Ovchinnikov M.Yu., Penkov V.I.,
Malphrus Benjamin, Brown Kevin,
Roldugin D.S.

Active magnetic attitude control algorithms for a Cubesat for astrophysics research

Recommended form of bibliographic references: Ovchinnikov M.Yu., Penkov V.I., Malphrus Benjamin, Brown Kevin, Roldugin D.S. Active magnetic attitude control algorithms for a Cubesat for astrophysics research // Keldysh Institute Preprints. 2014. No. 47. 18 p. URL: http://library.keldysh.ru/preprint.asp?id=2014-47&lg=e

Ордена Ленина
ИНСТИТУТ ПРИКЛАДНОЙ МАТЕМАТИКИ
имени М.В.Келдыша
Российской академии наук

M. Ovchinnikov, V. Penkov,
B. Malphrus, K. Brown
D. Roldugin

Active magnetic attitude control algorithms for a CubeSat for astrophysics research

Москва — 2014

Овчинников М.Ю., Пеньков В.И., Малфрус Б.К., Браун К., Ролдугин Д.С.

Алгоритмы магнитной ориентации кубсата для астрофизических исследований

Рассматривается магнитная система ориентации для спутника CXBN-2. Аппарат представляет собой двойной кубсат (стандарта 2U), предназначенный для изучения рассеянного фонового рентгеновского излучения Вселенной. Система ориентации спутника состоит из трех магнитных катушек. В работе рассматриваются четыре потенциальных режима ориентации аппарата. На основе ряда критериев, в частности, максимизации объема получаемых научных данных, выбирается оптимальный алгоритм ориентации.

Ключевые слова: магнитная система ориентации, Cubesat, астрофизические исследования

Michael Ovchinnikov, Vladimir Penkov, Benjamin Malphrus, Kevin Brown, Dmitry Roldugin

Active magnetic attitude control algorithms for a Cubesat for astrophysics research

Magnetic attitude control system for CXBN-2 satellite is considered. The satellite is of a 2U CubeSat standard designed to study the cosmic X-ray background of the Universe. Attitude control system is comprised of magnetorquers only. Four potential attitude modes are analyzed. Optimum according to a set of criteria (particularly data volume maximization and even celestial sphere coverage), algorithm is obtained.

Key words: magnetic attitude control system, CubeSat, astrophysics research

The work was partially supported by the Russian Scientific Foundation, grant № 14-11-00621 (Sections 2 – 4).

Contents

Introduction

CXBN-2 is in development as a follow-on mission to CXBN, a successful 2U CubeSat that was launched on September 13, 2012 as a secondary payload on the NASA ELaNa VI OUTSat mission [1]. While CXBN successfully operated on orbit, a number of improvements are incorporated into CXBN-2 that will improve the precision of the scientific measurement (increase the S/N) made by CXBN and improve the reliability of the spacecraft bus while advancing the flight software and therefore the mission and spacecraft capabilities. The goal of the CXBN-2 mission is to increase the precision of measurements of the Cosmic X-Ray Background in the 30-50 keV range to a precision of <5%, thereby constraining models that attempt to explain the relative contribution of proposed sources lending insight into the underlying physics of the early Universe. The mission addresses a fundamental science question that is clearly central to our understanding of the structure, origin, and evolution of the Universe by potentially lending insight into both the high energy background radiation and into the evolution of primordial galaxies. CXBN-2 will map the Extragalactic Diffuse X-Ray Background (DXB) with a new breed of Cadmium Zinc Telluride (CZT) detector (first flown on CXBN) but with twice the detector array area of its precursor and with careful characterization and calibration. The DXB is a powerful tool for understanding the early Universe and provides a window to the most energetic objects in the far-away Universe. Although studied previously, existing measurements disagree by about 20%. With the novel CZT detector aboard CXBN-2 and an improved array configuration, a new, high precision measurement is possible. In, approximately, one year of operation the experiment will have collected no less than 3 million seconds of good data, reaching a broadband S/N ~250 [2].

The science mission requirements fortunately allow for the design of a relatively simple spacecraft, making this mission ideal for the CubeSat form factor. All of the major subsystems comprising the satellite are highly evolved and have flight heritage – having been developed by the team for other missions, and having flown on CXBN. CXBN-2 is a 2U Cubesat whose total weight is 2.6 kg. Innovative systems include upgraded versions of the CXBN power distribution and handling system (PMD), command and data handling system (C&DH) now based on a Cortex Arm processor, and an innovative attitude determination and control system (ADACS) in design by the CXBN-2 team comprised of groups from the Morehead State University (Morehead, KY, USA) and the Keldysh Institute of Applied Mathematics (Russian Academy of Sciences, Moscow, Russia).

The concept of operations relative to the spacecraft dynamics is under investigation by the team. Trajectories over the primary Earth station at the Morehead State University (MSU in Morehead, KY) are necessary to acquire the science data and spacecraft telemetry as the MSU Earth station (21 meter antenna with a newly implemented UHF focal plane array) will serve as the primary command and data acquisition facilities.

