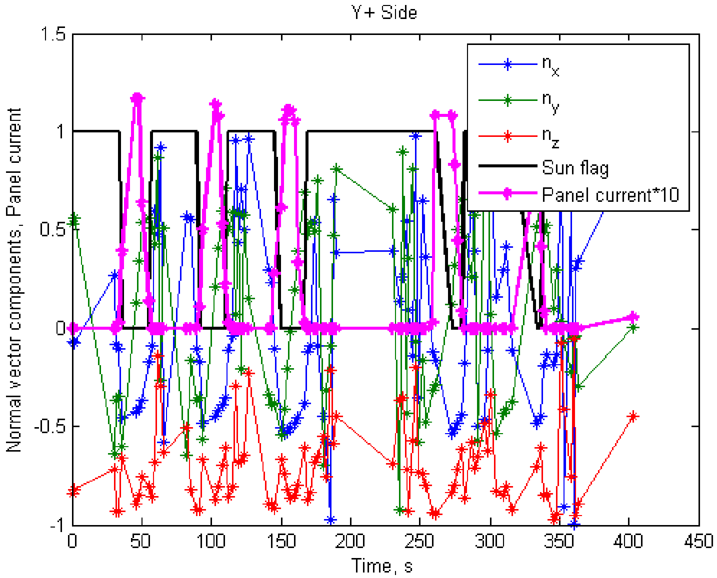


Illustration of the interaction of the passive attitude control system with Earth's magnetic field while passing the ground station in Berlin

Commissioning after five years in orbit

- After the launch in April 2013
  the communication with the BEESAT-3
  was not established
- After almost five years
  the first signal from BEESAT-3
  was received in January 2018 and
  since then the satellite operates regularly
- The retrieved telemetry includes the Sun sensor data and measurements from the solar panels
- The attitude motion of the satellite is reconstructed and the steady-state motion parameters are evaluated



Example of the Sun sensor and
solar panel measurements from Y+ side
obtained 10.01.2019

Attitude motion reconstruction technique

Motion equations

$$\mathbf{J}\dot{\boldsymbol{\Omega}} + \boldsymbol{\Omega} \times \mathbf{J}\boldsymbol{\Omega} = \mathbf{M}_{mag} + \mathbf{M}_{grav} + \mathbf{M}_{hist}$$

$$\dot{\Lambda} = \frac{1}{2}\mathbf{C}\Lambda \qquad \Lambda = \left(\mathbf{q}, q_0\right)$$

Sun sensor measurements model

$$\mathbf{S}_{\text{meas}} = \mathbf{A}\mathbf{S}_{o}$$

Initial conditions vector

$$\boldsymbol{\xi} = \left[q_1(t=0), q_2(t=0), q_{3,}(t=0), \omega_1(t=0), \omega_2(t=0), \omega_3(t=0)\right]^T$$

The problem of the vector of initial conditions determination reduces to the problem of the following function minimization

$$\Phi(\boldsymbol{\xi}) = \sum_{k=1}^{N}\left(\left|\tilde{\mathbf{S}}^{k}_{\text{model}} - \mathbf{S}^{k}_{\text{meas}}\right|\right)^2$$

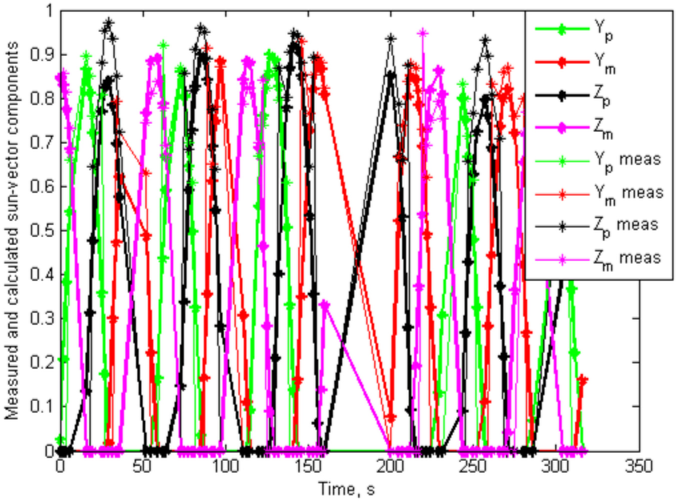
$\mathbf{S}^{i}_{\text{meas}}$ is the Sun direction vector obtained using measurements

$\tilde{\mathbf{S}}^{i}_{\text{model}}$ is the Sun direction vector calculated using model

