

The Specification and Subsystem Level Test of LAPAN-TUBSAT Reaction Wheels and Gyros

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Abstract

The paper discuss about the specification and test of LAPAN-TUBSAT reaction wheel and gyros. The discussion includes the theoretical background of the components, the components and subsystem design implementation on LAPAN-TUBSAT, as well as the component and subsystem level test.

1. Introduction

The attitude control of LAPAN-TUBSAT is based on angular momentum management. The attitude control system hardware consists of 3 reaction wheels placed orthogonally as satellite rotation actuator and angular moment absorber, 3 air coil type magneto-torquer as angular momentum generator/dissipator, 3 gyros as angular rate sensor, 4 solar panel and 2 sun sensors as coarse attitude sensor and a star sensor as fine attitude sensor.

This paper focuses on the reaction wheels and gyros of LAPAN-TUBSAT, which are the main attitude control system in the satellite. The wheel and gyro are coupled using its own microprocessor called wheel drive electronic. The electronic regulates power to the reaction wheel's motor, manages data from gyro, provides control law mechanism on the attitude control system, as well as managing the control system telemetry data.

2. LAPAN-TUBSAT Fiber optic gyro



Figure 1. LITEF MFORS-6U gyro

The gyro utilizes interferometer to principles to read rotation rate. A laser beam

is split using dichroic lens and fed into two fiber optic spools that run in opposite direction. At the end of the spool, the light is combined using another dichroic lens and read by a photodetector. If the gyro is rotated, the path traveled by the light propagating in the direction of rotation would be longer than the light propagating in inverse direction. Such different would result in phase different as the lights arrive at photodetector, which would be proportional to the rate of the rotation.

LAPAN-TUBSAT uses LITEF MFORS-6U gyro, which specification are :

- Bias, total error
 - Full temperature range <math><6^\circ/\text{hr}</math>
 - At stabilized temperature <math><3^\circ/\text{hr}</math>
- Random walk <math><0.15^\circ/\sqrt{\text{hr}}</math>
- Initialization time <math><100\text{ ms}</math>
- Power Supply + 5 VDC
- Power consumption <math><2\text{ W}</math>

The maximum angle rate reading can be configured according to the user's need. In LAPAN-TUBSAT, the value chosen is $8^\circ/\text{s}$ so that the rate reading could have good accuracy.

2.1. Bias test

In order to check the condition of the gyro before installation in the satellite component level test is done. The test is to check whether the performance of the gyro is as mentioned in the specification.

The objective of the bias test is to measure the bias or the error of the gyro. Knowing the error, one could estimate the attitude drift of the satellite when the rate damping mode is activated. In the component test, the satellite platform

(WDE, PCDH, TTC) is utilized to simplify data gathering process.

The test uses the orientation drift on the gyro due to rotation of the Earth. When placed on the surface of the earth, the gyro would read the rotation of the Earth as function of its location and direction. The Earth rotates at the rate of 15° per hour to the direction of North Pole axis.

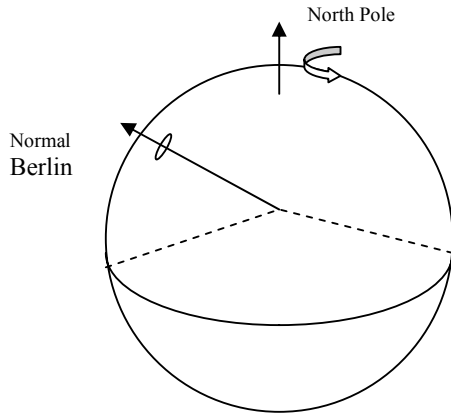


Figure 2. Geometry of Earth Rotation

For example in TU Berlin has the approximate latitude of $52^\circ 30'$. If the positive axis of the gyro is placed facing away the ground at TU Berlin (as illustrated in Figure 1), then it would read the drift rate of $\sin(52,5) * 15^\circ/\text{hr} = 11,9^\circ/\text{hr}$.

If the gyro at TU Berlin placed in perpendicular to the ground facing East, then it would not read any drift since it is perpendicular to the rotation axis. Meanwhile, if the gyro at TU Berlin placed in perpendicular to the ground facing North, then it would read the drift rate of $\cos(52,5) * 15^\circ/\text{hr} = 9,1^\circ/\text{hr}$.

