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Design and testing of magnetic controllers for Satellite stabilization

M. Guelman[a,*], R. Waller[a], A. Shiryaev[a], M. Psiaki[b]

[a]*Asher Space Research Institute, Technion, Haifa, 32000, Israel*
[b]*Cornell University, Ithaca, NY, 14853-7501, USA*

Abstract

A study was carried out of attitude control algorithms that are able to provide 3-axis stabilization of a satellite equipped with a magnetometer as the only sensor, and magnetic torquers as the only actuators. Two different solutions to the problem were developed, namely *Linear Quadratic Regulator* and *No Wheel* controllers. Their aptitude to achieve the required performance was confirmed by multiple numerical simulations under different initial conditions and various scenarios. The new algorithms were tested onboard the Israeli Gurwin-TechSAT micro-satellite, nominally momentum-biased, stabilized within 2–2.5° precision by the proportion-plus-derivative magnetic controller. In the flight tests of the new controllers, some valuable results were obtained, such as revealing the possibility to effectively maintain the satellite 3-axis stabilization even with a very small momentum bias, and the implementation and efficient performance of the properly modified extended and linear Kalman filters in the onboard computer.

1. Introduction

Generally, in order to achieve precise stabilization by the magnetic control, the magneto-torquers (MTQ) in the satellite's attitude control systems (ACS) are working together with other actuators, such as momentum or reaction wheels. The latter devices being costly and including rotating elements subject to failure, the advantages provided by the ACS without wheels are their robustness, reliability, low power consumption, and cost-efficiency. Furthermore, when proved effective, such purely magnetic control (PMC) algorithms could be considered as a contingency option in the ACS of the small satellites, flying alone, or in formations.

2. Gurwin-Techsat COMPASS controller [1,5]

The 50-kg Israeli Gurwin-Techsat micro-satellite was put in an 820-km circular Sun-synchronous orbit in July 1998, and has been successfully functioning for more than 4.5 years. Its ACS hardware includes a three-axis magnetometer (MGM), a three-axis MTQ, and the momentum wheel (MW). The satellite is three-axis stabilized within 2–2.5° precision by the proportion-plus-derivative *COMPASS* controller, as follows:

$$\bar{m} = -K(\dot{\bar{B}}_{\text{meas}} - \dot{\bar{B}}_{\text{exp}}) - C(\bar{B}_{\text{meas}} - \bar{B}_{\text{exp}}), \qquad (1)$$

* Corresponding author.

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where $\bar{m}$ is the control magnetic dipole moment, to be generated by the MTQ coils, $\bar{B}_{\text{meas}}, \dot{\bar{B}}_{\text{meas}}$ are the measured geomagnetic field (GMF) vector and its derivative, referred to the body frame (BF), and $\bar{B}_{\text{exp}}, \dot{\bar{B}}_{\text{exp}}$ are the expected GMF vector and its derivative, referred to the trajectory frame (TF), the latter also being known as the orbit-following local level frame.

For the onboard modeling of the GMF vector, the Fourier approximation is used of the international geomagnetic reference field 2000 (IGRF 2000) along the satellite orbit. The sets of the Fourier coefficients are calculated, using the SGP4 orbit predictor, and uplinked on a regular basis to the satellite.

Each one of three Gurwin-Techsat MTQ dipoles can have any of three possible values of the magnetic moment

$Msat$, 0, $-Msat$,

where $Msat \approx 1\,\text{A turn m}^2$ is the MTQ dipole saturation value. The total number of feasible standard dipole vectors for three-axis MTQ, to approximate the required control magnetic moment (1), is thus equal to 27.

To prevent the distortion of MGM measurements by MTQ actuation, they are separated in time. Within each second, 0.3 s are allotted for measurements, and the rest for control.

The typical flight performance of the Gurwin-Techsat attitude control system under *COMPASS* control for a number of revolutions is illustrated in Figs. 1–3.