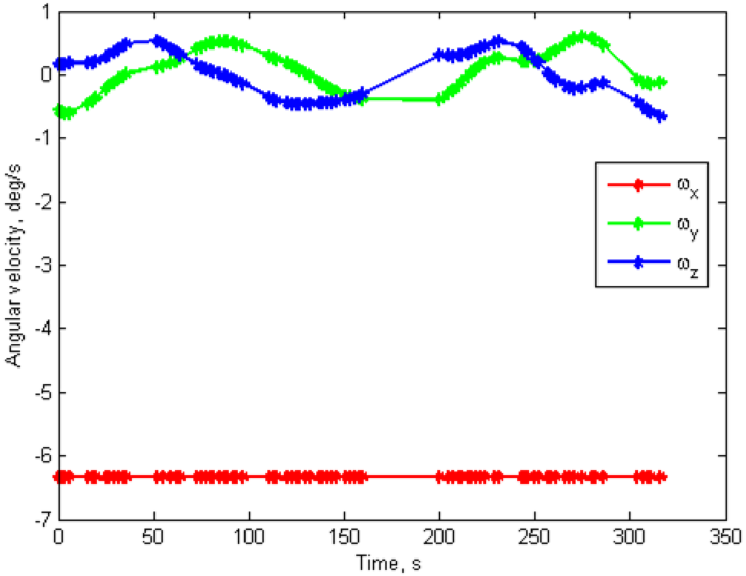
Measurements processing results

- Using the Sun sensor measurements the attitude motion is reconstructed
- The initial conditions for the motion equations are obtained

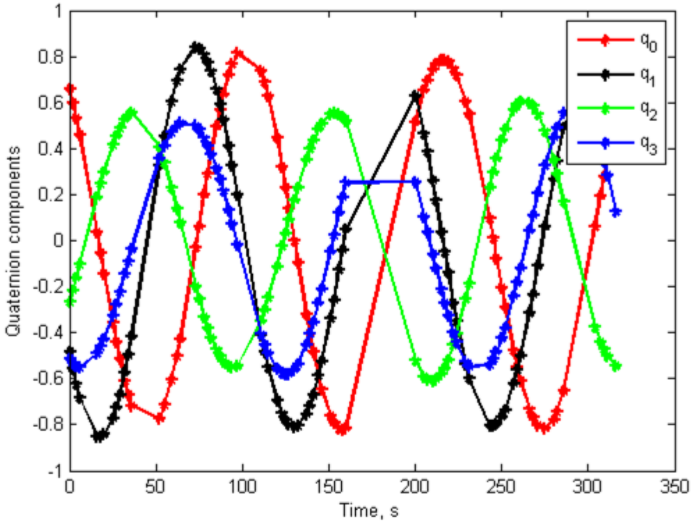
$$\boldsymbol{\omega}_0 = \begin{bmatrix} -6.33 \\ -0.57 \\ 0.16 \end{bmatrix} \mathrm{deg}/s \qquad \Lambda_0 = \begin{bmatrix} 0.67 \\ -0.46 \\ -0.28 \\ -0.50 \end{bmatrix}.$$