The same if the gyro was located somewhere on the equator. Then if placed facing away the ground, it will only read the instrument bias, since the $\sin(0) = 0$. If the gyro is placed perpendicular to the ground facing North, then it should read the drift rate of $15^\circ/\text{hr}$.

Therefore, if the drift reading of the gyro at such configuration is subtracted by drift from Earth rotation at such configuration, the result would show the bias or the error of the instrument.

There are 2 test procedures executed; those are to read positive rotation of Earth normal to Berlin, by placing the gyros with their positive axis away from the ground and read its angular readings for 90 minutes and by placing the gyros with their positive axis towards the ground and perform angular readings for 90 minutes. During the test, the three gyros were placed at room temperature (22°C) on a wooden base. The test result is as follows

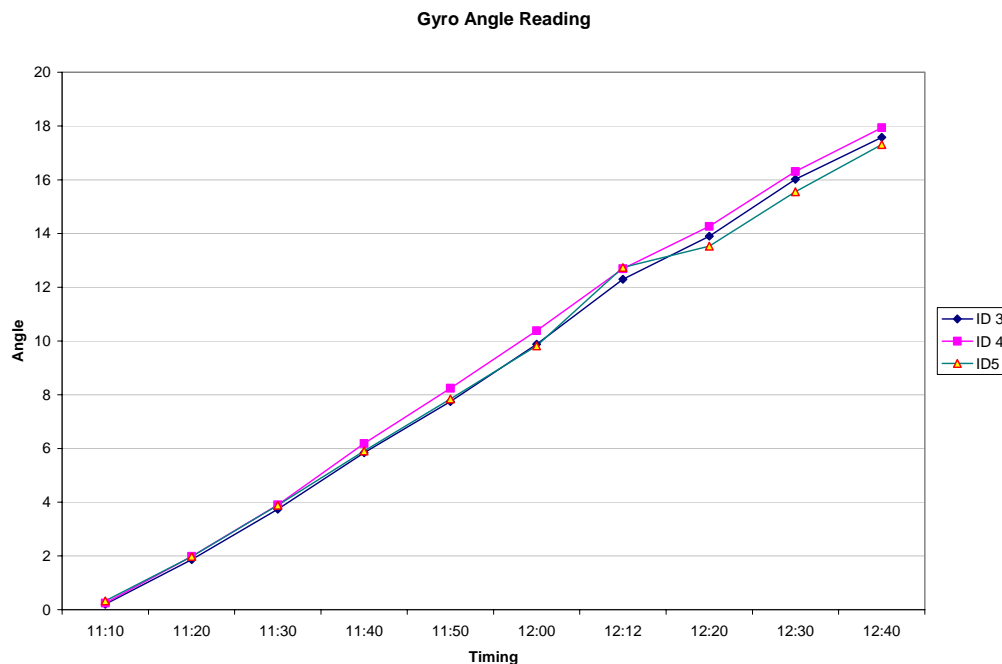


Figure 3. Positive Earth rotation normal in Berlin

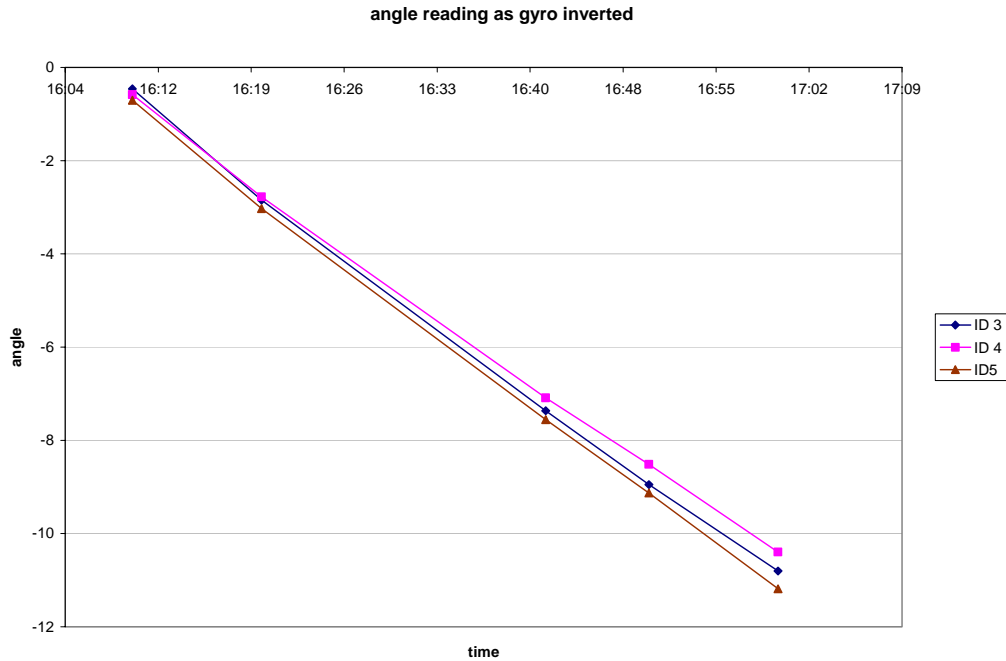


Figure 4. Negative Earth rotation normal in Berlin

On the positive reading, the data anomaly for ID 5 at 12.20 is most probably due to recording error. The time sampling accuracy is within one minute. The result shows that average drift from the above results is 11,9543 °/hr. Meaning that the instrument bias error is 0,0543 °/hr

On the negative reading, the average drift from the above results is -12,255 °/hr. Meaning that the instrument bias error is -0,35518 °/hr

2.2. Quantization Test

The test is to measure the quantization of angular rate reading done by the sensor. The test is done reading the angular velocity at random interval and perform division that .

The resolution of angle increment reading from gyro has a value of 0,000244° calculated from the maximum angle increment reading in the 16 bit digital conversion.

The test result is as follows.

Table 1. Quantization Test

Angular Velocity	Quantization Step	Resolution of Quantization (16 bit)
-0,00572	6	-0,00095
-0,00477	5	-0,00095
0,003815	4	0,000954
0,002861	3	0,000954
-0,00191	2	-0,00095