In Fig. 1, the components of $\bar{B}_{\text{exp}}$ vector (dark) are juxtaposed with those of $\bar{B}_{\text{meas}}$ (light). Although these vectors are referred to different reference frames, the smallness of their differences (Fig. 2) witnesses the closeness of BF and TF axes and, hence, the 3-axis stabilization of the satellite.

So do the plots of the satellite's Euler angles φ, θ, ψ (Fig. 3), as estimated by processing the MGM telemetry through the extended Kalman filter of the ground estimator software.

3. LQR controller [2]

The linearized model of the dynamical system under magnetic control can be described by the equation

$$\dot{\bar{x}} = A\bar{x} + \tilde{B}(t)\bar{m}, \tag{2}$$

where $\bar{x}$ is the process state vector

$$\bar{x} = (\dot{\varphi}, \dot{\theta}, \dot{\psi}, \varphi, \theta, \psi),$$

A is the time-invariant system matrix

$$A = \begin{bmatrix} 0 & 0 & w_0(1-\sigma_1) & -4w_0^2\sigma_1 & 0 & 0 \\ 0 & 0 & 0 & 0 & -3w_0^2\sigma_2 & 0 \\ -w_0(1+\sigma_3) & 0 & 0 & 0 & 0 & w_0^2\sigma_3 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix},$$

w_0 is the orbital mean motion, $\sigma_1 \equiv (I_{yy} - I_{zz})/I_{xx}$; $\sigma_2 \equiv (I_{zz} - I_{xx})/I_{yy}$; $\sigma_3 \equiv (I_{xx} - I_{yy})/I_{zz}$; I_{xx}, I_{yy}, I_{zz} are the satellite's principal moments of inertia; $\tilde{B}$ is approximately periodic control effectiveness matrix

$$\tilde{B} = \begin{bmatrix} 0 & b_z(t)/I_{xx} & -b_y(t)/I_{xx} \\ -b_z(t)/I_{yy} & 0 & b_x(t)/I_{yy} \\ b_y(t)/I_{zz} & -b_x(t)/I_{zz} & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix},$$

$\bar{b} = (b_x, b_y, b_z)$ is the GMF vector along the satellite orbit, and $\bar{m}$ is the control magnetic dipole moment. By the periodic linear quadratic regulator (LQR) technique, the solution to (2) was found in the form of the control law

$$\bar{m} = -R^{-1}\tilde{B}^{\mathrm{T}}(t)P_{\text{ss}}\bar{x}, \tag{3}$$

where P_{ss} is the asymptotic steady-state solution to the high-control-weighting time-dependent matrix Riccati equation, and R is the constant control weighting matrix. This LQR controller proved to be robust, when full-state feedback is available. Making use of the constancy of the A matrix, and hence, of the state transition matrix, a linear Kalman filter (LKF) was included in the controller, to provide it with the estimates of the state vector from MGM measurements. To eliminate the steady-state effects of the disturbances, the enlarged state vector $\bar{x}_{\text{aug}} = [\bar{x}, \bar{z}]$ was introduced instead of $\bar{x}$, with $\bar{z}$ being a vector of integrals of the attitude errors. The controller (3) was optimized and