Measured and predicted Sun direction vector



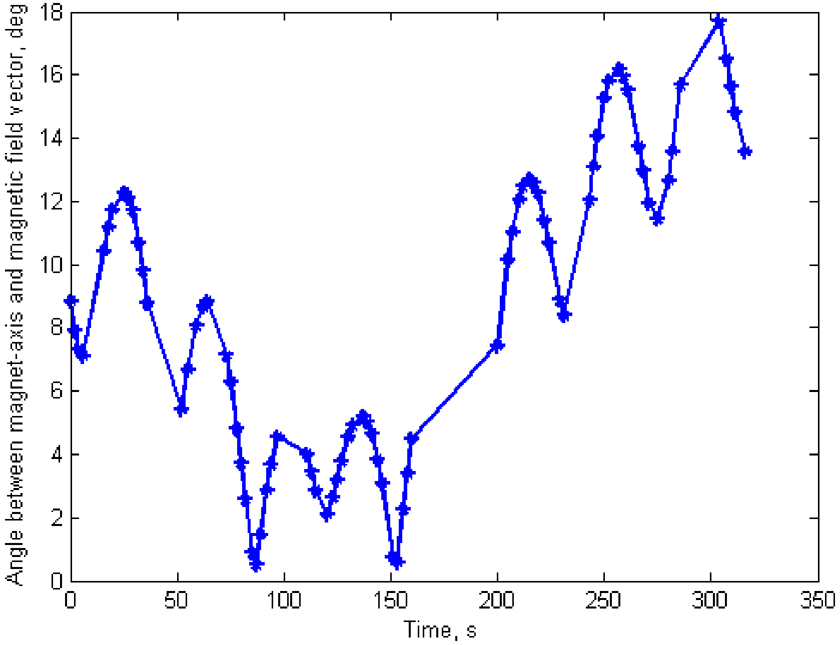
Estimated angular velocity vector



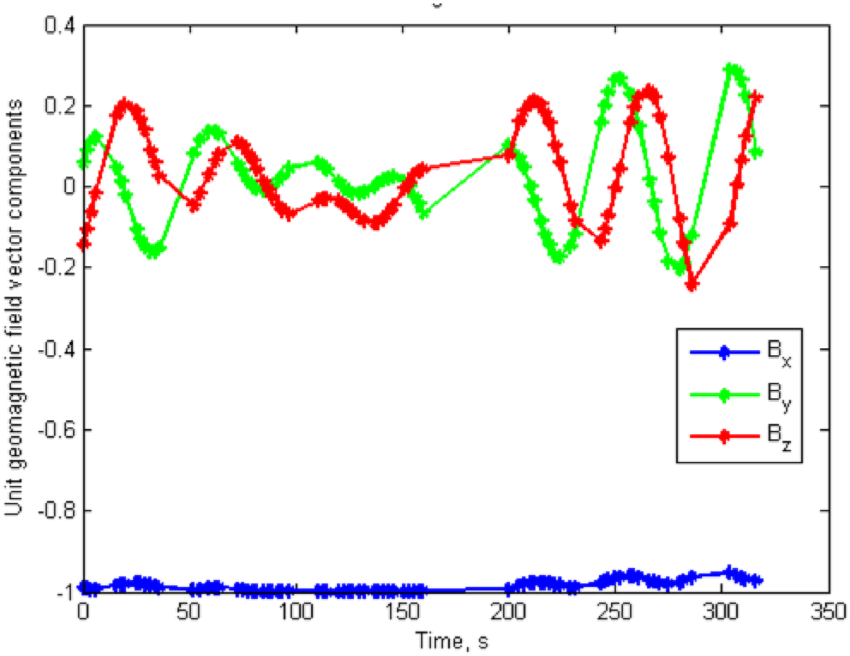
Estimated attitude quaternion

Magnetic stabilization

- Direction of the geomagnetic field vector in the body reference frame is obtained using the reconstructed model and IGRF model
- The deviation of X-axis from the local magnetic field does not exceed 18 deg
- The oscillations of this axis are caused by the stabilizing torque produced by the permanent magnet



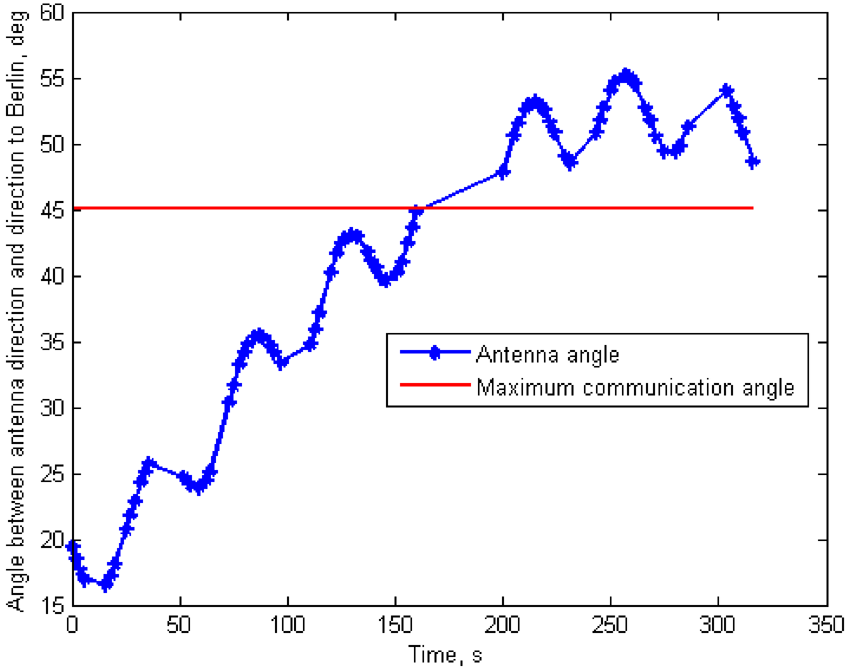
Deviation of the magnetic field vector from the satellite X-axis



Calculated magnetic field vector in satellite body reference frame

S-band antenna orientation

- Position of the satellite is calculated using TLEs and SGP4 model
- Using estimated attitude the angle between the direction of the S-band antenna and the direction towards the ground station in Berlin is obtained
- Initially the deviation was about 20 degrees
- After 200 seconds the antenna direction deviates up to 45 degrees that is close to the maximum angle for communication via the S-band antenna (opening angle of the cone is about 90 degrees)
- Nevertheless, this magnetic attitude allowed to receive data from the onboard camera



Angle between the transmission axis of the S-band antenna and the direction towards the ground station in Berlin

Conclusion

- Attitude reconstruction of the single unit CubeSat BEESAT-3 was performed by processing the Sun sensor readings
- In steady state motion the satellite rotates around the X-axis with angular velocity of approximately six degrees per second and oscillates with the velocity amplitude of about one degree per second around other two axes
- The passive attitude control system demonstrates the stabilization accuracy of 18 degrees relative to the local geomagnetic field
- The achieved attitude control allows to downlink data via the S-band during passes above the ground station in Berlin

Thank you for your attention!

Images of the Earth taken by BEESAT-3 in September 2018, which were received via the S-band