

25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

LIQUID REORIENTATION EFFECTS ON SGDC PROPELLANT TANKS

Henrique Oliveira da Mata

Téssio Perotti Arruda

COMAE - Comando de Operações Aeroespaciais, St. de Habitações Individuais Sul QI 13 - Lago Sul, Brasília - DF - CEP 70297-400
damatahom@fab.mil.br, perottitpa@fab.mil.br

Márcia Manuela Medrado Nunes

Vitor Mendes Pacheco de Freitas

TELEBRAS - Telecomunicações Brasileiras S/A, SIG Quadra 04 - Edifício Capital Financial Center, Brasília - DF - CEP 70610-440
marcia.nunes@telebras.com.br, vitor.freitas@telebras.com.br

Abstract. *During the operations of the Defense and Strategic Communications Geostationary Satellite (SGDC) at the Space Operations Center (COPE), the SGDC performs Station Keeping maneuvers periodically in order to maintain its orbit. At the end of its "boost phase", satellite has been exhibiting an anomalous behavior in the reaction wheels. The analysis of related telemetry shows that the satellite probably suffers from oscillation forces due to propellant reorientation inside the tanks, generating torques after end of burn. Thus, the actuators acts in order to maintain platform's attitude.*

Keywords: *Attitude and Orbit Control System, Reaction Wheels, Sloshing*

1. INTRODUCTION

This paper is related to the behavior of the Attitude and Orbit Control Subsystem (AOCS) after the Station Keeping (SK) maneuvers of the Defense and Strategic Communications Geostationary Satellite (SGDC).

Among the various sensors and actuators that make up SGDC AOCS, this work is restricted to the analysis of its Reaction Wheels (RW). RW are actuators capable of storing the satellite's angular momentum, allowing it to always maintain the desired attitude. In the event of any torque being applied at the satellite, the wheels are accelerated, changing its momentum in order to maintain the angular velocity of the platform - and therefore its constant attitude.

The mode adopted by AOCS during its operational life is Normal Mode (NM). In this mode the SGDC can be in one of the following three phases: cruise, wheel unloading, and boost. The propulsive phase is used to perform orbit correction maneuvers, which may be maneuvers in the East-West (EW) direction or in the North-South (NS) direction.

The objective of this work is to describe the behavior of the SGDC actuators in the period right after the end of the boost phase. It is expected that the activity of the actuators will return to normal levels observed during the rest of their orbit (cruise phase), since there are no more high intensity external torques acting on the satellite.

On the other hand, it was observed that, even at the end of the boost phase (EOB), the RW remain with a reasonable activity, demanding a higher than expected reaction wheels motor current.

This work uses the telemetry data of the SGDC and the tools developed by the Space Operations Center (COPE) in Python 3.6.3, a high-level, object-oriented, freely distributed programming language. Thus, a quick analysis of the satellite data can be obtained by comparing the theoretical and actual results.

2. CONTEXT

2.1 TELEBRAS HISTORY

In 2010, TELEBRAS was reactivated and become the company authorized to use, in its backbone, part of the fiber optic system implanted in Eletrobrás and Petrobrás, as well becoming responsible for the management of the Plano Nacional de Banda Larga, which aims to massify the provision of broadband access (TELEBRAS, 2018).

The TELEBRAS's fiber optic network covers only 51,8% of the total area of Brazil and the most viable solution to achieve the goal proposed by the Plano Nacional de Banda Larga (PNBL) would be the use of the satellite capable of providing the internet by having wide coverage, easy implementation and lowest cost.

Currently, TELEBRAS is responsible for the government program SGDC, launched in May 2017, in partnership with the ministry of Defense, with the objective of providing quality broadband internet in all Brazilian territory, in order to promote digital inclusion and ensure sovereignty in satellite control and strategic civil and military communications to the Brazilian government, and it is estimated that the SGDC satellite will be in operation for 18 years (VISIONA, 2018).

2.2 DUAL MISSION: A TELEBRAS AND MINISTRY OF DEFENSE PARTNERSHIP

In response to the National Defense Strategy, in 2008, it was up to the country to plan a geostationary satellite that, considering the segmented use of a commercial band, would provide a strategic communications domain. This premise was adopted by the Ministry of Defense with an investment of R\$ 489 millions in the project (Ministério da Defesa, 2015).

The artifact is the first to be 100% controlled by Brazilian institutions, giving Brazil full control of the information that orbit the national territory. This is because the satellite has a band of exclusive military use, which will guarantee total security in the transmission of strategic information of the country. This will bring even greater knowledge and autonomy in the most diverse protection operations, giving strength to projects such as the Sistema de Gerenciamento da Amazônia Azul (SISGAAz) and the Sistema Integrado de Monitoramento de Fronteiras (SISFRON).

Access to the internet through rural areas is difficult because they are vast regions without infrastructure. In the Fig. 1 below, it is possible to visualize internet coverage in rural areas after TELEBRAS's fiber optic network expansion, which consists of 51.8% of the total area. Therefore, the most viable solution would be the use of a satellite capable of providing the internet by having a wide coverage, easy implementation and lower cost (Coimbra, 2018).

