5th IAA Conference on University Satellite Missions and CubeSat Workshop
January 28-31, 2020, Italy, Rome

Flight Experimentation with Magnetic Attitude Control System of SiriusSat-1&2 Nanosatellites

Dmitry Roldugin, Danil Ivanov, Stepan Tkachev, Roman Zharkih, Artem Kudryavtsev

Keldysh Institute of Applied Mathematics of RAS
SPUTNIX LLC

Content

- SiriusSat-1&2 details
- On-flight sensors calibration
- Attitude and magnetometer bias estimation
- Algorithms testing results
- Conclusions

Nanosatellites SiriusSat-1&2

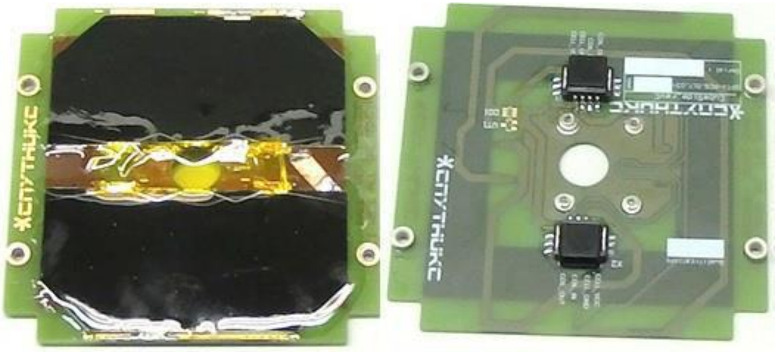
- **SiriusSat-1&2**
  - assembled by school students in a collaboration with SPUTNIX specialists
  - educational and space weather monitoring 1U CubeSats
- **Attitude control system:**
  - active magnetic:
    air core magnetorquers inbuilt in solar panels
- **Attitude sensors:**
  - magnetometer
  - angular velocity sensor
- **Inertia tensor and mass:**

Photo of the SiriusSat-1&2

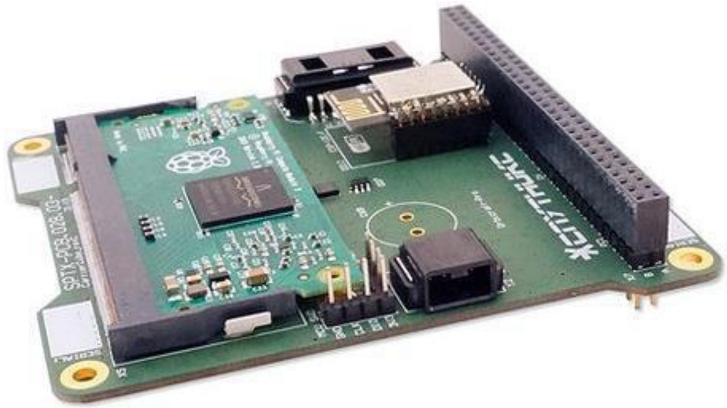
$$J = \begin{bmatrix} 6.9 & 0.3 & 0 \\ 0.3 & 6.9 & 0 \\ 0 & 0 & 2.9 \end{bmatrix} \cdot 10^{-3} \mathrm{kg} \cdot \mathrm{m}^2; \qquad m = 1.45\ \mathrm{kg}$$

ADCS parameters

- The SiriusSats satellites consist of:
  - main stack of electronic devices
  - an assembly frame
  - solar panels
- The on-board computer module SXC-MB-04 contains the following set of devices:
  - slot for the Raspberry-Pi CM3 processor
  - power supply system
  - angular velocity sensor and magnetometer
  - control unit for magnetorquers



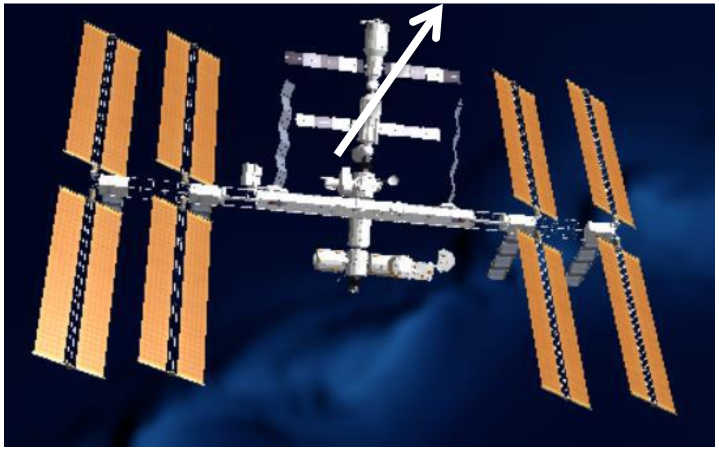
Solar panels and inbuilt air core magnetic coils