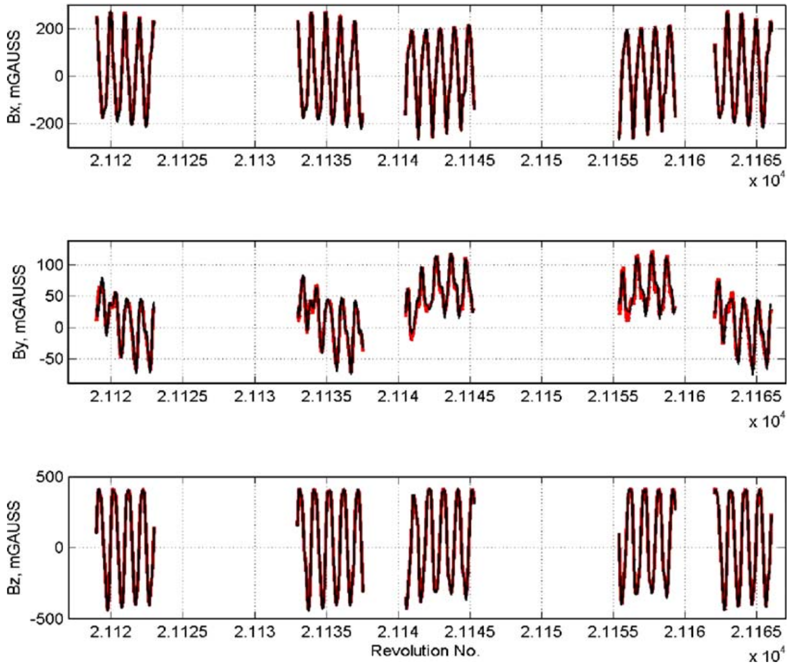

Fig. 1. MGM telemetry versus GMF reference.

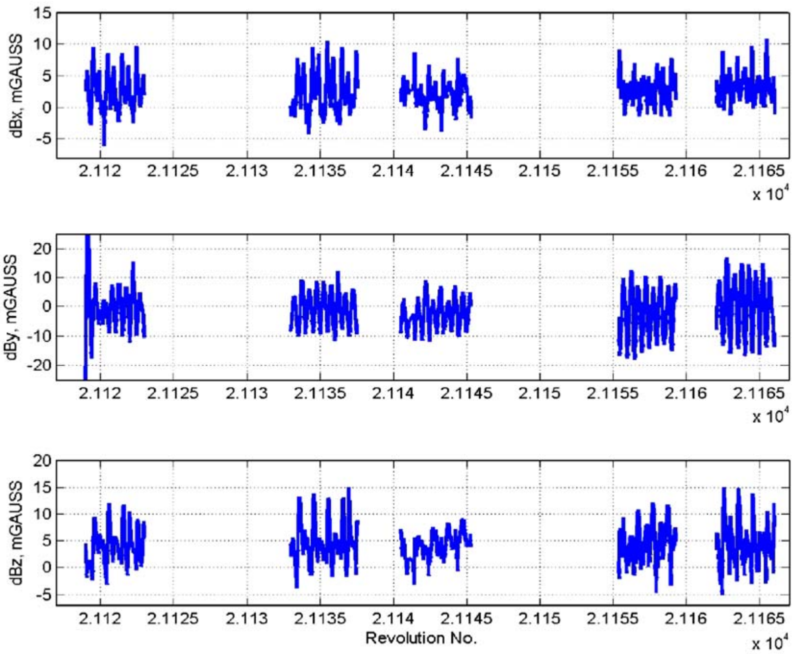

Fig. 2. MGM telemetry minus GMF reference.

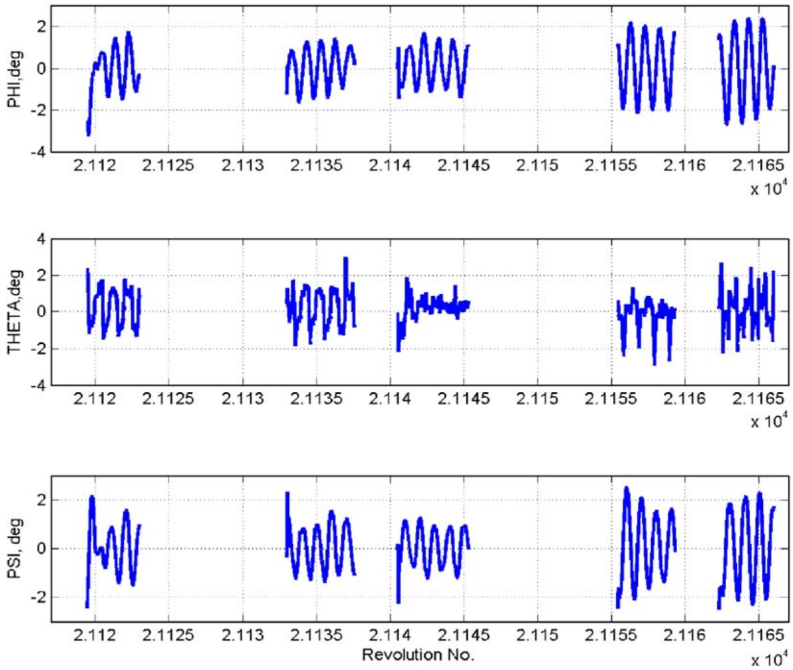

Fig. 3. Gurwin-Techsat attitude estimated by MGM telemetry processing.