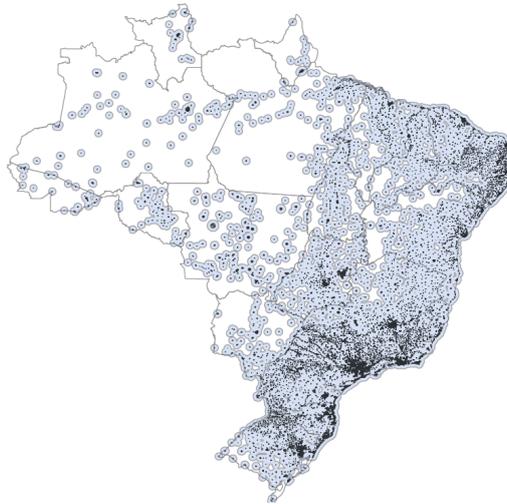


Figure 1. Rural coverage. Source: (Coimbra, 2018)

In Brazil, predominates the use of the C and Ku bands and table 1 shows the space capacity authorized in Brazil by Anatel (ANATEL, 2012).

Table 1. Authorized space capacity in Brazil

Satellites	C-Band	Ku-Band	Total	Participation
Foreign	10.292,76	6.406,20	16.698,96	61%
National	6.030,00	4.755,96	10.785,96	39%
Total	16.322,76	11.162,16	27.484,92	100%

However, the satellite sector in Brazil has high prices and a low internet speed due to the high tax burden, high costs with transportation, installation and equipment, not to mention the fact that the satellites that are operating in the Brazilian territory are properties of multinationals, which means that their operations are carried out in most cases by control stations outside Brazil (ANATEL, 2012).

Table 2. Prices practiced in the Ka and Ku bands in Brazil. Source: (Coimbra, 2018)

Company	Ku-Band		Company	Ka-Band	
	Download	Price		Download	Price
A	3 Mbps	R\$3500	E	15 Mbps	R\$400
B	1 Mbps	R\$3000	F	12 Mbps	R\$200
C	2 Mbps	R\$2800	G	8 Mbps	R\$120
D	2 Mbps	R\$2900	H	18 Mbps	R\$740

Table 2, there is a comparison between the prices practiced in Ku and Ka band, where there is information about the speed of download according to some companies and the prices practiced per month (Coimbra, 2018).

Thus, a strategic decision was taken to launch a government satellite with Brazilian military operations centers and use the Ka band for civilian use and the X band for military use, a result of the partnership between the Ministério da Ciência, Tecnologia, Informações e Comunicações (MCTIC), through TELEBRAS, and the Ministry of Defense.

Thinking about that, the SGDC and the PNBL have three major objectives:

- Provide sovereign and secure means for the strategic communication of the Brazilian government and the Ministry of Defense (Coimbra, 2018);
- Massify Internet access and provide high quality Internet services to 100% of the country's territory (Coimbra, 2018);
- Acquire critical technologies for the Brazilian space industry through technology absorption and transfer programs (Henriques, 2017), allowing the industry to assume increasingly important roles in space programs in the Brazilian future (ARIANESPACE, 2017).

3. SGDC SATELLITE

With dimensions of 7.10 m x 2.20 m x 2.0 m, SGDC was manufactured by Thales Alenia Space in Cannes, France using the reliable SPACEBUS 4000C4 platform (also called SB4000). Its mass was about 5.700 kilograms at launch and it operates at 75° west in a geostationary orbit (ARIANESPACE, 2017).

The SB4000 contains a AOCS in order to provide a three-axis body stabilization for all mission phases, based on a four Reaction Wheels system providing high angular momentum storage capacity and continuous 3-axis control in the geostationary configuration (Perriault *et al.*, 2005).

3.1 AOCS MODES, SENSORS AND ACTUATORS

According to Perriault *et al.* (2005), depending on the satellite necessity, the SB4000 AOCS assumes a specific mode. Each mode utilizes a certain group of sensors and actuators in order to keep the AOCS main objective: three-axis body stabilization.

The SB4000 AOCS usually have the equipment listed on table 3.

Table 3. Equipments available in a SB4000.

SENSORS	ACTUATORS
CSS: Coarse Sun Sensor STR: Star-Tracker GYRO: Gyrometers	UPS: The Unified Propulsion System (UPS) RW: Reaction Wheels (RW)

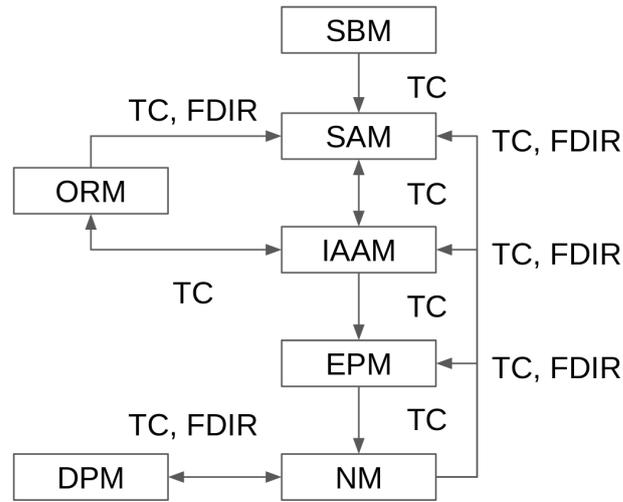
There are seven AOCS modes available, each one related to a specific function:

1. SBM (Stand-By Mode): is the primary mode engaged after launch separation;
2. SAM (Sun Acquisition Mode): is a mode which provides safe conditions to the platform in terms of power and thermal control;
3. IAAM (Inertial Attitude Acquisition Mode): is used in transfer orbit to perform Star-Tracker (STR) acquisition, GYRO drift calibration and reorientation towards boost attitude to prepare for the Orbit Raising Mode (ORM). It is also the transition mode towards the Earth Pointing Mode (EPM);
4. ORM (Orbit Raising Mode): allows for optimised orbit raising strategy through adequate apogee maneuvers;
5. EPM (Earth Pointing Mode): allows to reach and keep Earth pointing attitude;
6. NM (Normal Mode): is used during Geostationary orbit operations;
7. DPM (Drift and Positioning Mode): allows for optimised orbit repositioning strategy through adequate maneuvers.

Figure 2 shows the AOCS mode logic. It is possible to change from one mode to another or by sending a Telecommand (TC) or automatically due to a process called Failure Detection, Isolation and Recovery (FDIR).

Throughout satellite Launch and Early Orbit Operation (LEOP), it is expected to follow through the modes from SBM to NM by sending the respective TC as needed. In other words, the satellite passes from a more robust configuration to its most precise operation.

Figure 2. SGDC AOCS mode logic



On the other hand, if a failure is detected, an automatic process takes place and the satellite may assume a deprecated mode, where its main concern is to safeguard at least the minimum operation capability.

The different sensors and actuators configurations used in baseline for the control in each mode are presented in the Tab. 4. As can be seen, the RW is the main control system during satellite geostationary operation.

Table 4. Baseline SB4000 AOCS sensors and actuators

	CSS	STR	GYRO	RW	UPS
SAM	X		X		X
ORM		X	X		X
IAAM		X	X		X
EPM		X			X
NM		X		X	X
DPM		X			X

3.2 REACTION WHEELS

SGDC attitude and orbit control is based on the SB4000 AOCS to maintain its 3-axis stabilization for all modes used in the operation.

Of course, high pointing requirements strongly affects the AOCS. According to Payot (2007), reaction wheels are, generally, the most commonly used actuators for high pointing requirements because of the low noise produced (the spin can be stopped while observing). A precise characterisation of the static and dynamic imbalance shall be performed to avoid perturbations and sometimes damping systems are required. The unloading wheel management is to be considered: the time required to unload the reaction wheels and the frequency of the operations have to be discussed since it can affect the observing time.

The capacity of the wheels has to be thought through the quantitative assessment of the disturbing torques and is also a trade off between noise and unloading wheel management: highly capable reaction wheels has a high level of noise but they need to be unloaded less often, so more time for observation is available (Payot, 2007).

As can be seen at Tab. 4, NM is used to achieve a high precision Attitude control and Station keeping. So SGDC utilizes the three operating reaction wheels (the fourth is hot redundancy) and 16 thrusters control disposed through the satellite body.

The devices are arranged so that each wheel can contribute to each axis for the satellite attitude control. Figure 3 shows the arrangement of the wheels viewed by a satellite cross-section in the Z axis.

It provides an angular momentum storage capacity until 25 Nms depending on type of wheels (between 12 and 25 Nms), and motor torque of ± 220 Nm in a speed range from 4500 rpm to -4500 rpm.

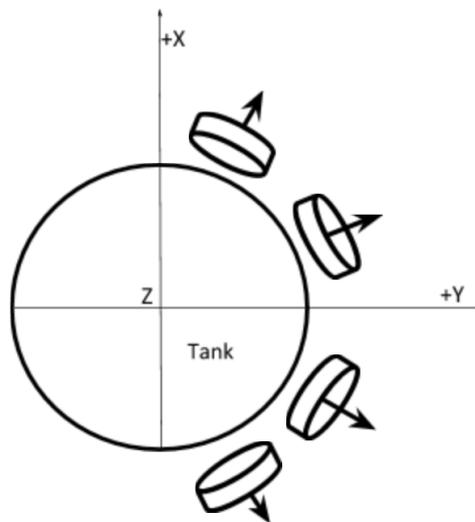


Figure 3. Reaction Wheels mounting at SGDC

3.3 ATTITUDE CONTROL DURING AN EAST-WEST MANEUVER

During its lifetime, the SGDC periodically performs Station Keeping maneuvers in order to maintain its orbit. There are two kinds of maneuvers: in the North-South direction (NM maneuvers) and in the East-West direction (EW maneuvers).

Generally speaking, maneuvers can be characterised in three distinct phases: the wheel unloading phase, the boost phase and the after End of Burn (EOB) phase.