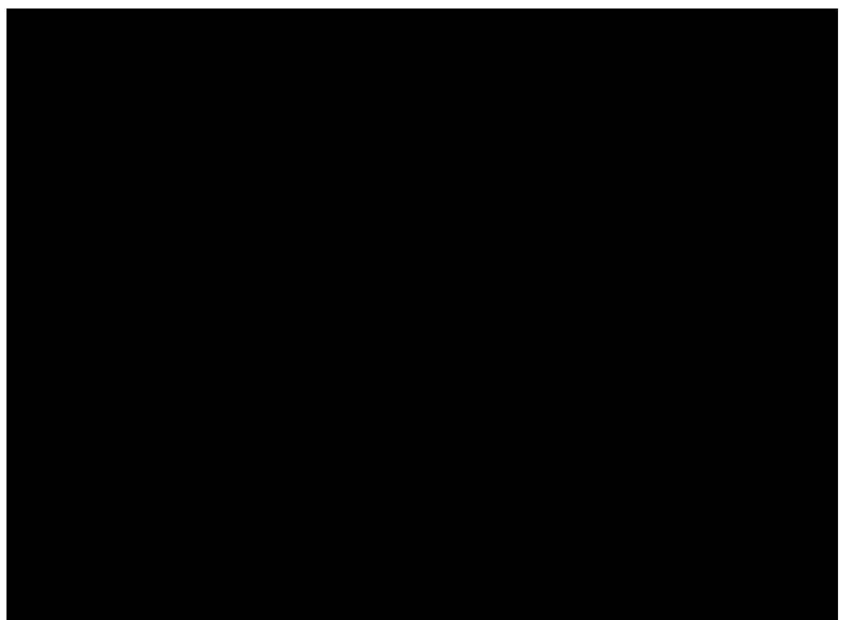
On-board computer SXC-MB-04

Launch on August 15, 2018

The direction of the SiruisSat-1&2 launch from ISS



Cosmonaut manual launch



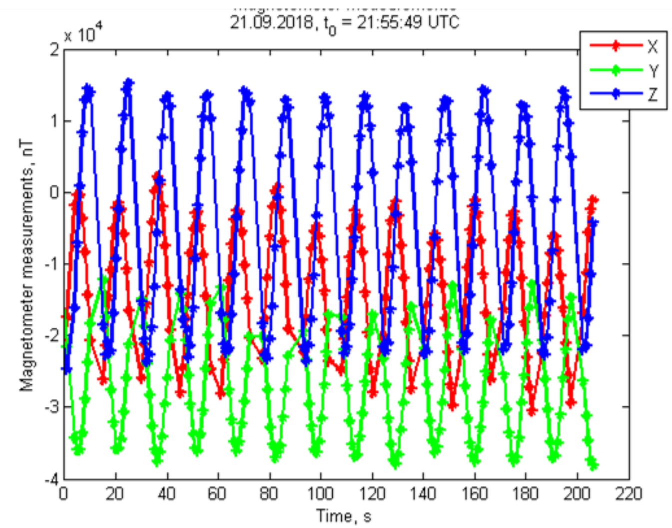
Magnetometer calibration

- Magnetometer measurement model:

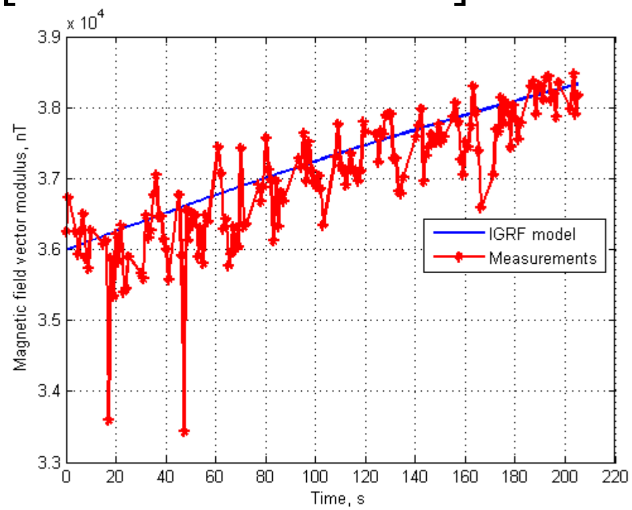
$$\mathbf{B}_{meas} = \mathbf{A}\mathbf{B}_{orb} + \Delta\mathbf{B} + \delta\mathbf{B}$$