supplied with the desaturation and pulse width modulation (PWM) options, to adequately approximate the required control dipole moment $\bar{m}$ by the feasible Gurwin-Techsat MTQ dipole moments.

4. No Wheel controller [3,4]

The control torque $\bar{T}$, ensuring the satellite's stabilization without MW, can be calculated by the formula

$$T_{\text{required}} = -(C_1\bar{\omega}' + C_2 I^{-1}\bar{q}), \tag{4}$$

where $\bar{\omega}'$ is the instantaneous angular velocity of the BF with respect to the TF, as referred to BF axes; $\bar{q}$ is the attitude quaternion; and I is the satellite's tensor of inertia, assumed diagonal.

As known, in the magnetic ACS the required control torque cannot be implemented directly, because

$$\bar{T}_{\text{control}} = \bar{m} \times \bar{B}, \tag{5}$$

where $\bar{m}$ is relevant control dipole moment, and $\bar{B}$ is GMF vector. In the "*No Wheel*" algorithm, a *feasible* control dipole moment is applied, defined as follows

$$\bar{m}_{\text{feasible}} = \frac{\bar{B} \times \bar{T}_{\text{required}}}{|\bar{B}|^2}. \tag{6}$$

The vectors $\bar{\omega}'$ and $\bar{q}$, entering (4), are supposed to be estimated from the MGM measurements by the extended Kalman filter (EKF). The quaternion $\bar{q}$ is updated for the steady-state effects in the attitude. The implementation of the *No Wheel* control is similar to that involved in the PWM technique.

5. Planning the flight tests

In the standard operating mode, the Gurwin-Techsat satellite is keeping its momentum bias H_w close to its nominal value ≈ -0.42 N ms. When choosing the testing sequence, the constraints as follows were taken into account:

a. The attitude control testing sequence should include the phase of slowing down and stopping the MW.

b. As a result of slowing down and stopping the MW, the satellite gets destabilized.