The wheel unloading phase aims to prepare the AOCS for its high usage during the boost phase. So the system utilizes the UPS thrusters to low the RW angular momenta to a predefined value.

The boost phase comprehends the maneuver itself, where UPS thrusters ejects propellants in order to acquire a defined velocity gain (ΔV). During this phase, unwanted torques are imposed to the platform and, then, the AOCS RW must operate so the satellite can maintain its correct attitude.

The after EOB phase is the phase where thrusters forces are ceased. In theory, no external forces means no RW high activity, and the AOCS should return to its normal cruise behavior.

But during the satellite operations the RW has been exhibiting an anomalous behavior at the after EOB phase. The analysis of related telemetries shows the satellite probably suffers from oscilation forces due to propellant reorientation inside the tanks, generating residual torques after EOB that last for several minutes. Then, these actuators are unexpectedly requested in order to maintain the satellite's attitude.

4. PROPELLANT REORIENTATION

Due to Station Keeping maneuvers, forces will act on the system and the liquids propellants inside the tanks tend to accumulate on the opposite side relative to the satellite acceleration direction. When the body force field is suddenly removed after the end of burn (EOB), capillary forces are dominant in relation to the hydrostatic forces and the capillary energy is considerably in excess of its equilibrium value. If there were not enough damping, when the interface reached its equilibrium configuration the liquid would possess this extra energy in the form of kinetic energy (Abramson, 1966).

According to Fung (1965), a physical explanation for the phenomenon may be as follows. After the EOB, the liquid will not be able to return to its equilibrium setting immediately due to its inertia. However, excess curvature and surface tension will act as a restorative force, inducing the resulting oscillations. In an analogy with a simple harmonic oscillator, it can be assumed that the free surface will oscillate around its microgravity setting.

It is very difficult to analytically predict how the liquid would oscillate during its reorientation. Fries *et al.* (2012) show the standard tool for dynamic sloshing calculations used at Astrium ST is the CFD tool FLOW-3D by Flow Science Inc.. Figure 4 shows the beginning of the propellant reorientation towards the microgravity configuration, where capillary forces dominate after the orbit maneuver is finished.

For the sake of simplicity, this behavior can be simplified by a mass-spring-damper model, where the applied external force defines the equilibrium point of the system, *i.e.* the internal mass distribution of liquid on its container. From the perspective of the mass-spring-damper model, the external force imposes a point of equilibrium in which the liquid center of mass (CM_L) is displaced from the tank center of mass (CM_T) - and hence the satellite center of mass.

At the end of burn (EOB), the external force is interrupted. The system adopts a new equilibrium point, in which the

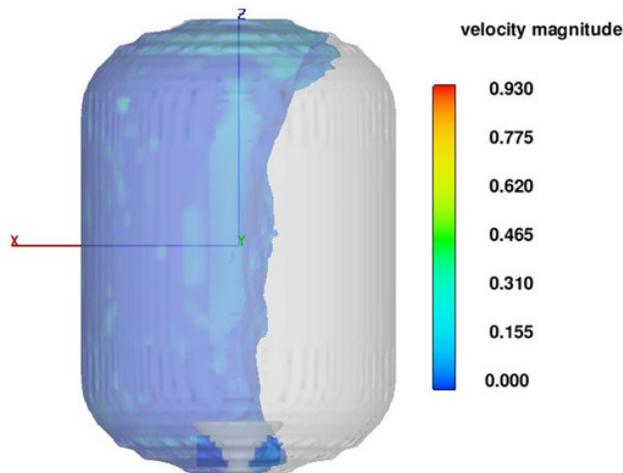


Figure 4. CFD simulation of transient propellant reorientation. Source: (Fries *et al.*, 2012).

$CM_L = CM_T$. Considering restorative forces and based on the mass-spring-damper model, it is expected to observe the CM_L damping dynamics.

In the SGDC case, since the tanks can be considered rigidly attached to the platform, the liquid reorientation inside the tanks generates apparent forces to the platform. Since the satellite has 2 distinct tanks containing liquids, 1 for the monomethylhydrazine fuel (or MMH) and 1 for the mixed oxides of nitrogen oxidant (or MON-1), each one fixed in a different position on the satellite, the reorientation generated forces create torques with different intensity, frequency and damping. This creates a complex system of difficult analytical modeling.

The reorientation shown at Fig. 4 apply forces at different points of the platform. Given the configuration of the tanks as seen on Fig. 5, arranged on top of each other on the z-axis, reorientation forces on the x-axis would generate torques on the satellite y-axis, whereas reorientation forces on the y-axis would generate torques on the x-axis.

