Attitude Control Systems for the Communication Spacecraft*

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Abstract: The *ISS Reshetnev* is the Russian leader in development, manufacture and operations of navigation, geodetic and communication spacecraft, as well as Russian State programme for satellite telecommunication systems development. The research results achieved by the *ISS Reshetnev* in attitude control of some communication spacecraft, are presented.

Keywords: communication spacecraft, gyromoment attitude control

1. INTRODUCTION

The *ISS Reshetnev* is known all over the world as a designer and manufacturer of communication, navigation and geodetic spacecraft (SC). It is less known that *ISS Reshetnev* is a designer and manufacturer of various types of Attitude & Orbit Control Systems (AOCS), which are the most complex and expensive among the onboard subsystems. The *ISS Reshetnev* have developed a wide spectrum of spacecraft AOCS types: the *passive*, *combined* and *active* systems, which use various types of electromechanical actuators and reaction-control thrusters, magnetic torques used for desaturation an angular momentum (AM) accumulated in electromechanical drivers, as well as electromechanical systems of autonomous pointing Solar Array Panels (SAPs) and the antenna platforms. For the purpose of orbit control (spacecraft orbit-keeping manoeuvres) the special types of propulsion units have been designed, using gas, thermal-catalytic and plasma thrusters. The AOCS developed by the *ISS Reshetnev* could be used for various spacecraft in circular, elliptic and geostationary orbits. This paper briefly presents the research results achieved by the *ISS Reshetnev* on the attitude control systems for some communication spacecraft.

2. THE AOCS FOR HIGH-ELLIPTIC ORBITS

During the recent 4 decades, *ISS Reshetnev* successfully operates the spacecraft on 12-hr high-elliptic orbit providing communication in high-latitudinal regions of the Earth. In practice, two variants of spacecraft AOCS have been implemented.

In *variant 1*, the SAPs are rigidly fixed on the SC body, and the normal to their surface coincides with the spacecraft x-axis oriented to the Sun. About x-axis the SC turns until the coincidence of the plane "Sun-Spacecraft-Earth" with the plane, in which the antennas are moved until coincidence of its informational axis with the direction to the Earth. In *variant 2*, antennas are fixed on the SC body, their axes are directed along the SC body x-axis oriented to the Earth. The SC rotates about the x-axis until the SAPs rotation axis coincides with the normal to the plane "Sun-Spacecraft-Earth", than the SAPs move with respect to the SC body and are oriented to the Sun. The first communication satellite *Molniya-1* (Fig. 1) had been launched by *ISS Reshetnev* in May 1965. The AOCS of that spacecraft had been designed in accordance with the 1st of above variants, and during the recent 40 years it undergone some refinements, which substantially improved its precision, resource and power-mass characteristics without breaking the main principles.

Fig. 1. The Russian communication SC *Molniya*

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Fig. 2. The Russian re-transmitter satellite *Lutch*

Today *ISS Reshetnev* have the 3rd generation *Molniya* spacecraft, the AOCS of which in all the operation modes employs only the two sensors: the Sun sensor (SS) installed on the SC body, and the Earth sensor (ES) fixed on the antenna unit. The onboard microprocessor controls the operation of the system.

ISS Reshetnev have recently designed the digital AOCS for the new generation SC employed on a high-elliptical orbit. These spacecraft have large deployment antennas, for which it is problematic to provide the rotation with respect to the SC body within a wide angular band, and it is preferable to provide mobility of the SAPs with respect to the SC body. Hence, AOCS of such satellites have been designed in accordance with the 2nd of above variants. AOCSs of this type SC are characterized by a number of substantial differences from the traditional AOCS of *Molniya* series spacecraft. In this case, more efficient electromechanical actuators are used. For the purpose the reaction wheels unload the thermal-catalytic hydrazine thrusters are used. The software of these AOCSs has been implemented in a more powerful onboard computer, as well as the efficient aids for autonomous diagnostics and control are available. In the AOCS the mode of autonomous solar orientation is also provided: it employs the reserved devices which are not active in main control modes and provide for survivability of spacecraft in cases of failures of onboard equipment at the main control loop.

3. THE AOCS FOR GEOSTATIONARY ORBIT

The possibility to provide uninterrupted communication service for distant regions of the world with the aid of one satellite is a unique property of the geostationary orbit (GEO). Furthermore, continuous tracking of the satellite with land-based antennas is not needed. As a rule, the AOCS of such SC on GEO must provide orientation of one of the SC body's axes to the Earth's center, the second one being oriented perpendicularly to the orbital plane, and the SAPs are oriented to the Sun move with respect to the second axis.

The directions to the Earth's center, to the Sun's center and in some cases to the stars (normally to the Polaris) are used as reference directions for such systems. High-precision angular stabilization of the spacecraft body in the orbit reference frame is the nominal mode the communication satellite's AOCS on the GEO. There is no need to perform large-scale spatial rotation manoeuvres of the SC body, and so electromechanical drivers are normally used in the AOCS.