The requirements for the CXBN science mission are relatively minimal. The science arrays (CZT detectors) are rigidly affixed within the body of the spacecraft (perpendicular to its z axis). The spacecraft dynamics will be used to allow the two CZT detectors to "sweep" the entire sky. The CZT detector has an approximately 36˚ field of view (FOV). The spacecraft dynamics must be configured such that:

1) The CZT detector sweeps the entire sky in $<10^6$ seconds (roughly 11.6 days)

2) Maximum desired slew rate is 10 degree per second

3) Minimum slew rate not zero

4) Desired attitude determination levels:

- 10 degrees for primary mission (DXB measurement)
- 1 degree for secondary science objectives (Gamma Ray Burst monitoring)
- Precise attitude determination is conducted during on the ground post-processing of downloaded data.

5) Downlink to at least one ground station at mid-latitude per day. Downlink technique (broadband, quasi-omnidirectional antenna) does not require precision pointing to the Earth. However, angular velocity cannot exceed 10 degree per second

6) Expected orbital parameters: inclination 60-70°, altitude 400-450 km.

With improvements derived from team's experience with CXBN and the significant experience in attitude control systems of the Keldysh team, CXBN-2 has the potential to increase the precision of an important measurement that will lend insight into the astrophysics of the early universe. CXBN-2 has been down-selected for flight through the NASA ElaNa Program and will be manifested for launch in 2016-2017.

Attitude determination and control system of the satellite consists of three magnetorquers as actuators and three-axis magnetometer, set of sun sensors and rate gyro. Magnetic attitude control systems are especially used when it is critical to have low-cost and low-mass control system capable of implementing conventional algorithms for onboard computer. The most common ways to utilize magnetic control are spin stabilization and angular velocity damping. Principal methods of magnetic attitude control of a spinning satellite are considered in [3] and [3], in [5] general dynamical properties of a spin-stabilized satellite along with technical issues are discussed. Overall magnetic control system performance in case spin-stabilization is used was studied by authors in [6], some other results related to the detumbling algorithm can also be found in [7].

This paper focuses on the control system assuming sensors provide necessary attitude data. Control system should provide possibly maximum number of data sets for the payload and possibly even celestial sphere coverage. Absolute minimum data volume is million seconds of scientific data. The main source of data loss is sensor sensitivity to high-energy illumination from close sources. Earth, Moon and Sun blanket exposure in case located in sensor field of view. Clearly the Earth is the main problem for low orbits. The sensor itself is resistant to this illumination and is not damaged, however the data are lost. Four different control strategies are proposed and studied. They are assessed according to a number of criteria, ranging from the scientific mission requirements to engineering and mathematical robustness of a system.

1. Problem statement

This section provides all main assumptions and control strategies description.

1.1. Control strategies

Magnetic attitude control systems are very capable in providing different attitude modes. Three main attitude regimes can be subtracted: three-axis attitude, spin-stabilization with one-axis attitude, angular velocity damping. Three-axis attitude, thought proven to be accessible [8], is way too complicated for the CXBN-2 mission. Moreover, the satellite does not need any specific attitude, and only overall celestial sphere coverage is of the utmost importance. So, two other well-known and extensively used regimes are considered. In order to provide full sphere coverage, following modes are studied:

1. Spin-stabilized satellite with regular spin axis rotation. The satellite is considered axisymmetrical one, CZT sensors are perpendicular to the spin axis. This provides continuous fast rotation for sensors field of view perpendicular to the spin axis. To cover full celestial sphere, spin axis is slowly rotates in the inertial space. This is basic spin-stabilization mode.
2. Spin-stabilization with Earth avoiding. This is advanced spin-stabilization mode. Spin axis is always directed roughly to the local vertical.

Though quite inaccurate due to fast spinning, this regime allows Earth avoiding and therefore increases scientific data volume.

3. Spin-stabilized with solar panels charging and Earth avoiding. Satellite faces the Sun for half an orbit to provide battery charge. Then it moves to local vertical stabilization. This regime generalizes the former one introducing necessary charging function.
4. Free-flying satellite with speed control. This regime provides no specific attitude. Angular velocity is affected only, the satellite should keep rotating to cover full sphere. This mode, having almost all advantages on mathematical and engineering side, can be worse than former two in terms of scientific data volume.

Another possible control scheme is spin-stabilization with bright sources avoiding. This scheme, however, involves solving optimization problems and dynamics prediction using complicated environment models, and therefore is considered inappropriate for simple and robust control. Second and third strategies are obviously most important and simple cases of this general scheme.

1.2. Satellite and environment assumptions

CXBN-2 is a spin-stabilized, 2U Cubesat with deployable solar panels producing 22.5 W of continuous power. The required orbit is a relatively high inclination (60°) orbital plane at approximately 420 km altitude. Four contacts with the MSU Earth station are expected per day, allowing 40 MB of data to be downlinked per day at S-band. A link margin of 10 dB is anticipated for high altitude passes.

The DXRB flux measurements to be made during this campaign will utilize two semiconductor detectors based on Cadmium zinc telluride (CdZnTe or CZT) arrays adapted from medical imaging devices used in nuclear magnetic resonance imaging. The instrument is direct bandgap semiconductor, used in a variety of applications including a radiation detectors in the gamma ray and X-ray spectra. Radiation detectors using CZT can operate in direct-conversion (or photoconductive) mode at room temperature. Advantages of this technology include high sensitivity to X-rays and gamma-rays, due to the high atomic numbers of Cd and Te, and better energy resolution than scintillator detectors. CZT can be formed into different shapes for different radiation-detecting applications, and a variety of electrode geometries making it ideal for space-based X-ray astronomy measurements.