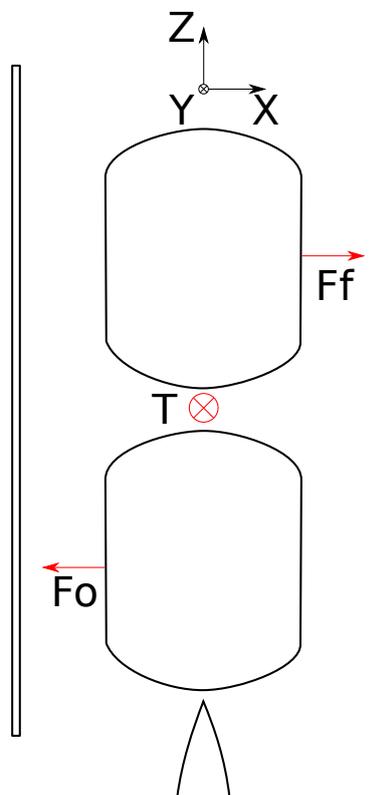


Figure 5. Forces (F) and resultant torque (T) on propellant tanks.

5. DATA ANALYSIS

Since the impossibility to directly measure propellant center of mass, the liquid reorientation effects on SGDC was analysed based on the Reaction Wheels (RW) responses after the End of Burn (EOB) of East-West (EW) maneuvers. A total of 82 RW responses was analysed spanning from 01-JUL-2017 to 31-MAR-2019.

The RW responses are measured based on the resultant angular momentum monitored through three different telemetries, one for each satellite reference axes. It may be observed an abnormal behavior on the X and Y components of RW angular momentum. These are the same axes expected to be influenced by the propellant reorientation (Fig. 5). Therefore, it is hypothesized that sloshing is the main cause of the torques that induces this abnormal RW response.

Figure 6 shows a typical momentum response of the RW 60 minutes after the EOB. The response appears to have two main characteristics: 1) a linear behavior associated with the long term course of the RW angular momentum and 2) an oscillatory behavior associated with the control torques against propellant reorientation forces.

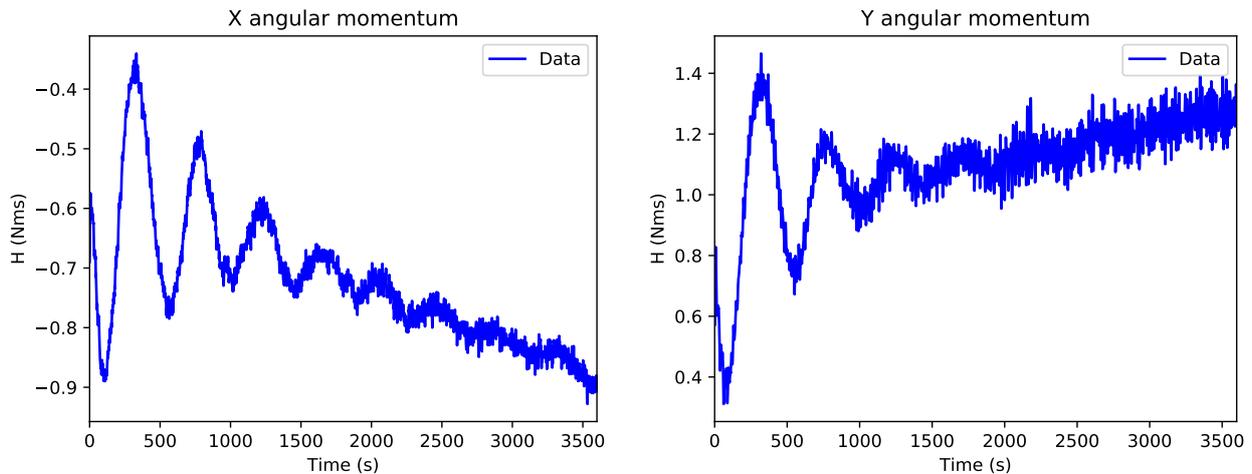


Figure 6. Example of the RW angular momentum in response of the EOB propellant reorientation

5.1 REGRESSION METHOD

The response oscillatory behavior resembles the expected response of a second order system subjected to an impulsive input added to a linear component. So the it is intended to model the responses as described at Eq. 1.

$$H(t) = A \exp(-\sigma t) \cos(\omega_d t + \phi) + a + bt \quad (1)$$

with the following coefficients:

- A = Amplitude
- σ = Dump
- ω_d = Frequency
- ϕ = Phase
- a = Linear
- b = Angular

The least square method is used to find the coefficients that best fit the model described by the Eq. 1 to the data available for the 82 responses. The fitting is based on a three steps process:

1) identify the linear behavior coefficients fitting the Eq. 2 to the original data;

$$H_{l_trend}(t) = a_1 + b_1 t \quad (2)$$

2) identify the oscillatory behavior coefficients fitting the Eq. 3 to the difference between the original data and the linear fit found at the first step; and

$$H_{o_trend}(t) = A_2 \exp(-\sigma_2 t) \cos(\omega_{d2} t + \phi_2) \quad (3)$$

3) identify the complete behavior coefficients fitting the Eq. 1 to the the original data with the coefficients bounded to values near the ones found at steps one and two, as defined at Eq. 6.

$$\epsilon = (A_2, \sigma_2, \omega_{d2}, \phi_2, a_1, b_1) \quad (4)$$

$$\delta = 0.5\epsilon \quad (5)$$

$$\text{bounds}(A, \sigma, \omega_d, \phi, a, b) = [\epsilon - \delta, \epsilon + \delta] \quad (6)$$

Figure 7 shows the steps applied to the example response of the Fig. 6. In this example, it can be seen a good agreement between final fit and the response data. The fit root mean square (RMS) error is equal to 0.016, about 2% of the data mean angular momentum.