The one momentum wheel scheme has some advantages. If the satellite is nominally oriented so that the AM vector of momentum wheel is directed along the bi-normal to the orbit, the gyroscopic coupling between the roll and yaw channels appears, this coupling being substantial for large values of the AM. This suggests a principal possibility of the efficient SC control with respect to the yaw channel, when information is available only concerning the deviation in attitude with respect to the roll channel, and allows to provide reliable long-term stabilization of the SC body in the orbit reference frame (ORF) with respect to all the three orientation angles.

The constrain of the momentum wheel with the SC body may be flexible-viscous or may be executed via the drives along one or two gimbal axes. On geostationary spacecraft it is possible to apply different (even functionally excessive) electromechanical actuators with nominal zero angular momentum. But in the latter case, information about the spacecraft deviations with respect to the yaw channel is needed, and such information can usually be obtained with the aid of optical sensors or high-precision inertial gyroscopic assembly (IGA) with astronomic correction. An active 3-axial AOCS for geostationary retransmission satellites had been for the first time designed by the *ISS Reshetnev* in 1974 and applied on communication spacecraft of the *Raduga* series. The main mode of this active system was implemented on the basis of a gyrostabilizer in the form a wheel in a 2-gimbal flexible-viscous suspension and a infra-red horizon sensor with circular scanning. The AOCS also includes an autonomous guidance the SAPs

Fig. 3. The Russian geostationary satellite *Express*

Fig. 4. The geostationary spacecraft *Sesat*

providing constant rate of their rotation which equals to the angular rate of the spacecraft orbital motion.

The second generation of AOCSs for spacecraft of above type is represented by the system designed by the *ISS Reshetnev* for the *Ekran* and *Gorizont* spacecraft in 1976. The 3rd generation of such AOCSs is represented by the unified active digital system *Vector* designed by *ISS Reshetnev* in 1982 for spacecraft *Lutch*, *Gals*, *Express*, *Arcos*, etc. The *Vector* belongs to the class of precision systems. This system includes the following components: the gyrostabilizer based on reaction wheel at 2-DOF gimbals with stepping motor drivers, digital ES, the SS and the Polaris star tracker. The onboard computer in the control loop allowed to increase the precision of attitude control, substantially improve the survivability and autonomy of the AOCS functioning at the expense of diagnostics of its state and reconfiguration of its structure in cases of failures in some elements. This AOCS provides the angular precision of geostationary communication spacecraft with respect to the ORF not less than $0^\circ.1$.

The *Sesat* and *Express-AM* spacecraft were manufactured by *ISS Reshetnev*, moreover these spacecraft have three axis stabilized during all phases of the mission. Their AOCS is based on a standard configuration of sensors (the Earth sensor, the Sun sensor, precise gyroscopes) and a momentum bias reaction wheel, mounted on 2-DOF gimbals, as the main actuator. Electrical plasma thrusters are used for a station-keeping, and hydrozine thrusters — for attitude control.

Propulsion unit is an important component of any geostationary spacecraft AOCS. It provides the spacecraft rotation with respect to the mass center, unloading the angular momentum accumulated by the electromechanical actuators due to external disturbances and precise keeping of the satellite orbital parameters, that is the most significant point. Satellite longitude correction does not require large power expenditures and so can be provided by the thermal-catalytic thrusters. But present day GEO communication satellites require also a precise latitude keeping through all lifetime. This results in incomparably much power consumption.

For a number of well known communication satellites having lifetime more than 10 years, fuel mass of the orbit correction propulsion unit based on liquid thrusters makes up to 50 percents of the overall unit mass. Electric reaction propulsion units are most satisfactory for solving the orbital correction problems. They may be based on stationary plasma thrusters or another type of electric reaction thrusters having 5–7 times more efficiency than traditional thrusters which use chemical fuel. Hence all the contemporary and perspective *ISS Reshetnev* GEO satellites are equipped with electric reaction propulsion units.

The *S*iberian-*E*urope *Sat*ellite (*Sesat*) is a first communication spacecraft produced jointly by Russia and Europe. The *Sesat* was orbited on April 18, 2000. The satellite operational lifetime is 10 years at orbital slot 36° East. The *Eutelsat* Director General *G. Berretta* declared after its placement on the GEO: "We are very proud to dedicate this satellite to Sir *Arthur C. Clarke*. His visionary theories on use of the geostationary arc (the *Clarke Belt*, 1945) opened the door to radically enhanced communications".

4. THE ADCS OPERATIONAL MODES

The *Sesat* attitude & orbit control system is based on the following configuration: the ES and the fine digital SS, the precise GU, a three-axial RG block, the GW, the SAP driver (AD) based on the GSDs, the RTs, Fig. 5. Electric plasma RTs are used for spacecraft station keeping, and hydrazine RTs — for attitude control and GW unloading.