CXBN-2 is a 2U, 2.6 kg nanosatellite whose bus is derived from the successful 2U CubeSat for the Cosmic X-Ray Background NanoSatellite mission. The subsystems have been flight proven on the CXBN OUTSat mission. The heritage systems include: power, communications, magnetic-torque coils, a sun sensor, and command and data handling. An exploded view of the Spacecraft subsystems is shown in Fig. 1. This combination of flight qualified hardware along with improvements to systems based on the CXBN mission significantly reduces the risk associated with the CXBN-2 mission.

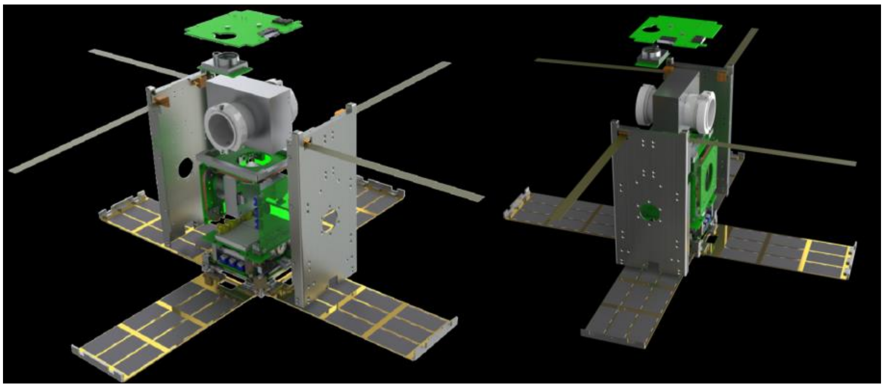

Fig. 1. Two Exploded CAD Model Views of CXBN-2 Subsystems

The CXBN-2 bus structure is based on a robust 2-wall structure matched to a central mounting block. Subsystem enclosures and braces reinforce the structure throughout the length of the body, allowing the frame to hold very tight tolerances. The design also provides rigidity required to maintain integrity during vibration. The combination of flight heritage combined with in-house manufacturing and rapid-prototyping capabilities facilitates rapid assembly and testing within an 18 month timeframe.

The CZT payload sensors are directed perpendicular to the axis of minimum moment of inertia. Spin-stabilization scheme cannot be used for this satellite without losing control robustness. So for the spin-stabilization four solar panels are unfolded to provide spinning about maximum moment of inertia. Two inertia tensors are used further, $\mathbf{J}_p$ for satellite with solar panels and $\mathbf{J}_0$ for satellite without. The latter is

$$\mathbf{J}_0 = diag\left(0.009, 0.011, 0.0062\right) kg \cdot m^2 .$$

This is approximate inertia tensor of a cylinder measuring 0.1 meters in diameter, 0.2 meters in height and 2.5 kilo of mass. Slight non-symmetry is added to make simulation results more general. Adding four 0.2 meter panels with 50 gramm mass attached at the end leads to approximate inertia tensor

$$\mathbf{J}_p = diag\left(0.009, 0.011, 0.014\right) kg \cdot m^2 .$$

We use conventional J2000 reference frame. This reference frame $O_aY_1Y_2Y_3$ has O_a as the Earth's center, the O_aY_3 axis is directed along with the Earth's axis, O_aY_1 lies in the Earth's equatorial plane and is directed to the vernal equinox for midnight on January 1, 2000, the O_aY_2 axis is directed so the system is right-handed. We will also use the bound reference frame $Ox_1x_2x_3$, its axes coincide with the principal axes of inertia of the satellite. Mutual attitude of $O_aY_1Y_2Y_3$ and $Ox_1x_2x_3$ reference frames is given by the direct cosines matrix $\mathbf{A}$. CZT Array sensors are assumed to be placed along Ox_1 axis, so their normals in bound frame are (1,0,0) and (-1,0,0). Sensors field of view (half-angle) is 18 degrees.

Orbital attitude above spherical Earth is 420 km, inclination is 60 degrees. The orbit is affected only by the Earth obliquity. This leads to slow drift of the longitude of ascending node. The orbit therefore is rotating along O_aY_3 axis. System geometry should be complemented with Sun and Moon directions and motion models. These are chosen according to [9]. Sun and Moon angular dimensions are considered to be half a minute (almost point sources). For the angular motion control and gravitational torques are taken into account.

IGRF, the most accurate, and inclined dipole model, allowing simple notation and fast computation, are used to represent geomagnetic field. Introduced assumptions highlight the general approach used in the paper on current mission design phase. Simple models are essential for fast qualitative analysis of proposed control algorithms. Further quantitative analysis using comprehensive models should be addressed to the algorithm chosen on current stage.