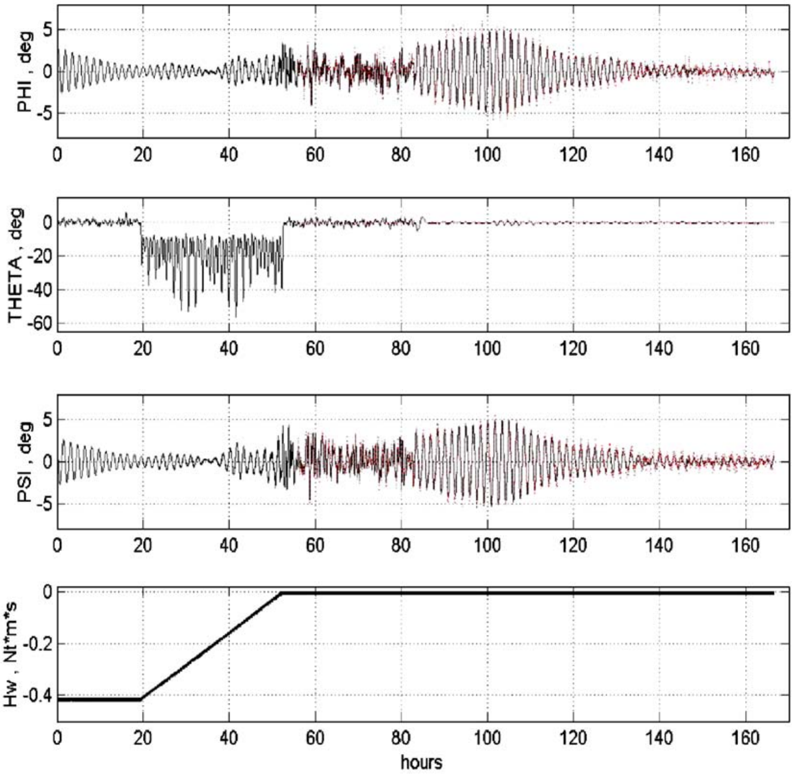

Fig. 4. Simulation of slowing down MW and switching to LQR controller.

c. Both PMC controllers can be actuated *only after* the initialization of the relevant Kalman filter.

d. The onboard computer (OC) could not keep pace with the nominal control application (once a 1 s) and a standard Kalman filter algorithm sequence, with all its *measurement update* phase to be completed at the measurement times.

To adjust the algorithms to OC capability, the *measurement update* sequence was split into 10 parts, each being executed once per 10 s. In order to make such a constrained filter comply with the satellite's kinematics, its rotation had to be slowed down, and the control to be applied once per 10 s.

The simulated performance of the ACS with the LQR controller is shown in Fig. 4 , with *COMPASS*-controlled 1st phase—initial stabilization (0–20 h), MW slowing down (40–55 h), additional stabilization together with initialization of the LKF (55–59 h), and LQR-controlled 2nd phase (starting at 59 h).

In Fig. 5, the simulation is represented of the ACS performance with *No Wheel* controller under scenario, which included *COMPASS* control phase (0–78 h), with EKF initialization, MW slowing down from H_w nominal to -0.005 N ms under once-per-1 s control rate, and from $H_w = -0.005$ to -0.0006 N ms under once-per-10 s control rate; and *No Wheel* control phase (78–305 h), with MW stopping.

In both figures, the parameters of the truth model are plotted in black, while those estimated either by LKF, or by EKF-in light. As can be seen, the *COMPASS* control enables three-axis stabilization even with a very small momentum bias. The modified Kalman filters provided in both cases adequate estimation of the state vectors and, thus, the convergence of the stabilization processes under purely magnetic control.

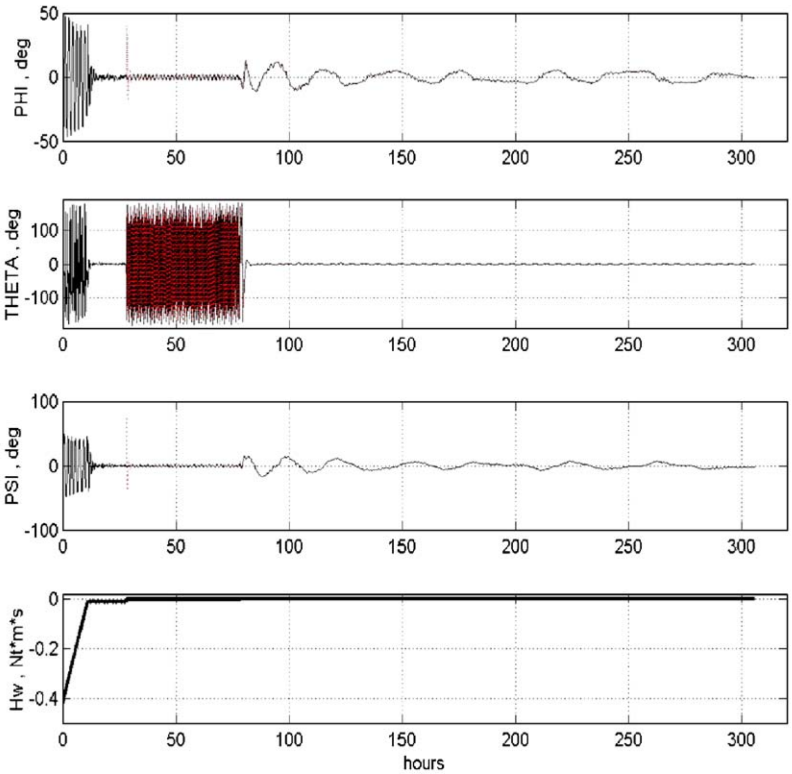

Fig. 5. Simulation of slowing down MW and switching to *No Wheel* controller.