4.1 Initial Orientation Modes

When the *Sesat* has been separated from *Proton* launcher, the Initial modes of Attitude Determination and Control System (ADCS) begin:

- Damping mode (DM) $\mapsto$ [RGs & RTs & AD]:
  - · braking the angular rate vector $\boldsymbol{\omega}(t)$ at the inertial reference frame (IRF) $\mathbf{I}_\oplus$;
  - · the SAPs turn to a fixed position when their normal $\mathbf{n}^p$ is oriented contrary the unit $\mathbf{b}_y$ of the body reference frame (BRF) $\mathbf{B} = \{\mathbf{b}_i\}$ (Oxyz), see Fig. 5;
- Sun Acquisition mode (SAM) $\mapsto$ [·] & [SS]:
  - · Sun unit $\mathbf{S}$ acquisition within one body revolution around the $-\mathbf{b}_y$ unit;
  - · Sun pointing by a fixed unit $\mathbf{b}'_y$, Fig. 5;
- Earth Acquisition mode (EAM) $\mapsto$ [·]&[ES]:
  - · the satellite is rotated around the unit $\mathbf{b}'_y$ keeping the same Sun pointing;
  - · Earth unit $\mathbf{E}$ acquisition by the ES;
- Preliminary Earth Orientation mode (EOPM) $\mapsto$ [·] & [AD & GW]:
  - · GW rotor acceleration;
  - · SAPs rotation in the Tracking mode.

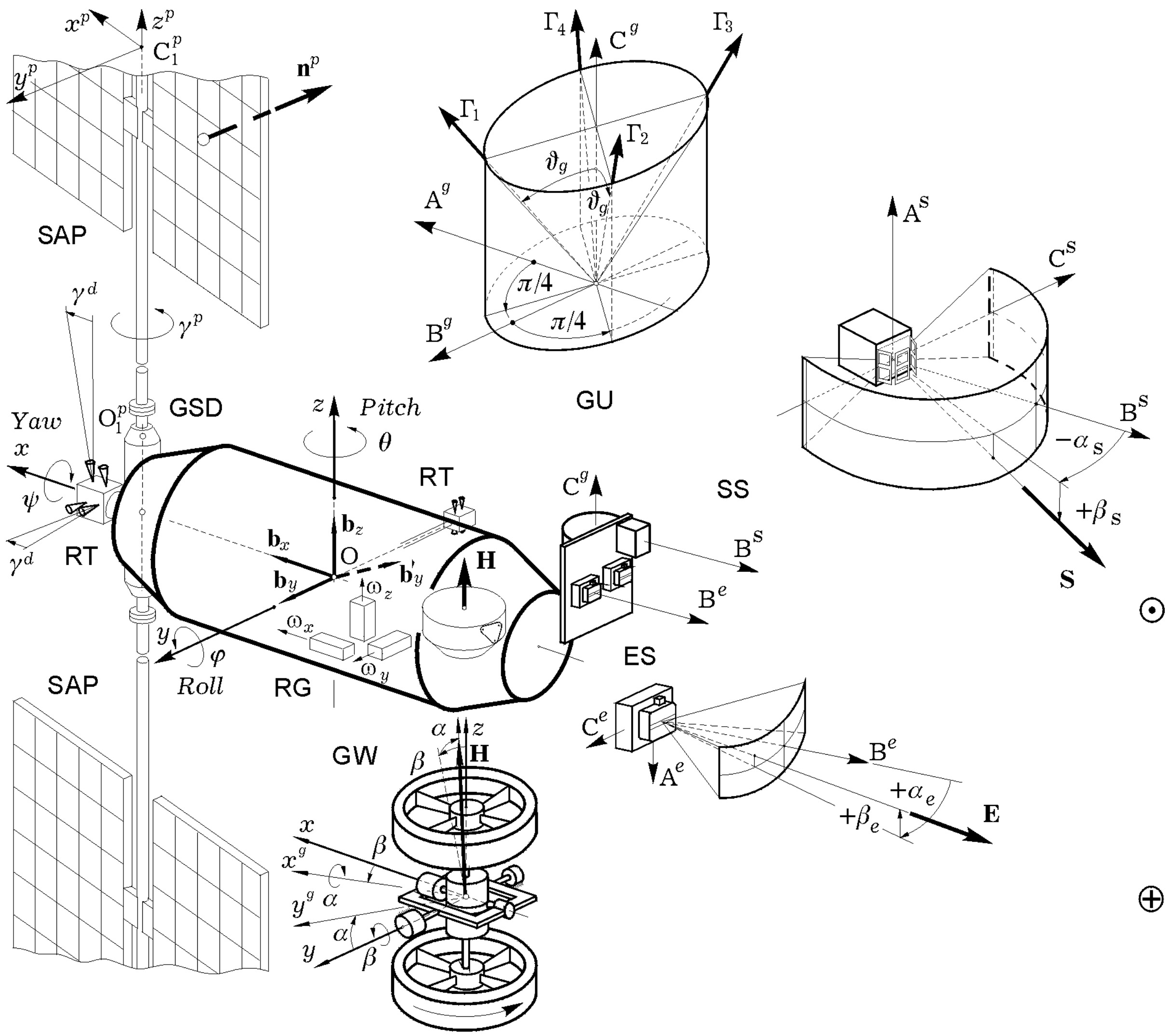

Fig. 5. The spacecraft *Sesat* onboard equipment layout scheme: ES — the Earth sensor; SS — the Sun sensor; GU — gyro unit; RG — rate gyrosensor; GW — gyrowheel (a momentum wheel mounted on 2-DOF gimbal); RT — reaction thruster; SAP — solar array panel; GSD — gear stepping drive.