- Comparing the magnitude with IGRF geomagnetic field model value the magnetometer bias obtained

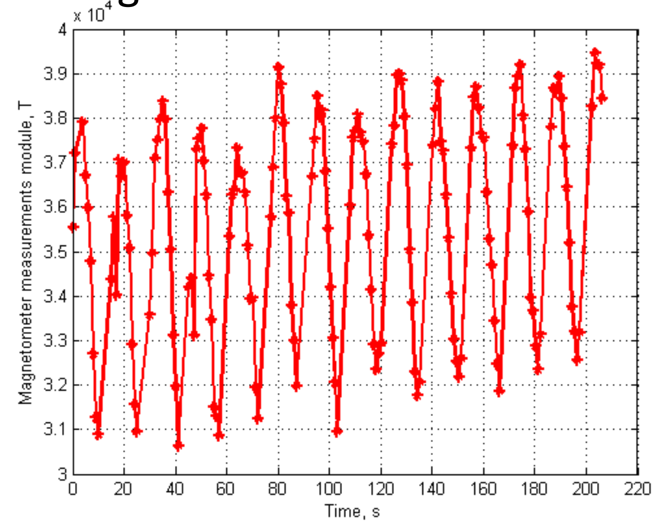
$$\Delta\mathbf{B} = \begin{bmatrix} 4.98 & -0.56 & -4.71 \end{bmatrix} \cdot 10^3 \, \text{nT}$$



Magnetometer measurements



Geomagnetic field calculated using IGRF and magnetometer measurements without bias



Magnetometer measurements value

Attitude motion reconstruction technique

Motion equations

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

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

Measurements model

$$\mathbf{B}_{meas} = \mathbf{A}\mathbf{B}_o + \mathbf{B}_{bias}$$

Initial conditions vector

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

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

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

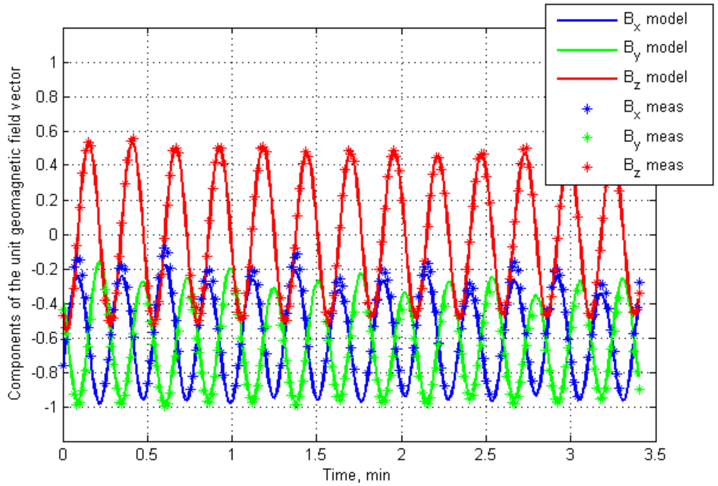
$\mathbf{b}^i_{meas}$ is the unit vector along the geomagnetic field calculated using measurements after excluding the constant bias

$\tilde{\mathbf{b}}^i_{\text{model}}$ is the unit vector along the geomagnetic field calculated IGRF model

