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# Analysis of Attitude Control System Flight Results of the Earth-Remote Sensing Nanosatellite OrbiCraft-Zorkiy

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**Abstract**

The paper analyzes 6U CubeSat telemetry data from all types of sensors collected during a session with a satellite in the stabilization mode in the orbital reference frame. The accuracy of the angular motion parameters estimation obtained using the extended Kalman filter is evaluated. Accuracy assessment for algorithms based on measurements of the magnetometer, Sun sensor and angular velocity sensor is carried out using measurements of the star sensor and analysis of attitude obtained using processing of images provided by onboard cameras. The results of modeling the operation of the algorithms for attitude determination from the received input data of the sensors and the results of the operation of onboard algorithms from the data obtained from the satellite are compared. The results of the work of the algorithm for tracking a point on the Earth's surface are presented, which provides the required orientation of the optical axis of the on-board remote sensing camera for taking a photo. The algorithm provides the ability to choose a free angle relative to the direction to the observed point. The paper analyzes the results of mathematical modeling and the results of flight tests of this algorithm.

**Keywords:** CubeSat, attitude control, extended Kalman Filter, remote sensing

## 1. Introduction

Earth-remote sensing satellites are widespread in orbit for solving tasks of weather forecast [1], urban and nature monitoring [2], it is used to study the natural resources of the Earth [3] and solve problems of meteorology. Traditionally, Earth-remote sensing satellites are heavy [4]. However, in last years the CubeSat-based satellites are able to provide images with rather good resolution, that is quite enough for many tasks. The bright example is constellation of 3U CubeSats by Planet Ltd, which capable to obtain daily images of any place with 3.7m resolution [5]. Payload for Earth-remote sensing satellites has high requirements for satellite attitude determination and control system. Due to restrictions in mass, size and cost it is rather challenging to obtain high quality images by nanosatellite.

In this paper the operation results of the onboard attitude control algorithms are presented. The telemetry data obtained from the OrbiCraft-Zorkiy is analyzed. The satellite has CubeSat 6U format and was launched on March 22, 2021. Its mission is Earth observation by onboard camera with 6.5 m per pixel resolution. The satellite is equipped with a three-axis reaction-wheels attitude control system and a set of sensors for the attitude motion determination. The sensors include an onboard magnetometer, a set of Sun sensors, an angular velocity sensor and a miniature star sensor. The onboard angular motion estimation algorithms are based on the extended Kalman filter, the state vector includes the quaternion of the satellite attitude relative to the inertial reference frame, the angular velocity vector, as well as the bias of the magnetometer and angular velocity sensor measurements. The current estimates of angular motion are used to calculate the control to achieve the required angular motion. A number of control algorithms have been implemented for damping the angular velocity, for orientation of solar panels in the direction to the Sun, for stabilization in the orbital reference frame, and also for achieving the tracking of a given point on the Earth's surface by the camera.

## 2. OrbiCraft-Zorkiy satellite details

The Zorkiy satellite is a 6U Earth remote sensing nanosatellite. The satellite is equipped with camera with resolution of up to 6.6 meters per pixel. The satellite is based on new satellite platform "OrbiCraft-Pro SXC6" developed by SPUTNIX Ltd. Main purpose of the satellite is technological demonstration of the company capabilities. OrbiCraft-Zorkiy can serve as the basis for a series of modern domestic nanosatellites able to compete in the international nano and microsatellite market [6].

The OrbiCraft-Zorkiy mission implies the deployment of a ground segment for satellite operation and data acquisition. The obtained data is processed by the SPUTNIX company itself, also it is transferred to the camera manufacturer and other interested parties. Data from satellite is open and does not carry a commercial component, which allows it to be received and used by radio amateurs and groups around the world. On the company's website instructions and software for receiving signals from the satellitebby everyone is posted.

The satellite is presented in Fig. 1. Satellite service systems are as follows:

- frame 6U with protective panels and separation sensors;
- expandable solar panels;
- a set of panels with electromagnetic coils;
- primary and backup controller of the attitude control system with a GNSS receiver;
- main and backup VHF transceivers;
- main and backup power controllers;
- duplicated battery pack;
- switching board with power switch;
- block of reaction wheels;
- X-band transmitter;
- Sun sensors;
- star tracker with adapter;
- VHF dipole antenna;
- VHF patch antenna;
- X-band patch antenna;
- GNSS patch antenna;
- cable network.