We use Euler equations and related variables to represent the satellite motion. The state vector comprises of the variables $\omega_1, \omega_2, \omega_3$ and Euler angles α, β, γ or attitude quaternion. Here ω_i are the absolute angular velocity components in the bound frame $Ox_1x_2x_3$ (i=1,2,3), Euler angles α, β, γ give the satellite and therefore the bound frame $Ox_1x_2x_3$ attitude with respect to $O_aX_1X_2X_3$. Euler angles rotation sequence is chosen in such a way that the direction cosines matrix $\mathbf{A}$ has the form

$$\mathbf{A}=\begin{pmatrix} \cos\alpha\cos\beta & \sin\beta & -\sin\alpha\cos\beta \\ -\cos\alpha\sin\beta\cos\gamma+\sin\alpha\sin\gamma & \cos\beta\cos\gamma & \sin\alpha\sin\beta\cos\gamma+\cos\alpha\sin\gamma \\ \sin\alpha\cos\gamma+\cos\alpha\sin\beta\sin\gamma & -\cos\beta\sin\gamma & -\sin\alpha\sin\beta\sin\gamma+\cos\alpha\cos\gamma \end{pmatrix}.$$

Motion equations for the satellite with arbitrary tensor of inertia $\mathbf{J}_x = diag(A, B, C)$ are as follows

$$A\frac{d\omega_1}{dt}+\left(C-B\right)\omega_2\omega_3=M_{1x},$$

$$B\frac{d\omega_2}{dt}+\left(A-C\right)\omega_1\omega_3=M_{2x},$$

$$C\frac{d\omega_3}{dt}+\left(B-A\right)\omega_1\omega_2=M_{3x}$$

where M_{1x},M_{2x},M_{3x} are the torque (both control and disturbing ones) components in the bound frame $Ox_1x_2x_3$.

Satellite dynamics is complemented using quaternion-based kinematics,

$$\dot{\mathbf{q}}=\frac{1}{2}\mathbf{\Omega}\mathbf{q}$$

where

$$\mathbf{\Omega}=\begin{bmatrix} 0 & \omega_3 & -\omega_2 & \omega_1 \\ -\omega_3 & 0 & \omega_1 & \omega_2 \\ \omega_2 & -\omega_1 & 0 & \omega_3 \\ -\omega_1 & -\omega_2 & -\omega_3 & 0 \end{bmatrix}.$$

Quaternions are used for numerical simulation due to the fast orthogonalization process. Euler angles or direct cosines matrix elements are used only for satellite motion visualization.

2. Control algorithms

Control algorithms are divided into two groups, i.e. spin-stabilization algorithms and angular velocity damping. Angular velocity *damping* is conducted using well-known “-Bdot” [10] algorithm,

$$\mathbf{m}_{damp}=-k_{damp}\frac{d\mathbf{B}_x}{dt}.$$

In case satellite should be spun “+Bdot” is used instead.

Spin stabilization algorithms are divided into control implementation stages. *Nutation damping* algorithm is essentially “-Bdot” one implemented by a single coil,

$$\mathbf{m}_{nut}=-k_{nut}\left(\frac{d\mathbf{B}_x}{dt}\mathbf{e}_3\right)\mathbf{e}_3.$$

This coil is directed along the spin axis, so spinning is not damped. In case satellite is spun too fast full “-Bdot” can be used to detumble it to reasonable spinning.

Spinning algorithm is

$\mathbf{m}_{spin} = k_{spin}\left(B_{2x}, -B_{1x}, 0\right)^T$,

reorientation algorithm is

$\mathbf{m}_{or} = \left(0, 0, k_{or}\left(\Delta\mathbf{L}\cdot\left[\mathbf{e}_3\times\mathbf{B}\right]\right)\right)^T$

where $\Delta\mathbf{L} = \mathbf{L}_f - \mathbf{L}$, $\mathbf{L}_f$ is necessary position of the axis of symmetry in inertial space. Since the satellite is spun around the axis of symmetry this axis coincides with the angular momentum of the satellite. Reorientation of the angular momentum therefore means reorientation of the axis of symmetry.

Spin-stabilization algorithms are integrated into one general attitude control scheme. Generally states of operation can be chosen according to two simple tables and depending on the current attitude. Table 1 presents different control regimes in the frame of spin-stabilization scheme. Table 2 brings control switching logic depending on the current satellite velocity and regime (initially $flag = 0$).

Table 1 – Control regimes

№	1	2	3	4	5
Alg-ms	Spinning, Nutation damp.	Set $flag = 1$	Reorient. Damping	Reorientation *or* Nutation damp.	Set $flag = 0$

Table 2 – Switching logic for spin stabilization

$flag$ \ ω_3	$\omega < \omega_f$	$\omega_f < \omega < \omega_f + \Delta\omega$	$\omega > \omega_f + \Delta\omega$
0	1	1	2
1	5	4	3

The fourth regime actual algorithm depends on the satellite velocity. The main algorithm here is the reorientation, so this is the main part of the control scheme. However, if satellite nutation rate exceeds some threshold value ω_0 it switches to nutation damping. As operations start ($flag = 0$) the satellite is spun till its spinning rate achieves necessary value ω_f with some offset $\Delta\omega$, that is $\omega_3 \geq \omega_f + \Delta\omega$. Satellite nutation rate is damped at the same time (mode 1). Nutation damping and spinning algorithms then switch off ($flag = 1$) and pass control to reorientation (3). However, it is complemented by the full damping due to possible glitches in control. If no glitches occur reorientation only is implemented (4). Reorientation clearly leads to increase in nutation rate, so it is complemented by nutation damping algorithm if necessary (4). If spinning rate drops below necessary rate, that is $\omega < \omega_f$, this process is initiated from the start ($flag = 0$). Values ω_f =3 deg/s, $\Delta\omega$=0.2 deg/s and ω_0 =0.2 deg/s are chosen.