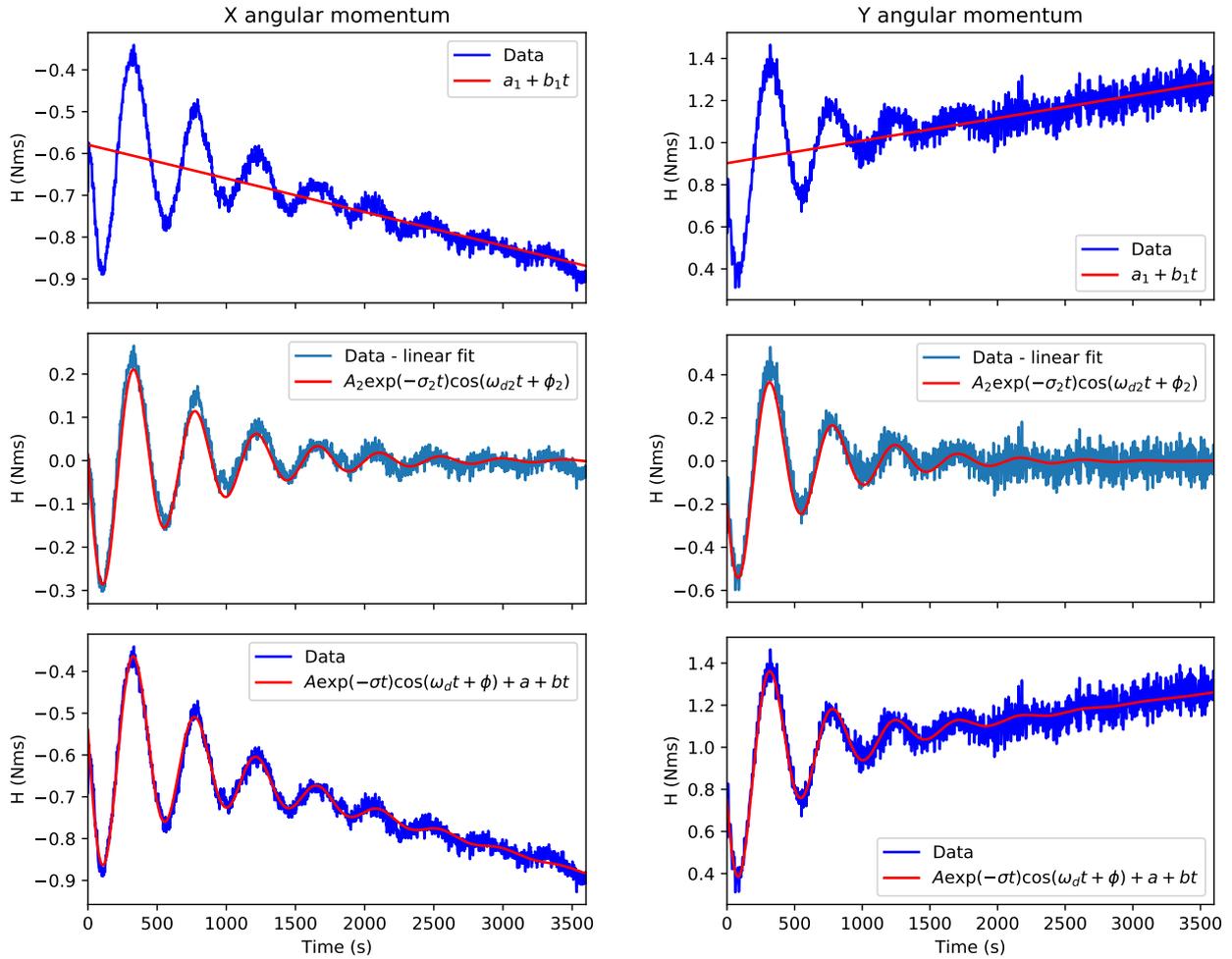


Figure 7. Regression method applied to RW angular momentum data

5.2 ANGULAR MOMENTUM STANDARD

Since we are interested in the RW behavior after EW maneuvers EOB regarding the control of satellite attitude upon propellant reorientation forces, the long term effects has to be removed from the data. This can be done disconsidering the linear and angular coefficients (a and b) obtained after the model fitting.

Also, the amplitude and phase coefficients (A and ϕ) are related to the initial conditions found at the EOB, but not directly related to the system itself. So, in order to analyse all 82 responses, only the dump and frequency coefficients (σ and ω_d) are compared.

Figure 8 shows these coefficients and the RMS error found with the Eq. 1 model fitting to each response data. The black line at the graphs represent the mean value of the correspondent parameter.