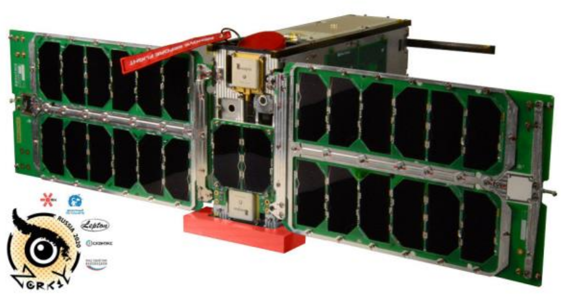

Fig. 1. Photo of OrbiCraft-Zorkiy satellite

The main payload is a camera manufactured by NPO Lepton. It is designed specifically for CubeSat 6U nanosatellites taking into account the capabilities of the SXC6 platform. The camera is equipped with a system of thermal stabilization, focusing, as well as a built-in memory, which allows to take an image on demand, without being tied to ground stations.

Initial height of the Sun-synchronous orbit is 550 km, inclination is 98 deg. The mass of the satellite is 8,5 kg. Its inertia tensor in satellite body reference frame is

$$J = \begin{bmatrix} 7.26 & 0.08 & 0.08 \\ 0.08 & 9.84 & 0.03 \\ 0.08 & 0.03 & 4.08 \end{bmatrix} \cdot 10^{-2}\,\text{kg}\cdot\text{m}^2 .$$

Four reaction wheels are placed in pyramid configuration with angle to the Z-axis of body reference frame of 15 deg. Inertia moments of reaction wheels is 1.6e-5, maximum rate value is 5000-6000 rpm. Satellite is equipped with magnetorquers alone three-axis with 1.0 $A{\cdot}m^2$ value each.

Star tracker is AZDK-1 developed by Azmerit company [7]. Its parameters are presented in Table 1.

Table 1. Parameters of AZDK-1 star tracker

| Parameters | Value |
|---|---|
| Entrance pupil | 18,6 m |
| Field of view | 22° |
| CMOS geometry | 1024×1280 pxls |
| Pixel size | 5,3 µm×5,3 µm (5,3"×5,3") |
| Dimensions, mass (with baffle) | 56×60×93 mm, 193 g |
| Power (w/o Peltier cooler) | 0,5 W |
| Volume of Stellar Catalogue | 2 400 stars up to $5{,}5^m$ |
| Accuracy $\sigma_x$, $\sigma_y$/$\sigma_z$ | 5"/30" (ω<3.5°/sec) |
| Update rate | 5 Hz |
| Supply Voltage | 5 V |

Magnetometer is build in iNEMO inertial module LSM9DS1 [8]. Angular velocity sensor is ADIS 16476 with random noise level of 0.07 deg/s, bias drift is 2 $deg/h^2$. Sun sensors are developed by SPUTNIX company, its field of view is 60 degree opening cone, random noise is 0.1 deg, total accuracy is 0.5 deg.

## 3. Attitude determination algorithms

There are two types of attitude determination algorithms implemented onboard – local algorithm TRIAD based on the magnetometer and sun sensor measurements, and extended Kalman filter based on the measurements of different set of sensors.

TRIAD based on magnetometer and Sun sensors measurements is used on the illuminated side of the orbit. Depending on the set of sensors and operating conditions of the satellite, a set of Kalman filters is used using the following groups of sensors:

- star tracker + angular velocity sensor;
- Sun sensors + magnetometer + angular velocity sensor;
- magnetometer + angular velocity sensor.

The two filters that do not use Star tracker measurements are switched depending on the availability of Sun sensor measurements.

Kalman filter is a recursive algorithm, that uses dynamic system model and sensors measurements to estimate system state vector [9]. The vector estimation can be calculated for time moments $\hat{\mathbf{x}}_k = \hat{\mathbf{x}}(t_k)$ in case the measurements are discretely obtained at $t_k$ moments. Discrete Kalman filter consist of two stages: prediction and correction.