Free-flying satellite control scheme is present in Table 3.

Table 3 – Switching logic for free flying

flag \ ω	$\omega < \omega_f$	$\omega_f < \omega < \omega_f + \Delta\omega$	$\omega > \omega_f + \Delta\omega$
0	No control, *flag*=1	No control, *flag*=0	-Bdot, *flag*=0
1	+Bdot, *flag*=1	+Bdot, *flag*=1	No control, *flag*=0

This scheme maintains satellite velocity in range $\omega_f < \omega < \omega_f + \Delta\omega$. If the velocity is smaller (*flag* sets to 1), the satellite is spun till $\omega_f + \Delta\omega$ and *fla*g is set to 0. If velocity exceeds maximum value it is damped. Small eddy currents are added in this case to provide slow velocity damping. Velocities exceeding maximum value occasionally arise due to the gravitational torque. Terminal velocity rate and offset are the same as in spin stabilization mode.

3. Algorithms performance

Four different algorithms performance is summarized in this section. Performance is analyzed during one day, one month and one year of operation. Prior to this analysis geomagnetic field model should be justified. General model is the inclined dipole one. It takes into account approximately 95% of the field given by IGRF. Since precise attitude is not of the interest for the mission and in this paper this simplification can be easily justified. The difference in scientific data gain for the first control scheme over one day of operation is less than 10^3 seconds of data among nearly 10^5 seconds overall, so it is only about one percent. Numerical simulation time is reduced more than twice using inclined dipole, so it was chosen here as the general field model. Another important dipole model feature is independence of epoch, while current IGRF should be used till 2015. Celestial sphere discretization was chosen as 5 degrees for both longitude and latitude.

3.1. Spin-stabilized with regular spin axis rotation

This regime implements continuous spin axis rotation. This rotation is defined by three angles. Spin axis rotates in a defined plane once a day; the plane inclination rotates in the inertial space once per ten days; its “ascending node” rotates once per fifteen days. This allows continuous spinning with even celestial sphere coverage during one year of operations. Fig. 2 shows the number of scientific datasets (one second = one set) for one day of operations January 1, 2017.

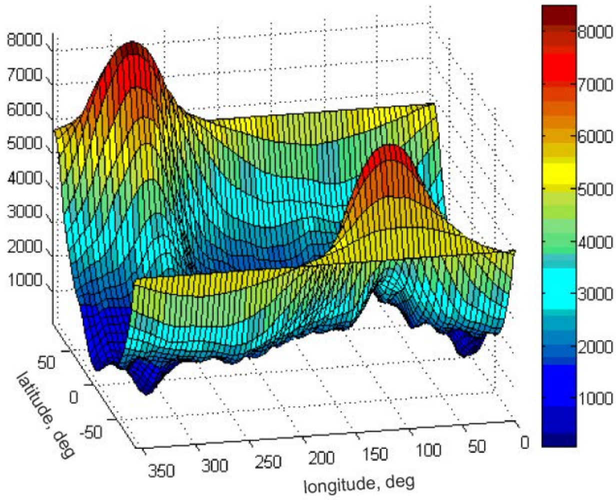

Fig. 2. One day of operation

Fig. 2 may be used to outline main tendencies in scientific data gain. Longitude is in bounds [0,360] degrees, latitude is in bounds [-90,90] degrees. Number of scientific data obtained for both poles is considered the same for each longitude. There are two areas with almost no scientific data. These are due to the Sun and Moon influence. Their position is almost constant during one day, so they provide inaccessible areas of celestial sphere. Two peaks in data gain are due to the specific attitude. Only one revolution out of three for the necessary spin axis direction is performed. One month of operations is shown in Fig. 3.

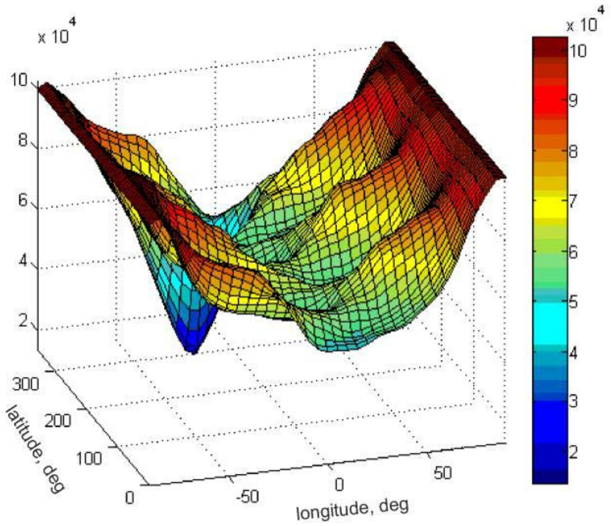

Fig. 3. One month of operation

Moon-related problem can be avoided during one month of operations since Moon will make roughly one revolution in the inertial space. Peaks due to the specific attitude are absent also since the necessary spin axis direction rotates in a factor of days. Sun still provides huge data loss. Nevertheless data is available for each celestial sphere point due to slight Sun displacement during one month. Several months are required to avoid Sun problem. Clearly on year of operations is preferable to achieve even scientific data distribution close to the equator. Fig. 2 and 3 prove polar regions to be better studied. This is due to all three radiation sources. Earth is located in the center of inertial space and only polar regions are not affected. Sun and Moon move close (no more than 30 degrees) to the equator. This problem leads to general pattern: the closer to the pole, the more data is available. Fig. 4 and 5 bring one year of operation.