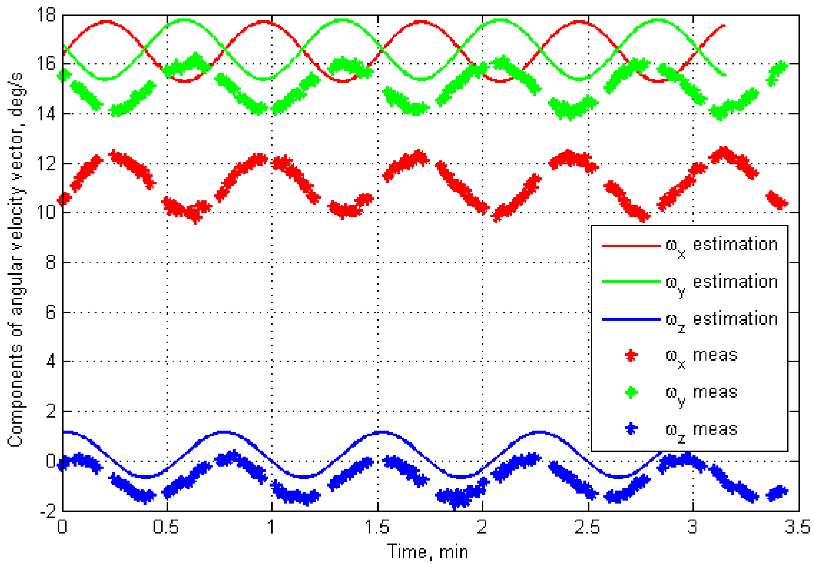
Measurements processing results

- Using magnetometer measurements the attitude motion is reconstructed
- Angular velocity sensor measurements are shifted relative to the estimated angular velocity
- The sensor bias is

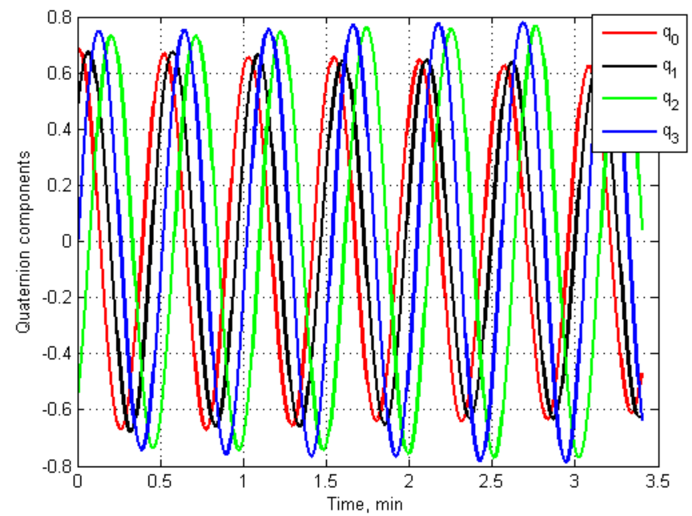
$$\Delta\boldsymbol{\omega} = \left[5.94 \quad 1.72 \quad 1.28\right]^T \text{ deg/s}$$



Measured and predicted unit vector along the geomagnetic field



Angular velocity vector and angular velocity sensor measurements



Attitude quaternion

Magnetic control algorithms

- Magnetic three-axis attitude control to be tested

$$\mathbf{m} = -k_{\omega}\mathbf{B}\times\mathbf{\Omega} - k_{a}\mathbf{B}\times\mathbf{S}$$

- Real-time attitude determination is necessary
- Magnetometer bias as well as angular velocity sensor bias are changing due to the onboard magnetic sources
- Extended Kalman filter using the magnetometer measurements is applied to the problem
- Magnetometer bias is included in the state vector

State vector of the system

$$\mathbf{x} = [\mathbf{q},\ \mathbf{\Omega},\ \Delta\mathbf{B}]^{T}$$

Linearized motion equations

$$\delta\dot{\mathbf{x}}(t) = \mathbf{F}(t)\,\delta\mathbf{x}(t)$$

Dynamics matrix

$$\mathbf{F} = \begin{pmatrix} -\mathbf{W}_{\mathbf{\Omega}} & \frac{1}{2}\mathbf{E} & \mathbf{0}_{3\mathrm{x}3} \\ \mathbf{J}^{-1}\mathbf{F}_{qw} & \mathbf{J}^{-1}\left(\mathbf{F}_{gir}^{\mathbf{\Omega}} - \mathbf{W}_{\mathbf{A}\boldsymbol{\omega}_{orb}}\mathbf{J}\right) & \mathbf{0}_{3\mathrm{x}3} \\ \mathbf{0}_{3\mathrm{x}3} & \mathbf{0}_{3\mathrm{x}3} & \mathbf{0}_{3\mathrm{x}3} \end{pmatrix}$$

Measurement model

$$\mathbf{z} = \mathbf{A}\mathbf{B}_{orb} + \Delta\mathbf{B} + \boldsymbol{\eta}_{V},$$