Let the system be described by the following equations

$$\dot{\mathbf{x}}(t) = \mathbf{f}(\mathbf{x},t) + \mathbf{G}\mathbf{w}(t),$$
$$\mathbf{z}(t) = \mathbf{h}(\mathbf{x},t) + \mathbf{v}(t),$$

where $\mathbf{x}$ is the state vector, $\mathbf{z}$ is the measurements, $\mathbf{G}$ is weighting matrix, $\mathbf{w},\mathbf{v}$ are the model and the measurements noises with corresponding covariance matrices $\mathbf{D}, \mathbf{R}$. We utilize extended Kalman Filter, so motion and measurements models must be linearized

$$\mathbf{H}_k = \left.\frac{\partial \mathbf{h}(\mathbf{x},t)}{\partial \mathbf{x}}\right|_{\mathbf{x}=\mathbf{x}_k^-,\, t=t_k}, \quad \mathbf{F}_k = \left.\frac{\partial \mathbf{f}(\mathbf{x},t)}{\partial \mathbf{x}}\right|_{\mathbf{x}=\mathbf{x}_k^-,\, t=t_k}.$$

Predicted parameters are obtained using

$$\mathbf{x}_k^- = \int_{t_{k-1}}^{t_k} \mathbf{f}(\mathbf{x}_{k-1}^+, t)dt;$$
$$\mathbf{P}_k^- = \mathbf{\Phi}_k \mathbf{P}_{k-1}^+ \mathbf{\Phi}_k^{\mathrm{T}} + \mathbf{Q}_k,$$
$$\mathbf{Q}_k = \int_{t_{k-1}}^{t_k} \mathbf{\Phi}_k \mathbf{G}\mathbf{D}\mathbf{G}^T \mathbf{\Phi}_k^T dt = \mathbf{\Phi}_k \mathbf{G}\mathbf{D}\mathbf{G}^T \mathbf{\Phi}_k^T \Delta t$$

where $\mathbf{\Phi}_k = \mathbf{E} + \mathbf{F}_k dt$, $\mathbf{P}$ is Kalman filter estimation covariance matrix. Corrected parameters are defined by

$$\mathbf{K}_k = \mathbf{P}_k^- \mathbf{H}_k^{\mathrm{T}} (\mathbf{H}_k \mathbf{P}_k^- \mathbf{H}_k^{\mathrm{T}} + \mathbf{R}_k)^{-1}$$
$$\mathbf{x}_k^+ = \mathbf{x}_k^- + \mathbf{K}_k [\mathbf{z}_k - \mathbf{h}(\mathbf{x}_k^-, t_k)]$$
$$\mathbf{P}_k^+ = [\mathbf{E} - \mathbf{K}_k \mathbf{H}_k] \mathbf{P}_k^-$$

Satellite model of motion includes gravity gradient and reaction wheels control torques. Kinematics is described using quaternions

$$\mathbf{J}\dot{\boldsymbol{\omega}} = \mathbf{M}_g - \boldsymbol{\omega} \times (\mathbf{J}\boldsymbol{\omega} + \mathbf{h}) - \dot{\mathbf{h}},$$
$$\dot{\mathbf{Q}} = \frac{1}{2} \mathbf{Q} \circ \boldsymbol{\omega} = \frac{1}{2} \begin{pmatrix} 0 & -\boldsymbol{\omega}^T \\ \boldsymbol{\omega} & [-\boldsymbol{\omega}]_\times \end{pmatrix} \begin{pmatrix} q_0 \\ \mathbf{q} \end{pmatrix}.$$

Here $\mathbf{J}$ is the satellite tensor of inertia, $\boldsymbol{\omega}$ is its angular velocity, $\mathbf{h}$ is the total angular momentum of reaction wheels, $\mathbf{Q} = (q_0,\ \mathbf{q})^T$ is the satellite attitude quaternion,

$$\mathbf{M}_g = \frac{3\mu}{R^3} \mathbf{e} \times \mathbf{J}\mathbf{e},$$

$\mu$ is the Earth gravitational parameter, $\mathbf{R}$ is the satellite position, $\mathbf{e} = \mathbf{R}/|\mathbf{R}|$, and skew symmetric of vector product is introduced

$$\mathbf{a} \times \mathbf{b} = [\mathbf{a}]_\times \mathbf{b} = \begin{pmatrix} 0 & -a_3 & a_2 \\ a_3 & 0 & -a_1 \\ -a_2 & a_1 & 0 \end{pmatrix} \mathbf{b}$$

In addition, sensor biases are included in the model of motion. It is supposed that they do not change over time, and their time variation is caused only by model noise.