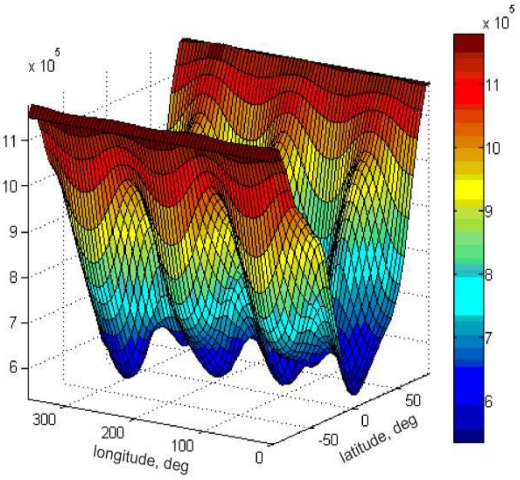

Fig. 4. One year of operation

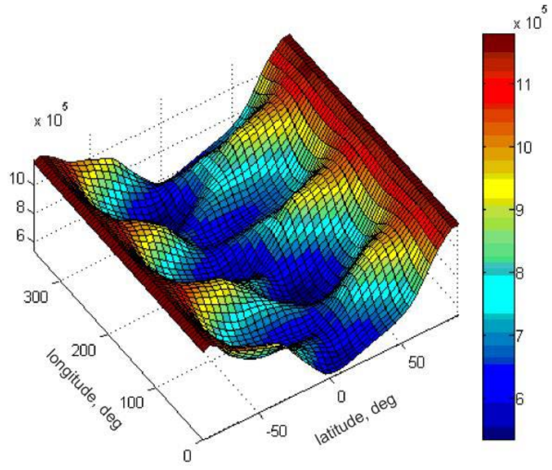

Fig. 5. One year of operation

During one year general performance holds: polar regions are covered much better than equatorial ones. Regular necessary direction motion and Sun motion (Fig. 12) lead to some regular pattern in near-equatorial regions. Overall number of data sets is 31.346.066, minimum value for different sphere points is 534.320, maximum 1.177.844.

3.2. Spin stabilization with Earth avoiding

Earth avoiding should lead to some gain in a number of scientific data sets. This is due to the enormous Earth's angular dimension. This gain is reduced due to the fast necessary direction rotation in the inertial space. Magnetorquers can hardly maintain this attitude. Spin rate is reduced to 1 deg/s and maximum dipole moment is increased to 0.15 Am^2. This provides 60 degrees attitude accuracy most of the time.

This is enough to avoid Earth in CZT field of view. One month of operations is shown in Fig. 6.

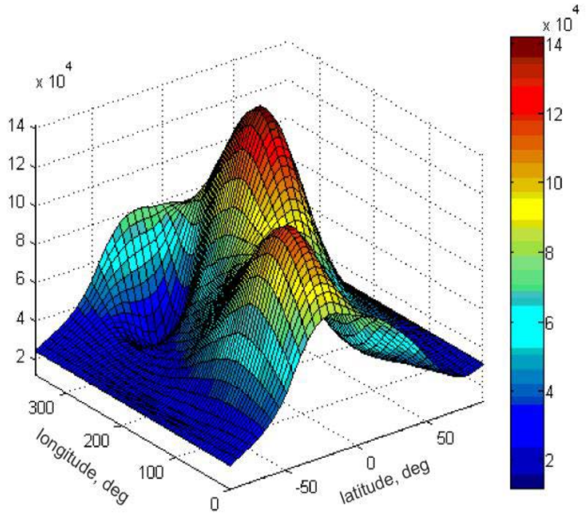

Fig. 6. One month of operation

Contrary to previous scheme polar regions are loosely covered. This is due to the orbit inclination and necessary direction to the Earth’s center. Polar regions are rarely viewed with this geometry. This holds for one year of operation, Fig. 7.

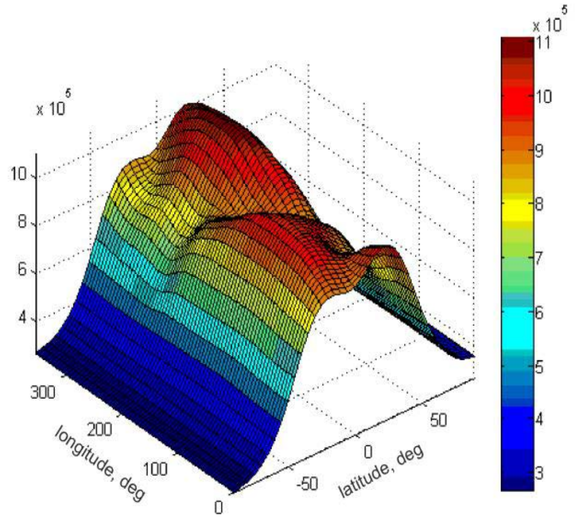

Fig. 7. One year of operation

Overall number of data sets is 31.875.472, minimum value is 266.819, maximum 1.106.402. Overall number increases slightly, minimum drops twice.