The Earth Orientation mode (EOM) is used for the body three-axes orientation and stabilization in the ORF $\mathbf{I}_o$ $(\mathrm{O}x^o y^o z^o)$ by the device base [ES & GW] with GW unloading by the RTs and for SAPs Sun pointing by the AD. A digital control law does not employ physical measurement of the yaw angle or its rate but certainly provides the body attitude control in the ORF using coupling roll and yaw channels.

Three Axes Stabilization mode (TASM) is the main nominal mode of ADCS operation. It has the device base [GU & GW & AD] with an infrequent calibration of the GU by the SS and ES digitally filtered signals. TASM provides precise body attitude stabilization in the ORF and the SAPs Sun pointing in three sub-modes:

- nominal sub-mode;
- GW momentum unloading (GWMU);
- station keeping manoeuvre (SKM).

The Twirl mode (TWM) is intended to provide positive power balance in an emergency case. Here the ADCS ensures a single-axis attitude stabilization of the SC body in the IRF by its rotation around the BRF Oz axis.

5. MATHEMATICAL MODELS

5.1 Nonlinear Model of Body Attitude Motion

Position of the spacecraft mass center C on given circular orbit is defined by radius-vector $\mathbf{r}_o(t)$ with unit $\mathbf{r}^o$ and the true anomaly $\nu_o(t)$, which is combined with the orbit latitude $u_o(t) = \omega_\pi + \nu_o(t)$, where ω_π is a conventional latitude of orbit perigee. The BRF $\mathbf{B}$ attitude with respect to the ORF is defined by quaternion $\mathbf{\Lambda}^o = (\lambda_0^o, \boldsymbol{\lambda}^o)$ with $\boldsymbol{\lambda}^o = (\lambda_1^o, \lambda_2^o, \lambda_3^o)$, by angles of yaw ψ, roll φ and pitch θ (see Fig. 5) for the rotational sequence {1-3-2} and by matrix $\mathbf{T}_o^b = [\varphi]_2\,[\theta]_3\,[\psi]_1$, where $[\alpha]_i$ is well-known matrix of elementary rotation. The ORF angular rate vector $\boldsymbol{\omega}_o(t) = \dot{\boldsymbol{\nu}}_o(t)$ with respect to IRF $\mathbf{I}_\oplus$ have the form $\boldsymbol{\omega}_o^o = \{0, 0, \omega_o\}$ in the ORF and the representation $\boldsymbol{\omega}_o^b = \mathbf{T}_o^b \boldsymbol{\omega}_o^o$ in the BRF. At a body rate vector $\boldsymbol{\omega}(t) = \{\omega_i(t)\}$ the kinematic relations $\dot{\mathbf{\Lambda}}^o = (\mathbf{\Lambda}^o \circ \boldsymbol{\omega} - \boldsymbol{\omega}_o^o \circ \mathbf{\Lambda}^o)/2$ for quaternion $\mathbf{\Lambda}^o(t)$ and the Euler-Krylov angles of yaw ψ, roll φ and pitch θ

$$\begin{bmatrix} \dot{\psi} \\ \dot{\varphi} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} (\omega_{xz} - \omega_o^o S_\psi S_\theta)/C_\theta \\ \omega_y + (\omega_{xz} S_\theta - \omega_o^o S_\psi)/C_\theta \\ -\omega_x S_\varphi + \omega_z C_\varphi - \omega_o^o C_\psi \end{bmatrix} \tag{1}$$

with $\omega_{xz} \equiv \omega_x C_\varphi + \omega_z S_\varphi$ for the attitude angle vector $\boldsymbol{\alpha} = \{\alpha_i\} \equiv \{\psi, \varphi, \theta\}$, uniquely determine the *Sesat* BRF orientation in the ORF. Moreover, the attitude matrix $\mathbf{T}_o^b = \mathbf{I}_3 - 2[\boldsymbol{\lambda}^o \times]\mathbf{Q}_\lambda^{\rm t}$, where $\mathbf{Q}_\lambda = \mathbf{I}_3\lambda_0^o + [\boldsymbol{\lambda}^o \times]$ with $\det(\mathbf{Q}_\lambda) = \lambda_0^o$. At some simplified assumptions the nonlinear model of the *Sesat* body attitude dynamics is appeared as follows

$$\begin{bmatrix} \mathbf{J} & \mathbf{D}_q \\ \mathbf{D}_q^{\rm t} & \mathbf{A}^q \end{bmatrix} \cdot \begin{bmatrix} \dot{\boldsymbol{\omega}} \\ \ddot{\mathbf{q}} \end{bmatrix} = \begin{bmatrix} \mathbf{F}^\omega \\ \mathbf{F}^{\rm q} \end{bmatrix}, \tag{2}$$

where $\mathbf{F}^\omega = -\boldsymbol{\omega} \times \mathbf{G} + \mathbf{M}_o^p + \mathbf{M}_o^{\rm g} + \mathbf{M}_o^{\rm d} + \mathbf{M}_o + \mathbf{Q}_o^{\rm v}$;