The measurement models of sun sensor, magnetometer, angular velocity sensor and star sensor are as follows:

$$\mathbf{b}_{meas} = \mathbf{A}\mathbf{b}_{orb} + \Delta\mathbf{b} + \delta\mathbf{b},$$
$$\mathbf{s}_{meas} = \mathbf{A}\mathbf{s}_{orb} + \delta\mathbf{s},$$
$$\boldsymbol{\omega}_{meas} = \boldsymbol{\omega} + \Delta\boldsymbol{\omega} + \delta\boldsymbol{\omega},$$
$$\mathbf{q}_{meas} = \mathbf{q} + \delta\mathbf{q},$$

where $\mathbf{A}$ is the transition matrix from orbital reference frame to body-fixed reference frame, $\mathbf{b}_{orb}$ and $\mathbf{s}_{orb}$ are magnetic field vector and Sun direction in orbital reference frame, $\Delta\mathbf{b}$ and $\Delta\boldsymbol{\omega}$ are magnetometer and angular velocity sensor biases, $\delta\mathbf{b}$, $\delta\mathbf{s}$, $\delta\boldsymbol{\omega}$, $\delta\mathbf{q}$ are Gaussian white noise with zero mean value.

Estimated state vector consists of twelve parameters: attitude quaternion vector part, angular velocity, magnetometer and ARS biases:

$$\mathbf{x} = \begin{bmatrix} \mathbf{q} \\ \boldsymbol{\omega} \\ \Delta\boldsymbol{\omega} \\ \Delta\mathbf{b} \end{bmatrix}.$$

Model of motion must be linearized. It is supposed that control torques, i.e. $\dot{\mathbf{h}}$, are constant between the time steps. After the mathematics, it can be represented by

$$\mathbf{F} = \begin{bmatrix} -[\boldsymbol{\omega}]_{\times\, 3\times3} & \frac{1}{2}\mathbf{I}_{3\times3} & \mathbf{0}_{6\times3} \\ \left(\frac{6\mu}{R^5}\mathbf{J}^{-1}\mathbf{F}_g\right)_{3\times3} & \left(-\mathbf{J}^{-1}\mathbf{F}_x\right)_{3\times3} & \mathbf{0}_{6\times3} \\ \mathbf{0}_{3\times6} & \mathbf{0}_{3\times6} & \mathbf{0}_{6\times6} \end{bmatrix}_{12\times12}.$$

where

$$\mathbf{F}_g = [\mathbf{e}]_\times \mathbf{J} [\mathbf{e}]_\times - [\mathbf{J}\mathbf{e}]_\times [\mathbf{e}]_\times,$$
$$\mathbf{F}_x = [\boldsymbol{\omega}]_\times \mathbf{J} - [\mathbf{J}\boldsymbol{\omega}]_\times.$$

Expression for the linearized measurements matrix depends on the set of sensors used by Kalman Filter. For the full set of sensors it is

$$\mathbf{H}=\begin{bmatrix} 2\left[\mathbf{b}^s\right]_{\times\,3\times3} & \mathbf{0}_{3\times3} & \mathbf{0}_{3\times3} & \mathbf{I}_{3\times3} \\ 2\left[\mathbf{s}^s\right]_{\times\,3\times3} & \mathbf{0}_{3\times3} & \mathbf{0}_{3\times3} & \mathbf{0}_{3\times3} \\ \mathbf{0}_{3\times3} & \mathbf{I}_{3\times3} & \mathbf{I}_{3\times3} & \mathbf{0}_{3\times3} \end{bmatrix}_{9\times12},$$