3.3. Spin stabilization with Earth avoiding and batteries charging

This regime is more general and sensible improvement of the latter. Sun-pointing not only provides batteries charging but also eliminates bad poles coverage. Since Sun moves close to the equator polar regions receive increased coverage. One month (Fig. 8) proves this and presents rather even coverage.

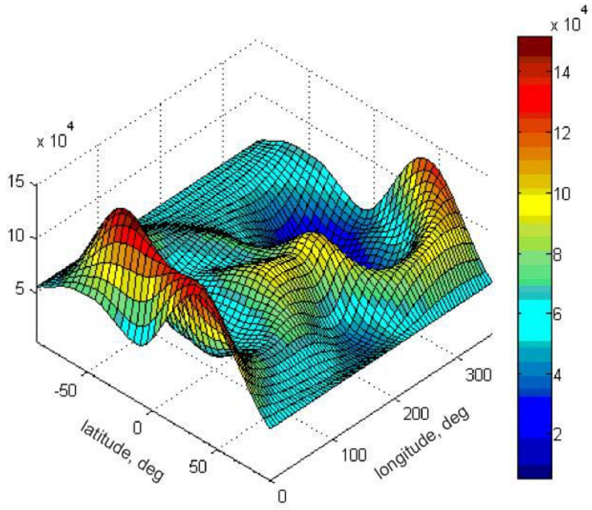

Fig. 8. One month of operation

One year of operation (Fig. 9 and 10) holds this tendency.

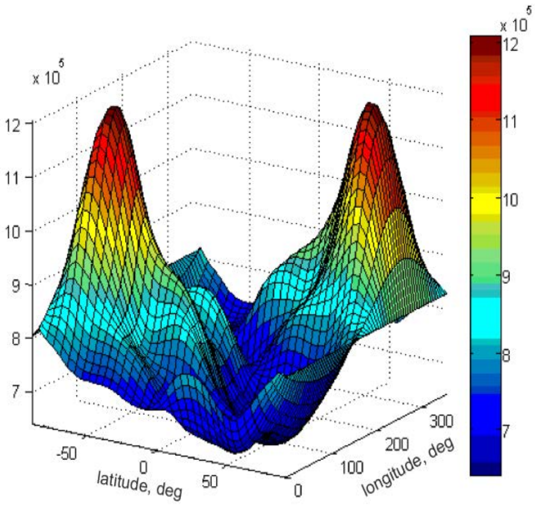

Fig. 9. One year of operation

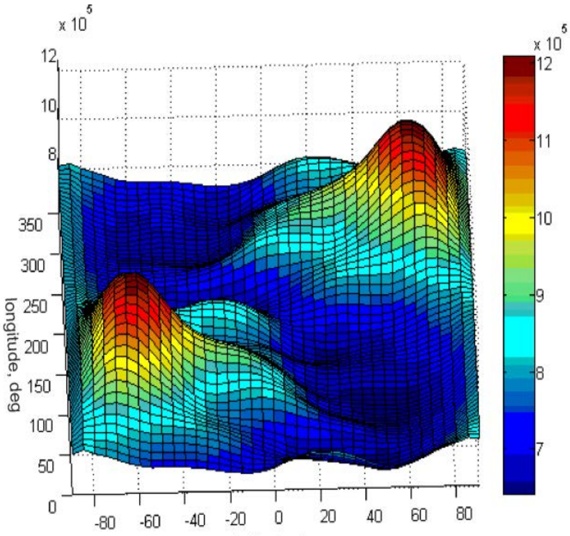

Fig. 10. One year of operation

Celestial sphere coverage remains rather even apart from two peaks arising from reorientation process. Slow attitude system response leads to delay in Sun acquisition and, therefore, uneven near-polar regions coverage. Overall number of data sets is 32.244.917, minimum value is 641.783, maximum 1.207.403.

3.4. Free-flying

The simplest case provides most even celestial sphere coverage. Fig. 11 brings one month of operation.