$\mathbf{F}^{\rm q} = -\mathbf{A}^q(\mathbf{S}_q\dot{\mathbf{q}} + \mathbf{W}_q\mathbf{q}) - \mathbf{P}_q^{\rm t}\ddot{\gamma}^p + \mathbf{Q}_q^{\rm v}; \mathbf{S}_q = \mathbf{V}_q + \boldsymbol{\Phi}_q$;

$\mathbf{G} = \mathbf{J}\,\boldsymbol{\omega} + \mathbf{D}_q\dot{\mathbf{q}} + \mathbf{H}$; $\mathbf{H} = \mathrm{H} \cdot \mathbf{h}_{\rm g}(\alpha, \beta)$; $\mathbf{M}_o^{\rm g} = -\dot{\mathbf{H}}$;

$\mathbf{h}_{\rm g} = \{C_\alpha S_\beta, -S_\alpha, C_\alpha C_\beta\}$; $\dot{\mathbf{H}} = \mathrm{H}\,\mathbf{A}_{\rm h}\{\dot{\alpha}, \dot{\beta}\} + \dot{\mathrm{H}}\,\mathbf{h}_{\rm g}$;

$\mathbf{V}_q = \mathbf{N}_q\boldsymbol{\Omega}_q$; $\mathbf{W}_q = \boldsymbol{\Omega}_q^2$; $\mathbf{N}_q = \lceil \nu_s^p \rfloor$; $\boldsymbol{\Omega}_q = \lceil \Omega_{\rm s}^{\rm p} \rfloor$;

$\nu_s^q = \delta_s^q/\pi$; $\boldsymbol{\Phi}_q = -(\boldsymbol{\Phi}_q)^{\rm t} = [\{\phi_{sl}\}]$, $\phi_{sl} = -2\mathbf{g}_{ls}^{\rm t} \cdot \boldsymbol{\omega}$;

$\mathbf{Q}_o^{\rm v} = -\mathbf{L} \times \mathbf{w}_o$; $\mathbf{Q}_q^{\rm v} = -\mathbf{M}_q^{\rm t}\mathbf{w}_o$; $\mathbf{w}_o = \overset{*}{\mathbf{v}}_o + \boldsymbol{\omega} \times \mathbf{v}_o$;

$$\mathbf{M}_o^p = \begin{bmatrix} (J_{xy}^{pd}(S_{2\gamma^p}\,\omega_x - C_{2\gamma^p}\,\omega_y) - 2J_z^p\omega_y) \cdot \dot{\gamma}^p \\ -(J_{xy}^{pd}(C_{2\gamma^p}\,\omega_x - S_{2\gamma^p}\,\omega_y) + 2J_z^p\omega_y) \cdot \dot{\gamma}^p \\ -2J_z^p \cdot \ddot{\gamma}^p \end{bmatrix};$$

$$\begin{aligned} J_{xy}^{pd} &= J_x^p - J_y^p; \\ \mathbf{M}_o^{\rm d} &= \mathbf{M}_o^{do} + \mathbf{M}_o^{dk}; \\ \mathbf{M}_o &= \mathbf{M}_o^{gr} + \mathbf{M}_o^{s}; \end{aligned} \qquad \mathbf{A}_{\rm h} = \begin{bmatrix} C_\alpha C_\beta & -S_\alpha S_\beta \\ 0 & -C_\alpha \\ -C_\alpha S_\beta & -S_\alpha C_\beta \end{bmatrix},$$

the symbols $\circ$, $\tilde{}$ for quaternion, $\times$, $\{\cdot\} \equiv \mathrm{col}(\cdot)$, $[\cdot] \equiv \mathrm{line}(\cdot)$ for vectors and $[\cdot\times]$, $(\cdot)^{\rm t}$, $\lceil\cdot\rfloor \equiv \mathrm{diag}(\cdot)$ for matrix are conventional denotations.

5.2 Attitude Measurement and Estimation

Models of the *Sesat* body attitude state (the ES and the SS, the GU, the RG block), the GW and the SAPs state sensors take into account:

- their own dynamic properties;
- nonlinear static characteristics, for example because of constraint on the SS and the ES field of view ;
- noise, systematic and instrumental errors;
- time delays, time sampling, quantization and boundedness of their outputs;
- GU calibration by a digital observer based on the SS and the ES discrete filtered signals;
- possible faults and embedded diagnosis.

Digital observers are used for filtering the physical measurements of the body attitude angles and discrete dynamic estimation of the SC angular rate vector.