Accuracy of Kalman filter's estimation depends on gain matrix $\mathbf{K}$. The accuracy also depends on the angle between direction of sun vector and geomagnetic field vector [10]. During the motion along the orbit these vectors could be almost collinear and the state vector estimations accuracy degrades significantly. According to the numerical study the accuracy degradation related to the large errors in the sensors bias estimations. For this reason the previous formula for the state correction has been transformed to the following form:

$$\hat{\mathbf{x}}_{k+1}^{\Delta\boldsymbol{\omega},\Delta\mathbf{b}}=\hat{\mathbf{x}}_{k}^{\Delta\boldsymbol{\omega},\Delta\mathbf{b}}+\left[\sin\left(s\cdot b\right)\right]^N\cdot\Delta\hat{\mathbf{x}}_{k+1}^{\Delta\boldsymbol{\omega},\Delta\mathbf{b}},$$

where k is an iteration number, $\hat{\mathbf{x}}^{\Delta\boldsymbol{\omega},\Delta\mathbf{b}}$ is an estimation of sensors biases (magnetometer and angular velocity sensor), $s\cdot b$ is an angle between sun direction vector and geomagnetic field vector, $\Delta\hat{\mathbf{x}}^{\Delta\boldsymbol{\omega},\Delta\mathbf{b}}$ is a sensors bias correction increment in standard Kalman filter, N is a tuning parameter.

For the case of star sensor and angular velocity measurements the state vector consists of quaternion vector part, angular velocity and AVS biases:

$$\mathbf{x}=\begin{bmatrix}\mathbf{q}\\ \boldsymbol{\omega}\\ \Delta\boldsymbol{\omega}\end{bmatrix}.$$

The matrix of dynamics is as follows:

$$\mathbf{F}=\begin{bmatrix} -\left[\boldsymbol{\omega}\right]_{\times\,3\times3} & \frac{1}{2}\mathbf{I}_{3\times3} & \mathbf{0}_{3\times3} \\ \left(\frac{6\mu}{R^5}\mathbf{J}^{-1}\mathbf{F}_g\right)_{3\times3} & \left(-\mathbf{J}^{-1}\mathbf{F}_x\right)_{3\times3} & \mathbf{0}_{3\times3} \\ \mathbf{0}_{3\times3} & \mathbf{0}_{3\times3} & \mathbf{0}_{3\times3} \end{bmatrix}_{9\times9}.$$

The measurement matrix is:

$$\mathbf{H}=\begin{bmatrix} \mathbf{I}_{3\times3} & \mathbf{0}_{3\times3} & \mathbf{0}_{3\times3} \\ \mathbf{0}_{3\times3} & \mathbf{I}_{3\times3} & \mathbf{I}_{3\times3} \end{bmatrix}_{6\times9}.$$

### *4. Attitude control algorithms*

Three attitude control algorithms are used onboard the OrbiCraft Zorkiy satellite:

- "-Bdot" algorithm [11] for damping the initial angular velocity and for unloading the kinetic momentum of the reaction wheels;
- algorithm for unloading reaction wheels angular momentum while maintaining the target orientation;
- three-axis Lyapunov control for inertial, orbital orientation and tracking of a point on the Earth's surface [12].

Attitude control performed using reaction wheels is time derivative of its reaction wheels momentum:

$$\dot{\mathbf{h}}=\mathbf{u}_{ctrl}.$$

The control is calculated using one of the following algorithms [13]:

$$\mathbf{u}_{ctrl}=\mathbf{M}_{ext}-\boldsymbol{\omega}\times\mathbf{J}\boldsymbol{\omega}+\mathbf{J}\left(\boldsymbol{\omega}_{rel}\times\mathbf{D}\boldsymbol{\omega}_0\right)-\mathbf{J}\mathbf{D}\dot{\boldsymbol{\omega}}_0+ +k_\omega\boldsymbol{\omega}_{rel}+k_n\left(\mathbf{D}\mathbf{n}_0\right)\times\mathbf{n}-\boldsymbol{\omega}\times\mathbf{h};$$

$$\mathbf{u}_{ctrl}=\mathbf{M}_{ext}-\boldsymbol{\omega}\times\mathbf{J}\boldsymbol{\omega}+\mathbf{J}\left(\boldsymbol{\omega}_{rel}\times\mathbf{D}\boldsymbol{\omega}_0\right)-\mathbf{J}\mathbf{D}\dot{\boldsymbol{\omega}}_0+ +k_\omega\boldsymbol{\omega}_{rel}+k_q\mathbf{q}_{rel}-\boldsymbol{\omega}\times\mathbf{h};$$