Linearized measurement model

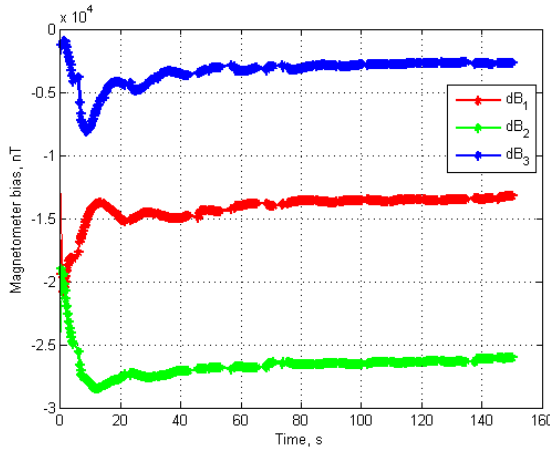
$$\delta\mathbf{z} = -2\mathbf{W}_{\delta\mathbf{q}}\hat{\mathbf{B}} = -2\mathbf{W}_{\hat{\mathbf{B}}}\delta\mathbf{q}$$

Measurement matrix

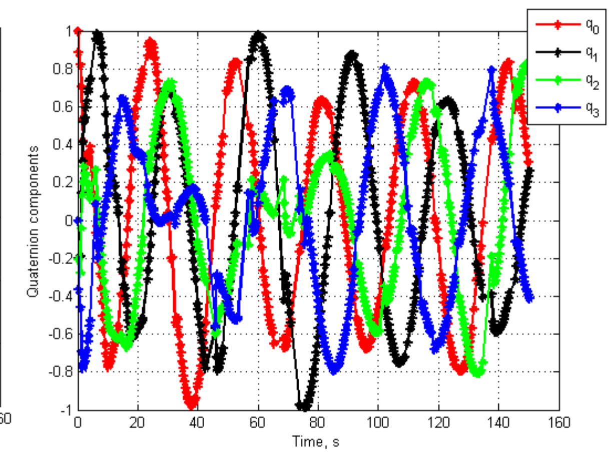
$$\mathbf{H} = \left[-2\mathbf{W}_{\hat{\mathbf{B}}} \quad \mathbf{0}_{3\mathrm{x}3} \quad \mathbf{E}_{3\mathrm{x}3}\right]$$

EKF Testing Using Engineering Model

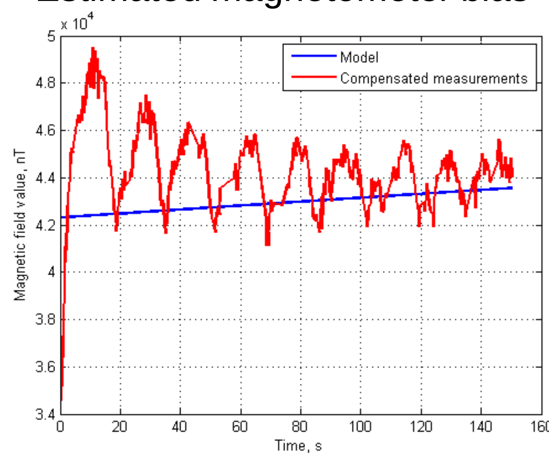
- Implemented EKF using the magnetometer measurements obtained on August 06, 2019
- State vector estimations converged close to real values
- Magnetometer bias is estimated with 1000 nT accuracy
- The attitude motion estimation accuracy is about 3 deg
- This accuracy is enough for coarse three-axis attitude control



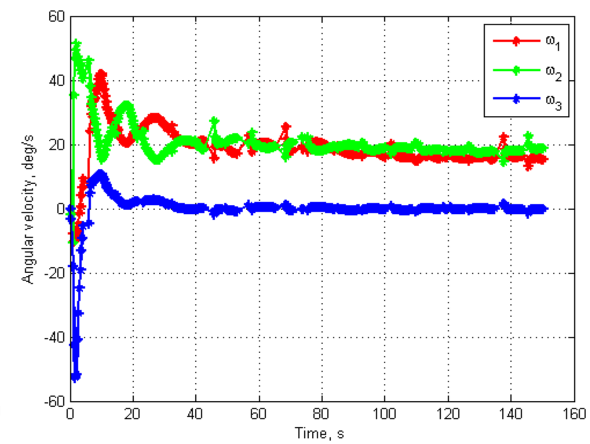
Estimated magnetometer bias



Estimated attitude quaternion



Value of the model geomagnetic field vector



Estimated angular velocity

Conclusions

- Results of the angular motion analysis using the telemetry data are discussed
- The algorithm is proposed for the attitude motion and magnetometer bias estimation in real time
- The algorithm is tested using the hardware-in-the-loop technique
- Real flight data was successfully processed by the onboard computer identical to the one installed on SiriusSat satellites
- The relevant software is currently uploaded via the UHF antenna

The work is supported by Russian Science Foundation, grant 17-71-20117

Thank you for attention!

Our web-site:
http://keldysh.ru/microsatellites/eng/