Both dump and frequency coefficients show a constant trend with minor dispersion on both X and Y angular momentum. This may be due to the fact that these coefficients are most related to the system characteristics, which suffered no important changes during the evaluated period.

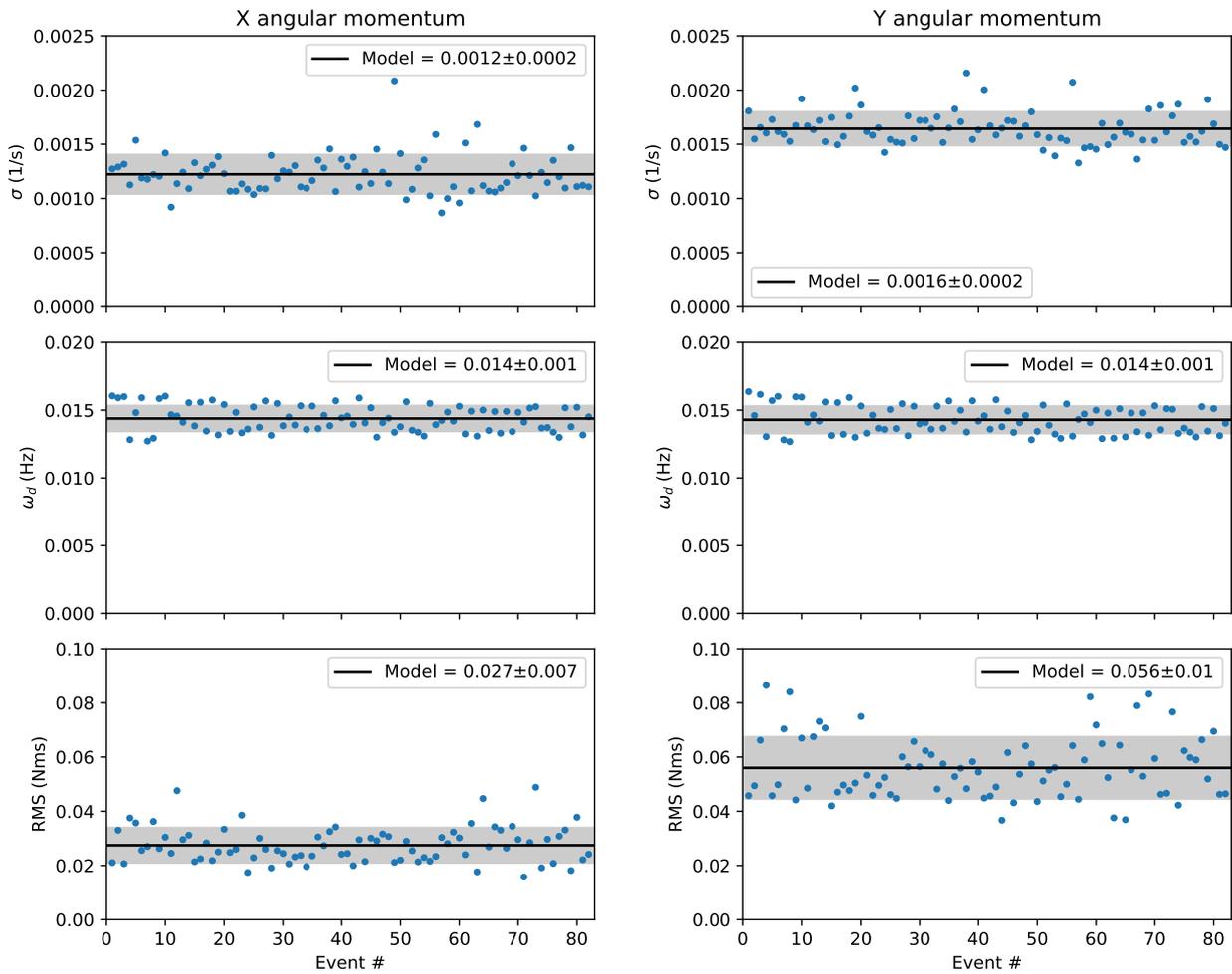


Figure 8. RW momentum standard behavior

Defining the oscillator model based only on the dump and frequency coefficients as seen on Eq. 7, Fig. 9 shows in coloured lines all the oscillators for each 82 responses. The black line represents the oscillator based on the mean dump coefficient and mean frequency coefficient. This is the angular momentum standard and can be used to evaluate the expected peak-to-peak period and the time until the RW angular momentum is contained between maximum and minimum thresholds, for example.