depending on which of the attitude motion regimes are implemented – one-axis or three-axis (first and second algorithm correspondingly). Here $\mathbf{D}$ is the attitude transition matrix from inertial to body reference frame, $\boldsymbol{\omega}_0,\dot{\boldsymbol{\omega}}_0$ are reference angular velocity and angular acceleration vectors in inertial reference frame, $\boldsymbol{\omega}_{rel}$ is angular velocity deviation from the reference value

$$\boldsymbol{\omega}_{rel}=\boldsymbol{\omega}-\mathbf{D}\boldsymbol{\omega}_0,$$

$\mathbf{q}_{rel}$ is the vector part of quaternion $Q_{rel}$ of attitude deviation from the reference quaternion $Q_0$, calculated as follows

$$Q_{rel}=Q_0\circ Q,$$

$\mathbf{M}_{ext}$ is the external torques acting on the satellite (gravitational and magnetic), $k_\omega,k_n,k_q$ are positive control parameters, $\mathbf{n}_0$ is required direction of defined satellite axis in inertial reference frame (for example, normal to solar panels direction), $\mathbf{n}$ is this axis direction in body-fixed reference frame.

### 4. Telemetry data analysis

#### *4.1. TRIAD and extended Kalman filter comparison*

Consider a telemetry during the period of 25 s obtained at 25.05.2021. Fig. 2, 3 and 4 demonstrates the measurements of magnetometer, Sun sensor and angular velocity sensor.

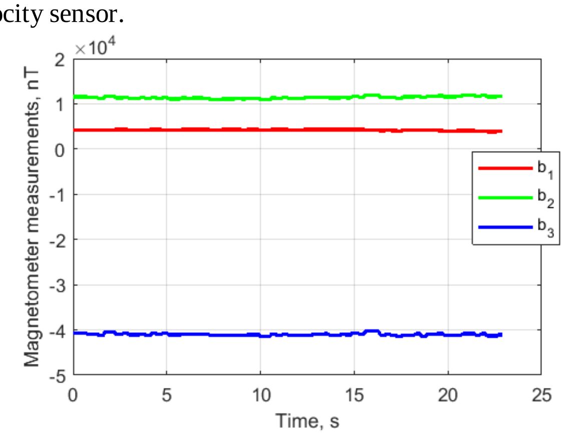


Fig. 2. Magnetometer measurements

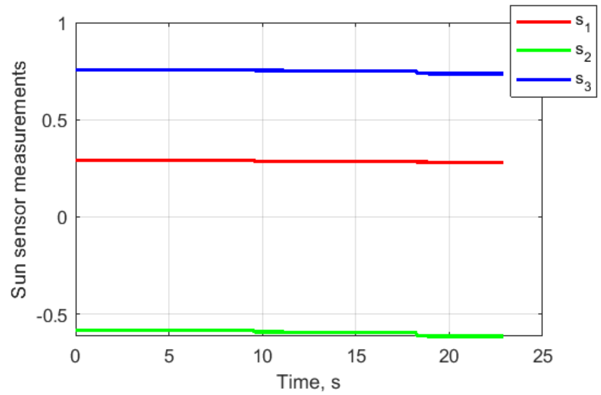

Fig. 3. Sun sensor measurements

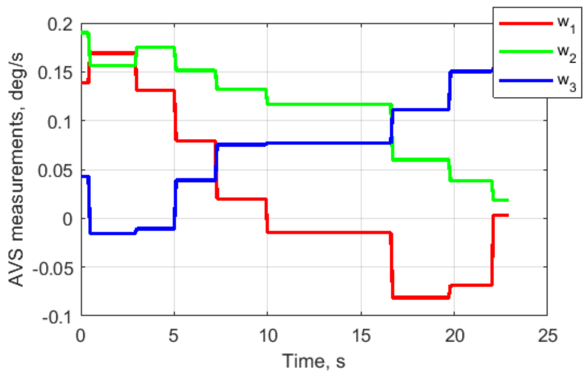

Fig. 4. Angular velocity sensor measurements

Using these measurements two algorithms provided their estimations – TRIAD and Kalman filter. Fig. 5 shows the attitude quaternion estimations by these algorithms, and Fig. 6 – difference between these estimations. Difference can be explained by the magnetometer bias, that is estimated in real time by the Kalman filter and not taken into account by TRIAD algorithm.