6. Flight experiments

The flight experiments with both PMC algorithms were carried out according to the scenarios just outlined, including phases of gradual MW slowing down from the nominal H_w to zero, with initialization of the relevant Kalman filters under *COMPASS* control, and attempts to switch to PMC controller.

6.1. LQR flight experiment

In Fig. 6, the MGM telemetry versus expected GMF vectors are plotted for some revolutions with MW stopped. Seen are the perturbations in $\bar{B}_{\text{meas}}$. In Fig. 7, where the differences $\bar{B}_{\text{meas}} - \bar{B}_{\text{exp}}$ are shown, these perturbations are more noticeable.

Still, according to Fig. 6, both the measurements and GMF reference matched in phase and partly in magnitude, which means, that despite these perturbations, the satellite was keeping its three-axis stabilization throughout the whole time-span with the MW stopped. Meanwhile, in the attitude estimation from the measurements, these perturbations were not modeled, so the estimates (Fig. 8), obtained both by onboard LKF (light plots) and ground EKF (dark plots), seen to be inadequate.

Thus, since LKF couldn't perform well, the switch to the LQR control was impossible.

6.2. No Wheel flight experiment

Comparison of the MGM telemetry with the expected GMF vector, plotted in Fig. 9, evidences the satellite's three-axis stabilization till stopping the MW (at the revolution No. 19020). Then, after switching to *No Wheel* controller, the satellite started tumbling (Fig. 10), which could not be damped down, until switching to nominal *COMPASS* control with the momentum bias.

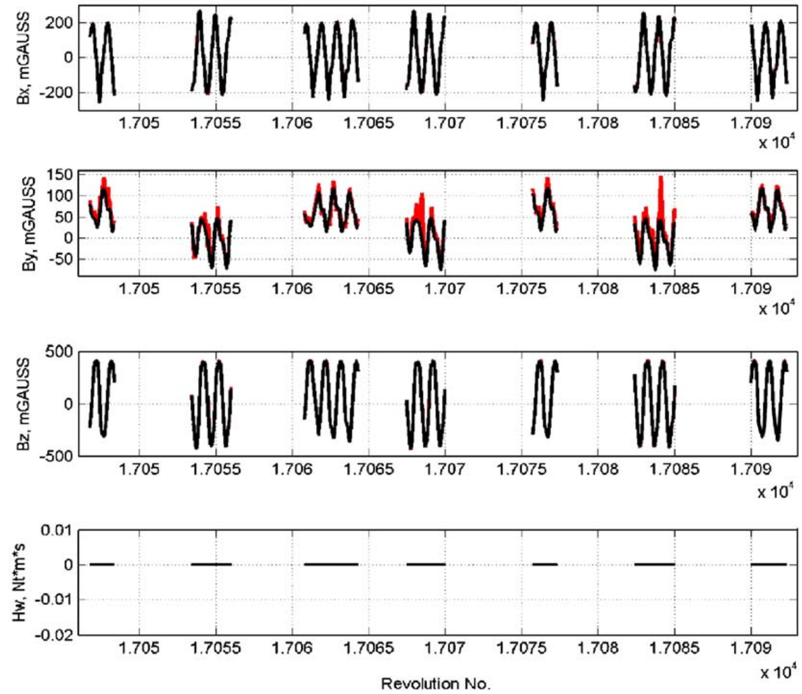

Fig. 6. MGM telemetry versus GMF reference in LQR flight experiment.