$$H_{osc}(t) = \exp(-\sigma t) \cos(\omega_d t) \quad (7)$$

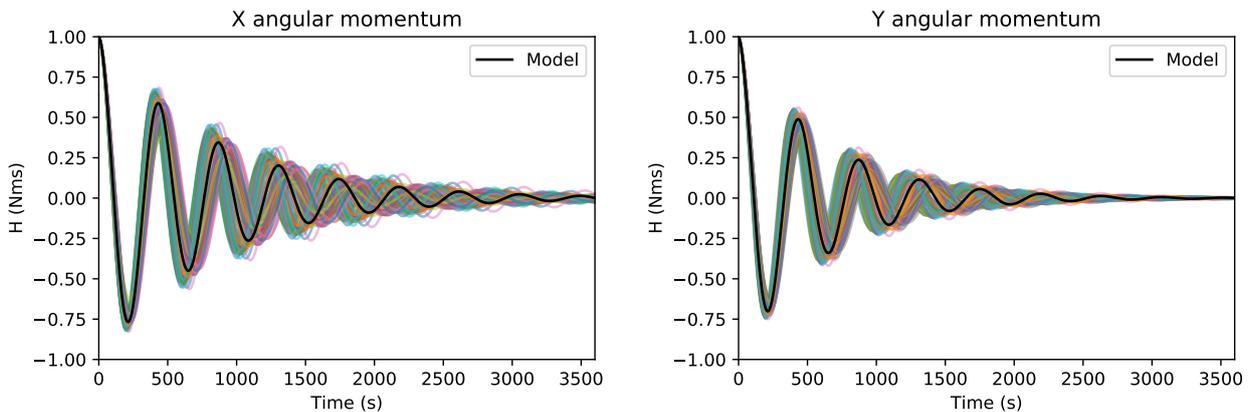


Figure 9. RW momentum standard behavior

6. CONCLUSION

The Defense and Strategic Communications Geostationary Satellite (SGDC) plays an important role in the Brazilian communications sovereignty. Being 100% controlled by Brazilian institutions, its dual mission allows government and private sector to have cheaper and more reliable source of broadband communication.

During its control at the Space Operations Center (COPE), the satellite performs Station Keeping maneuvers that change the propellant orientation inside the satellite tanks. After the End of Burn, the capillary force acts as a restorative force that reorients the liquid inside the tanks back to its zero-g configuration. These forces applied in different points in satellite platform generate disturbance torques.

In response to the propellant reorientation torques, the AOCS RW controls platform attitude, acting on the RW angular momentum. 82 responses were modeled as second order responses through a data fitting method resulting in a good adjustment.

Since the control feedback loop is unknown, it is hard to mathematically obtain the real disturbance effect behind the RW angular momentum response. But, since no other remarkable disturbance is expected during the after EOB phase, it is safe to assume that the liquid reorientation in satellite tanks shall be the main source of the abnormal RW behavior modeled.

Therefore, due to a satellite internal behavior, it can be foreseen a higher than expected RW control in the following minutes after maneuver end of burn.

7. ACKNOWLEDGEMENTS

We would like to thank TELEBRAS for their assistance sharing the SGDC data.

We also wish to acknowledge the help provided by all colleagues at the Engineering Division of the Space Operations Center for the valuable discussions and insights.

8. REFERENCES

- Abramson, H.N., 1966. *The Dynamic Behavior of Liquids in Moving Containers - With applications to Space Vehicle Technology*. NASA, Washington, D.C.
- ANATEL, 2012. "Relatório". URL <http://www.anatel.gov.br/Portal/verificaDocumentos/documento.asp?numeroPublicacao=297390&pub=original&filtro=1&documentoPath=297390.pdf>.
- ARIANESPACE, 2017. "Launch Kit VA236". URL http://www.arianespace.com/wp-content/uploads/2017/03/DDP_VA236-May-2017_GB.pdf.
- Coimbra, A., 2018. "O papel do satélite no PNBL - SGDC". URL legis.senado.leg.br/sdleg-getter/documento/download/0d38d72d-e921-415d-a724-855a1a918eba.
- Fries, N., Behruzi, P., Arndt, T., Winter, M., Netter, G. and Renner, U., 2012. "Modelling of fluid motion in spacecraft propellant tanks - sloshing". *Space Propulsion 2012 conference*.
- Fung, F.C.W., 1965. "Dynamic response of liquids in partially-filled containers suddenly experiencing weightlessness". In *Symposium on Fluid Mechanics and Heat Transfer Under Low Gravitational Conditions*. Lockheed Missiles & Space Co., Palo Alto, CA.
- Henriques, B., 2017. "O satélite brasileiro – gerência de tecnologia e soluções satelitais". In *IX Fórum 11*. URL <https://forum.ix.br/2017/>.
- Ministério da Defesa, 2015. "Projetos estratégicos". URL https://www.defesa.gov.br/arquivos/industria_defesa/projetos_estrategicos/projetos_estrategicos_portugues.pdf.
- Payot, F., 2007. *Recurring service modules for future science missions*. URL <http://sci.esa.int/future-missions-department/40553-recurring-service-modules-for-future-science-missions/>.
- Perriault, N., Célérier, B. and Dussy, S., 2005. "Medium to low class gyros for spacebus 4000 application". *6th International ESA Conference on Guidance, Navigation and Control Systems*. URL <http://adsabs.harvard.edu/full/2006ESASP.606E..41P>.
- TELEBRAS, 2018. "Histórico". URL http://www.telebras.com.br/inst/?page_id=41.
- VISIONA, 2018. "SGDC". URL <http://www.visionaespaical.com.br/sgdc>.