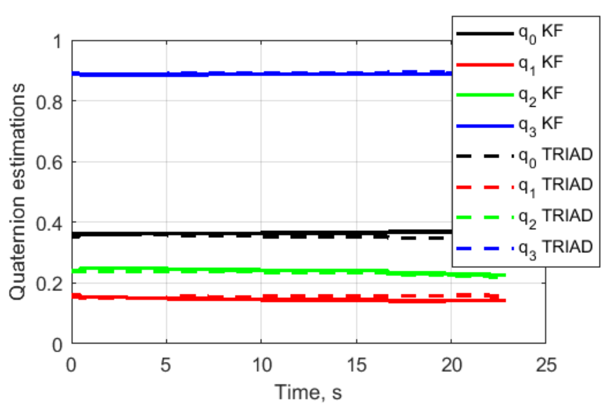

Fig. 5. Attitude quaternion estimations by Kalman filter and TRIAD

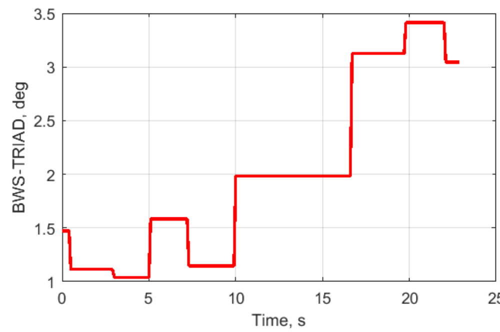

Fig. 6. Difference between quaternion estimations

Fig. 7 shows the difference in the magnetic field value calculated by IGRF magnetic field model and by magnetometer measurements that is about 1200 nT that can explain the error of the TRIAD algorithm of 1-3 deg.

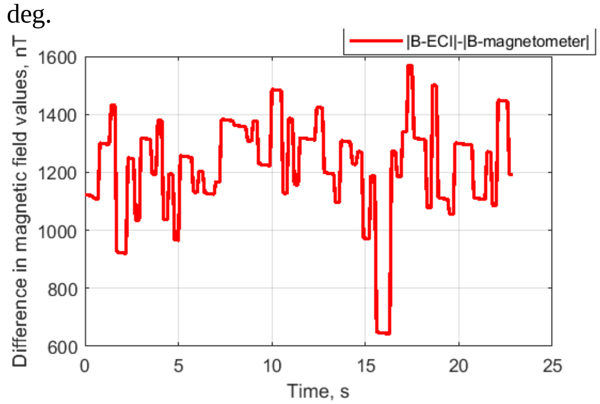

Fig. 7. Difference in magnetic field values by IGRF magnetic field model and by magnetometer measurements

*4.2. Tracking of a point on the Earth's surface*

An example of attitude control using reaction wheels for Earth point tracking during the imaging is presented in Fig. 8. At moment about 7:33 the satellite flyby above the point, the angular velocity is the highest at the moment, the attitude quaternion is close to [1 0 0 0], that mean that satellite is in the orbital attitude.

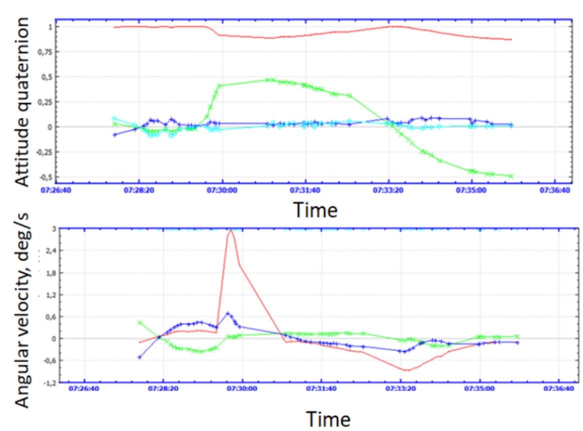

Fig. 8. Attitude quaternion and angular velocity estimations during the tracking of a point on the Earth's surface

In order to validate the estimated attitude the side camera images are used. In Fig. 9 demonstrates an example of camera image and Fig. 10 present the same view of satellite in numerical simulation using the obtained attitude estimation. The angles between the solar panel edge and the local horizon are close to each other on the images with accuracy of 0.1 deg, which gives some confidence in attitude determination.