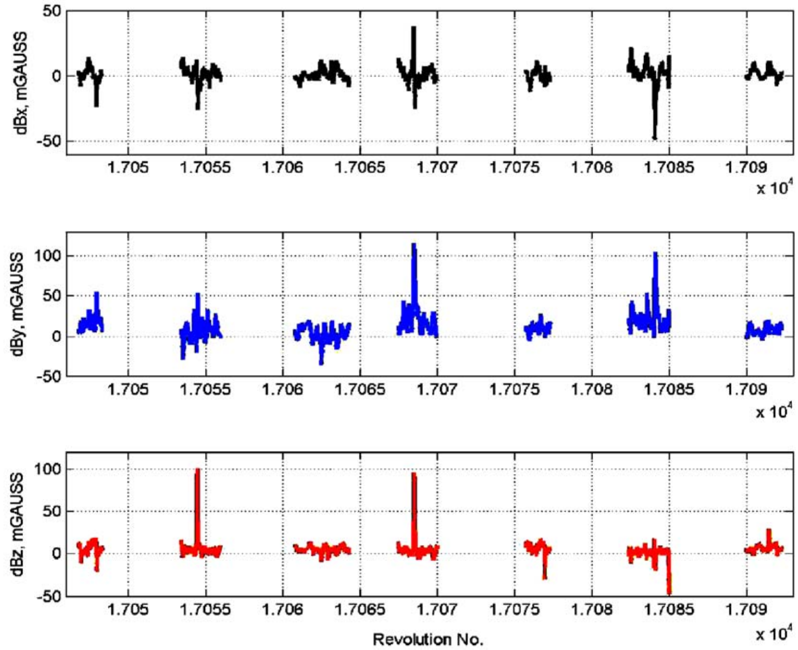

Fig. 7. MGM telemetry minus GMF reference in LQR flight experiment.

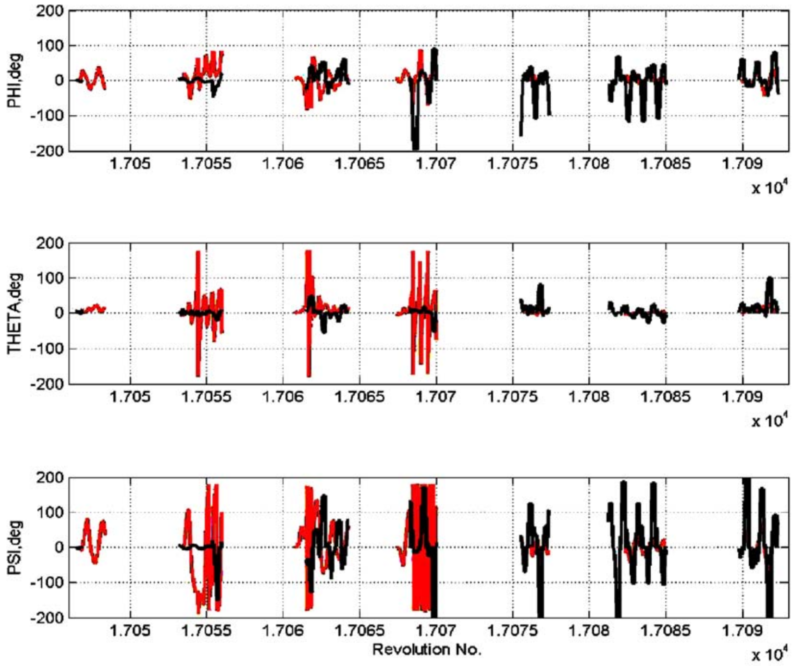

Fig. 8. Attitude estimates during LQR flight experiment.