5.3 Actuators for Attitude Control

Attitude Reaction Thrusters. The pulse width modulation (PWM) model of a *normed* controlling torque $m_n^d(t)$ by any RT under an input command v_k^d taking into account a time delay T_{zu}^d is defined by the differential equation

$$\mathrm{T}^d\dot{m}_n^d(t) + m_n^d(t) = \mathrm{s}_k \cdot \mathrm{u}^n(t - T_{zu}^d, \tau_k, t_k), \tag{3}$$

where $t_k = k \cdot T_u$, $k \in \mathbb{N}_0 \equiv [0, 1, 2, \dots)$ and

$$\tau_k = |\mathrm{v}_k^d|;\ \mathrm{s}_k = \mathrm{Sign}\,\mathrm{v}_k^d;\ \mathrm{T}^d = \begin{cases} \mathrm{T}_+^d & \mathrm{u}^n(\cdot) \neq 0, \\ \mathrm{T}_-^d & \mathrm{u}^n(\cdot) = 0; \end{cases}$$

$$\mathrm{u}^n(t, \tau_k, t_k) \equiv \begin{cases} 1 & t_k \le t < t_k + \phi(\cdot, \tau_k), \\ 0 & t_k + \phi(\cdot, \tau_k) \le t < t_{k+1}; \end{cases}$$

$$\phi(\tau_m, \tau^m, T_u, \tau_k) = \begin{cases} 0 & \tau_k < \tau_m; \\ \tau_k & \tau_m \le \tau_k < \tau^m; \\ \tau^m & \tau^m \le \tau_k < T_u; \\ T_u & \tau_k \ge T_u. \end{cases}$$

The description (3) is used for modelling the control torque vector $\mathbf{M}_o^{do}(t) = \{\mathrm{M}_i^{do}(t)\}$ of the attitude RT set at the PWM mode for their thrust control on a discrete command vector $\mathbf{v}_k^d = \{\mathrm{v}_{ik}^d\}$.

The GW precession model have the form

$$\mathrm{H}\begin{bmatrix} 0 & -C_\alpha \\ C_\alpha & 0 \end{bmatrix}\begin{bmatrix} \dot{\beta} \\ \dot{\alpha} \end{bmatrix} - \mathrm{H}\,\mathbf{A}_{\rm h}^{\rm t}\,\boldsymbol{\omega} = \begin{bmatrix} \mathrm{Q}_\beta' \\ \mathrm{Q}_\alpha \end{bmatrix}; \tag{4}$$

$$C^r\,\mathbf{h}_{\rm g}^{\rm t}(\alpha, \beta) \cdot \dot{\boldsymbol{\omega}} + \dot{\mathrm{H}} = \mathrm{Q}_r, \tag{5}$$

where C^r is the GW rotor moment of inertia, $\mathrm{Q}_\beta' \equiv \mathrm{Q}_\beta + S_\alpha\,\mathrm{Q}_r$, and $\mathrm{Q}_\nu \equiv \mathrm{M}_\nu - \mathrm{M}_\nu^{\rm f}$, $\nu = \beta, \alpha, r$ are generalized forces with the controlling M_ν and dry friction $\mathrm{M}_\nu^{\rm f}$ torques. The GW model of its motion on gimbal axes (4) have most cross-ratio

$$\begin{aligned} \dot{\beta} &= \ \ (\mathrm{M}_\alpha - \mathrm{Frk}_\alpha - \mathrm{M}_\alpha^\omega)/(\mathrm{H}\,C_\alpha); \\ \dot{\alpha} &= -(\mathrm{M}_\beta - \mathrm{Frk}_\beta - \mathrm{M}_\beta^\omega)/(\mathrm{H}\,C_\alpha) \end{aligned} \tag{6}$$

with the notations for $\nu = \alpha, \beta$: $\zeta_\nu = \mathrm{M}_\nu - \mathrm{M}_\nu^\omega$; $\mathrm{M}_\alpha^\omega = \mathrm{H}(\omega_\beta\,S_\alpha + \omega_y\,C_\alpha)$; $\mathrm{M}_\beta^\omega = \dot{\mathrm{H}}\,S_\alpha - \mathrm{H}\,\omega_\alpha\,C_\alpha$; $\omega_\alpha \equiv \omega_x C_\beta - \omega_z S_\beta$; $\omega_\beta \equiv \omega_x S_\beta + \omega_z C_\beta$ and

$$\mathrm{Frk}_\nu \equiv \mathrm{Frk}\,(\mathrm{M}_\nu^{\rm fo}, \dot{\nu}, \zeta_\nu) = \begin{cases} \mathrm{M}_\nu^{\rm fo} \cdot \mathrm{Sign}\,\dot{\nu} & \dot{\nu} \neq 0; \\ \mathrm{Sat}\,(\mathrm{M}_\nu^{\rm fo}, \zeta_\nu) & \dot{\nu} = 0, \end{cases}$$

where $\mathrm{M}_\nu^{\rm fo} > 0$ is value of a dry friction torque. At some time moments t_ν of a GW steady-state when $\dot{\nu} = 0$ for $\nu = \alpha \vee \beta$, a *principle problem* consists in determination of value M_ν for certain value M_ν^ω from *nonlinear set-valued* algebraic equation

$$\mathrm{M}_\nu - \mathrm{M}_\nu^\omega = \mathrm{Sat}\,(\mathrm{M}_\nu^{\rm fo}, \mathrm{M}_\nu - \mathrm{M}_\nu^\omega).$$