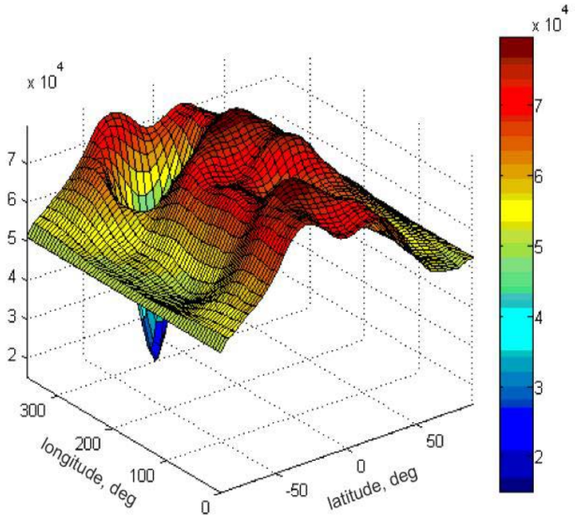

Fig. 11. One month of operation

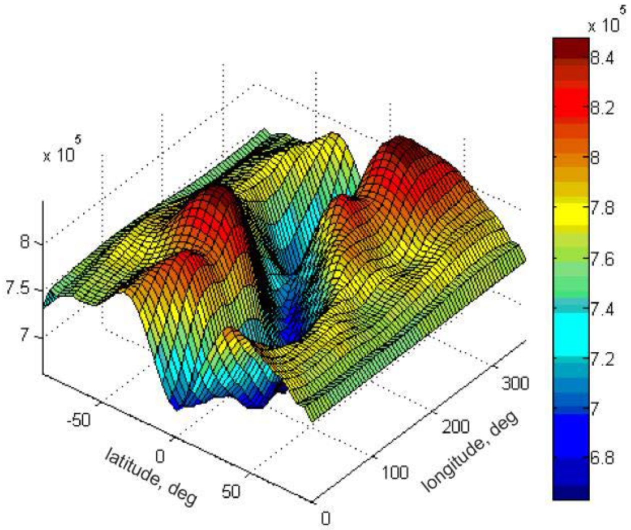

Fig. 12. One year of operation.

Polar regions are covered slightly worse. This is due to the gravitational torque that tends to stabilize satellite along local vertical. One year of operation (Fig. 12) allows Sun problem visualization. With the most even coverage only Sun motion leads to clear drop in number of sets. Overall number of data sets is 31.229.476, minimum value is 663.068, maximum 847.258.

4. Algorithms comparison

All four algorithms can be compared using Table 4. All relative values are present in comparison with the free flying mode.

Table 4 – Control schemes comparison

Scheme	Overall sets/year	Min. sets	Max. sets	Dipole moment, Am^2
Spin stabilization	31.346.066 (100.3%)	534.320 (80.6%)	1.177.844 (139.0%)	0.05
SS with Earth avoiding	31.875.472 (102.1%)	266.819 (40.2%)	1.106.402 (130.6%)	0.15
SS, Earth avoiding, charge	32.244.917 (103.3%)	641.783 (96.8%)	1.207.403 (142.5%)	0.15
Free flying	31.229.476 (100%)	663.068 (100%)	847.258 (100%)	0.05

Table 4 allows simple schemes comparison. Main parameters are overall number of data sets and their minimum number. Free flying scheme leads to the smallest overall data set. The difference is only a handful of percent and can be omitted. Minimum number of data sets makes free flying and spin stabilization with Earth avoiding and charging the best schemes. Free flying has a number of technical advantages: lower energy consumption (lower dipole moment and control active time); simple mission profile; no unfolding parts; more accurate attitude determination (magnetometers provide better readings with recent control residual dipole moment).

Conclusion

CXBN-2 mission magnetic control schemes are compared in terms of number of scientific data sets and celestial sphere even coverage. Free flying with occasional (de)tumbling is proved to be the best solution in comparison with different spin stabilization schemes. Although the simulations modeling the free flying concept of operations will result in less effective sky coverage near the polar regions, this is not anticipated to be a problem given that the science data is expected to be less usable in these regions owing to potential false positive detections by the array caused by the production of secondary X-ray photons produced by interactions with trapped charged particles associated with the magnetic poles. Data taken near polar regions would therefore likely have been eliminated in favor of the use of science data collected at mid-latitudes. The expected scientific data gain is present.

Bibliography

1. Brown K., Malphrus B. et al. The cosmic X-ray background nanoSat (CXBN): measuring the cosmic X-ray background Using the cubeSat form factor // 26th Annual AIAA/USU Conf. Small Satellites, Logan, Utah, 2012, paper: SSC12–VII–6.
2. Malphrus B., Jernigan G. The Cosmic X-Ray Background NanoSat-2 (CXBN-2): An Improved Measurement of the Diffuse X-Ray Background // Proposal Submitted to NASA CubeSat Launch Initiative, 2012, Solicitation Reference Number: NNH12SOMD001L, NAIC.
3. Shigehara M. Geomagnetic attitude control of an axisymmetric spinning satellite // Journal of Spacecraft and Rockets. 1972. Vol. 9, № 6. P. 391–398.
4. Renard M.L. Command laws for magnetic attitude control of spin-stabilized earth satellites // Journal of Spacecraft and Rockets. 1967. Vol. 4, № 2. P. 156–163.
5. Artuhin Y.P., Kargu L.I., Simaev V.L. Spin-stabilized satellites control systems. Moscow: Nauka, 1979 (in Russian).
6. Ovchinnikov M.Y., Roldugin D.S., Penkov V.I. Asymptotic study of a complete magnetic attitude control cycle providing a single-axis orientation // Acta Astronautica. 2012. Vol. 77. P. 48–60.
7. Ovchinnikov M.Y. et al. Investigation of the effectiveness of an algorithm of active magnetic damping // Cosmic Research. 2012. Vol. 50, № 2. P. 170–176.
8. Ovchinnikov M.Yu., Penkov V.I., Roldugin D.S. Active magnetic attitude control system providing three-axis inertial attitude. Keldysh Institute preprints, 2013, No. 74, 23 p. URL: http://library.keldysh.ru/preprint.asp?id=2013-74&lg=e.
9. Fundamentals of Astrodynamics and Applications. 2nd ed. / ed. Vallado D.A. El Segundo: Microcosm, Inc, 2001. P. 958.
10. Stickler A.C., Alfriend K.T. Elementary Magnetic Attitude Control System // Journal of Spacecraft and Rockets. 1976. Vol. 13, № 5. P. 282–287.