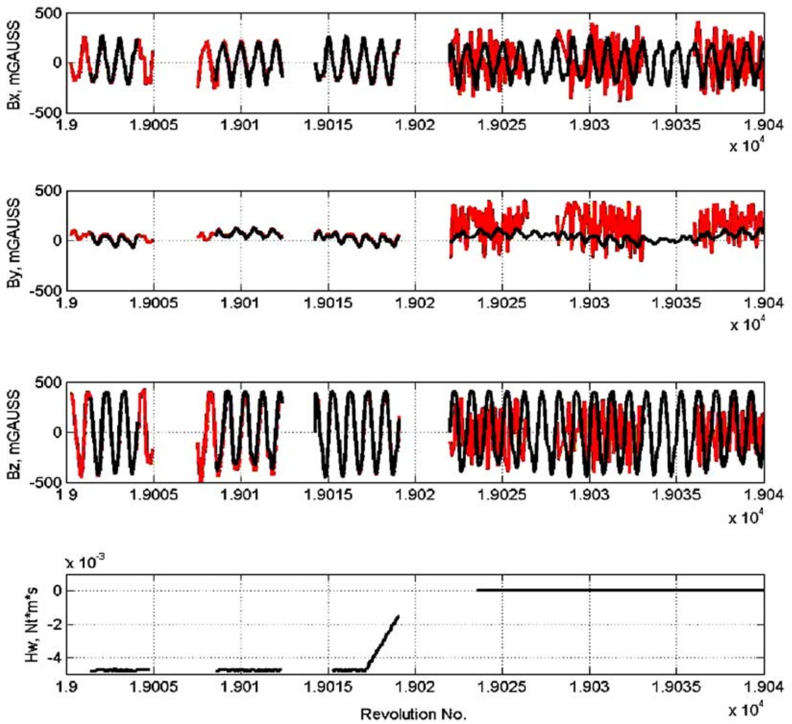

Fig. 9. MGM telemetry versus GMF reference in *No Wheel* experiment.

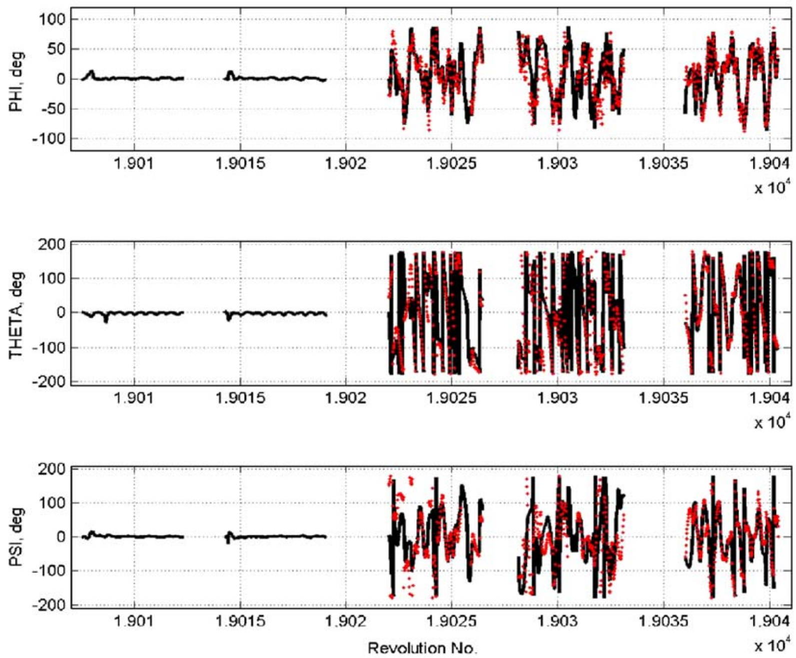

Fig. 10. Attitude estimates during *No Wheel* flight experiment.

7. Conclusions

Two PMC controllers, providing three-axis stabilization of the satellite without MW, were designed and tested.

Onboard LKF and EKF functioned properly even with the algorithms modified due to the onboard computer constraints.

During the flight tests, the ability of the *COMPASS* controller to maintain three-axis stabilization with the next-to-zero momentum bias was confirmed. The LQR controller was not activated because of LKF failure, believed to be caused by magnetic field disturbances of the MW.

The activation of the *No Wheel* controller resulted in the satellite's tumbling, probably, due to the same reason. Still, both PMC algorithms might perform well, when being actuated in the satellite without MW, or with MW kept fixed by a mechanical brake after the satellite's release from the launcher.

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