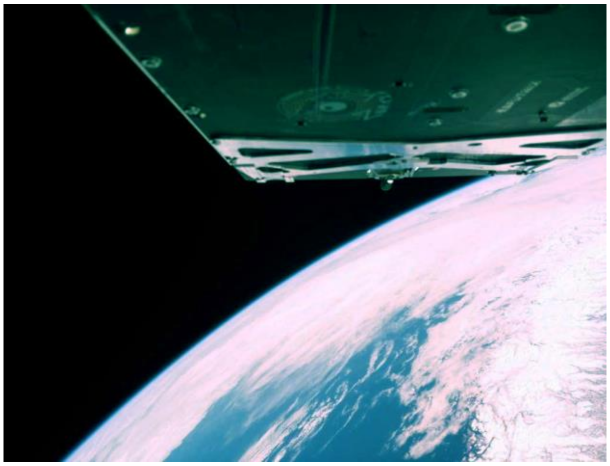
Fig. 9. View from the side camera

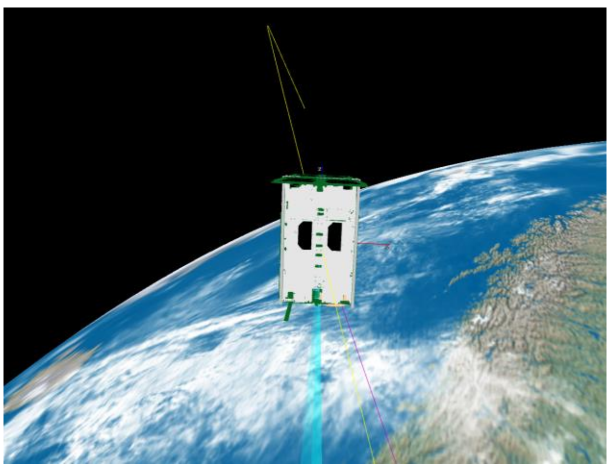
Fig. 10. Satellite attitude reconstruction using onboard estimations

*4.3. Imaging*

An example of the monochrome image taken by the main camera in orbital orientation is presented in Fig. 11. It shows that the attitude stabilization accuracy provided by the attitude control system is enough for the sharp images acquisition. Its actual resolution is 7.3 m.

Fig. 12 demonstrates the satellite ground-track on the map during the flyby above the Earth point presented image. As one can see, the misalignment of the optical axis from nadir direction is about 1 km that is acceptable error.

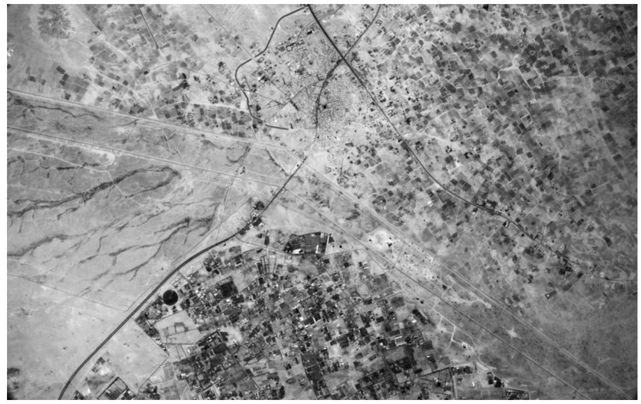
Fig. 11. Example of image by main camera

Fig. 12. Satellite ground-track on the map during the image acquisition

## 5. Conclusions

The presented telemetry analysis results shows that attitude determination and control system of 6U CubeSat OrbiCraft Zorkiy provides enough attitude stabilization accuracy for the acquisition of sharp images by the camera. Extended Kalman filter estimations of sensors biases allows to obtain more accurate attitude motion parameters compared with TRIAD algorithm. Currently, the authors are running a set of orbital experiments to compare the attitude estimations obtained using star tracker measurements and using measurements of the rest onboard sensors.

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