New method for extension of definition by the GW precession model (4) at such time moments was developed, its correctness was verified by results at both land-based and flight tests. At an input discrete signal x_k the holder model has the form: $\mathrm{Zh}[x_k, T_u] = x_k\ \forall t \in [t_k, t_k + T_u)$. The discrete control signals $\mathrm{u}_{\nu k}^d, \nu = \alpha, \beta$ lead to the gear output control torques M_ν taking into account the gear backlash d_ν and flexibility k_ν:

$$\mathrm{M}_\nu(t) = \mathrm{Satd}(\mathrm{M}_\nu^{\rm m}, b_{\rm m}^\nu, k_\nu, \delta\nu(t)), \tag{7}$$

where $\delta\nu(t) = \nu^{\rm g}(t) - \nu(t)$; $\nu^{\rm g}(t) = \mathrm{Zh}[\mathrm{u}_{\nu k}^d, T_u]$; $b_{\rm m}^\nu \equiv d_\nu/2$ and for $b_\nu^{\rm m} \equiv \mathrm{M}_\nu^{\rm m}/k_\nu - b_{\rm m}^\nu$ the function

$$\mathrm{Satd}(\cdot, x) \equiv \begin{cases} 0 & |x| \le b_{\rm m}^\nu; \\ k_\nu(x - b_{\rm m}^\nu \mathrm{Sign}\,x) & b_{\rm m}^\nu < |x| \le b_\nu^{\rm m}; \\ \mathrm{M}_\nu^{\rm m}\ \mathrm{Sign}\ x & |x| > b_\nu^{\rm m}. \end{cases}$$

Model of the control torque $\mathrm{M}_r(t)$ have the form

$$\mathrm{T}_r^{\rm h}\,\dot{\mathrm{M}}_r + \mathrm{M}_r = \mathrm{Sat}(\mathrm{M}_r^{\rm m}, k_r\,\mathrm{Zh}[\mathrm{u}_{rk}^d, T_u]) - b_r^{\rm h}\mathrm{H}. \tag{8}$$

The SAP driver model for a digital input $\dot{\gamma}_k^{pd}$ with some simplifying assumptions has the form $\dot{\gamma}^p(t) = \mathrm{Zh}[\dot{\gamma}_k^{pd}, T_u]$, moreover the $\ddot{\gamma}^p(t)$ modelling is effected by an impulse function.

5.4 Onboard Diagnostics and Reconfiguration

The *Sesat* ADCS diagnostics is carried out automatically by the onboard computer. The diagnosis algorithms are

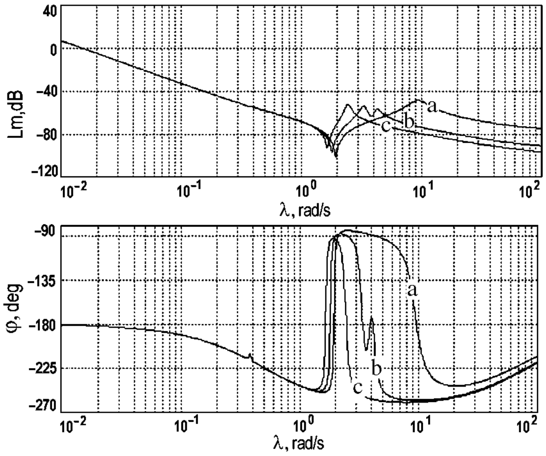

Fig. 6. Frequency characteristics on pitch channel: a) $\gamma^p = 0$; b) $\gamma^p = \pi/4$; c) $\gamma^p = \pi/2$

different for the ADCS modes. At TASM the *logic* reconfiguration algorithms are fulfilled by onboard computer basing on the diagnosis results, in addition a change of the applied onboard composition is possible by the Flight Control Center commands.

6. RESEARCH AND DEVELOPMENT

6.1 Properties of Spacecraft Flexible Structure

Contemporary computer-aided methods were applied for modelling the *Sesat* large-scale flexible SAPs, by 10 lower modes for each panel. Own dynamic properties of the *Sesat* flexible structure were carefully investigated by both spectral and frequency methods taking into account its parametric uncertainty and a panel angle $\gamma^p \in [0, 2\pi]$. These properties were also studied for its out-loop control by both the RT with the PWM and the GW at digital type, see Fig. 6, where the absolute pseudo-frequency $\lambda = (2/T_u)\text{tg}(\omega T_u/2)$.

6.2 Synthesis of Observers and Control Laws

The synthesis of discrete observers and control laws at all ADCS modes was carried out by association of the *exact feedback linearization* method and *vector Lyapunov function* (VLF) method. Let T_u and $T_q \leq T_u$ are fixed *multiplicity* sampling periods of control and state measurement, and $x_k = x(t_k)$; $t_k = k\,T_u$; $t_s = s\,T_q$; $x_k^{\text{f}} = \boldsymbol{\mathcal{F}}_{\text{T}_u}(x_s)$, where x_k^{f} is a value of the variable x_s measured with the sampling period T_q, which is filtered out at the time $t = t_k$, and $\boldsymbol{\mathcal{F}}_{\text{T}_u}(\cdot)$ is the *digital* filtering operator with the sampling period T_u.

Control in Initial Orientation Modes:

- at the DM: $\text{v}_{ik}^d = k_p \cdot k_i^\omega\,(\omega_i^{\text{c}} - \omega_{ik}^{\text{f}}), i = x, y, z$, where k_p is an adjusted coefficient and vector $\boldsymbol{\omega}^{\text{c}} = \{\omega_i^{\text{c}}\}$ is given constant command;
- at SAM the following measured and *digitally* filtered variables are applied: $\boldsymbol{\omega}_k^{\text{f}}$; $\alpha_{\text{S}k}^{\text{f}}$ and $\beta_{\text{S}k}^{\text{f}}$ with a computing the vector $\mathbf{S}_k^{\text{f}}$ (Fig. 5) and the single-axis error vector $\boldsymbol{\varepsilon}_{\text{S}k} = \mathbf{b}'_y \times \mathbf{S}_k^{\text{f}}$;
- at the EAM and the EOPM, in addition to the SAM, the variables α_{ek}^{f} and β_{ek}^{f} are used with a computing the vector $\mathbf{E}_k^{\text{f}}$ (see Fig. 5), moreover also a command discrete signal on the Sun declination is applied.

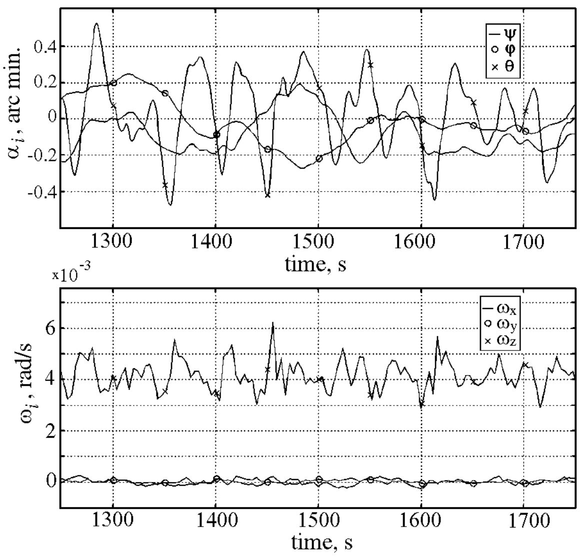

Fig. 7. The *Sesat* body orbital stabilization in TASM nominal sub-mode by the GU and GW

Observers and Control Laws in the EOM are *nonlinear* and use only the following digitally filtered variables: $\alpha_{ek}^{\text{f}}, \beta_{ek}^{\text{f}}$ and $\text{H}_k^{\text{f}}, \alpha_k^{\text{f}}, \beta_k^{\text{f}}$.

Observers and Control Laws in the TASM are also *nonlinear.* At first in addition to the EOM a computed discrete value ψ_k^{sd} is applied in discrete observer basing on the filtered variables $\alpha_{\text{S}k}^{\text{f}}$ and $\beta_{\text{S}k}^{\text{f}}$ obtained by the fine digital Sun sensor. Then in nominal TASM sub-mode only the command values $\psi_k^{\text{c}}, \varphi_k^{\text{c}}, \theta_k^{\text{c}}$ for the *Sesat* orbital attitude angels, the GU output filtered signals $\psi_k^{\text{gf}}, \varphi_k^{\text{gf}}, \theta_k^{\text{gf}}$ and the GW filtered values $\beta_k^{\text{f}}, \alpha_k^{\text{f}}$ are applied in discrete observers and control laws.

6.3 Analysis and Computer Simulation

Applied *linear* methods for dynamic analysis are based on original theoretical results for general multiple continuous-discrete control systems with the different delays at a partial discrete measurement of the state vector and a physical forming control both on the PWM and digital type. The VLF method was used for a rigorous *nonlinear stability analysis* of the *Sesat* ADCS model (1) – (8) at all modes. The *Sesat* ADCS operation has been carefully simulated at all modes as well as all kind of their switching for a wide range of logic conditions, see Fig. 7.

7. FLIGHT RESULTS

The following activities were successfully performed between the *Sesat* launch (April 18, 2000) and passing the control hand-over to *Eutelsat* (June 7, 2000): initial modes passage; in-orbit testing; communication performance measurement. The in-orbit testing program includes in-flight verification of communication performances over both Stretched and Steerable antenna. The TM-data obtained during these procedures provide information on the SC attitude and rates every 8 seconds. Their comparison with the communication performance data obtained on ground at the same time confirms that these performances are fine. Further analysis of attitude data showed that attitude determination errors at these tests had been less than $0°.02$ in pitch, and $0.°05$ in roll and yaw channels.