The test result shows that the quantization (step interval/resolution) of the Angular Velocity data is 0,000954. The result is because the wheel drive electronic sampling is done every 256 milliseconds, and therefore the smallest resolution (0,000244) is divided by 0,256. Therefore, instead of reading exact "0" of angular velocity of the satellite, the gyro will give the result of 0,000954 as minimum resolution.

3. LAPAN-TUBSAT Reaction Wheels & Wheel Drive Electronics

Reaction wheel works on the principle of conservation of angular momentum, i.e.

$$H = I_r \cdot \omega_r + I_p \cdot \omega_p \quad (1)$$

Where I_r is the inertia of wheel, ω_r is the angular velocity of the wheel, I_p is the inertia of platform (or satellite) and ω_p is the angular velocity of platform. Therefore, the equation means that without external torque, the total angular momentum would be the same. Meaning that, the rotation rate of the platform/satellite can be produced or eliminated by changing the rotation rate of the reaction wheel.



Figure 5. IRE RW 203

The wheel unit has an outer dimension of 100x100x70 mm and weight 1,2 kg. Its electrical interface is a DSUB 9 pin. The hardware is developed by Institute für Raumfahrt-Elektronik based on the reaction wheel developed for MAROC-TUBSAT and DLR-TUBSAT project.

The wheel consist of Faulhaber 2444-048B DC brushless motor and brass wheel in a hermetically seal aluminum housing. The maximum power consumption is 1,2 A at 12-15 VDC. The maximum speed of the wheel is 5000 rpm and the inertia of 0,00088 kg.m².

The operating temperature of the wheel is -44 to 85 °C. The speed control accuracy (above 100 rpm) is 0,2 rpm. The construction of the motor-wheel is seated on the spring damper to protect the bearing of the motor and the electronics components against the vibration load.

The wheel drive electronics has a DC/DC converter to regulate 12-15 V DC power from the satellite to 5 V as required by the gyro. It has a Hitachi H8 for its microcontroller, which programmed to regulate 5 operating modes, i.e.

1. wheel speed control - In this mode, the speed of the motor is read by the Hall sensor and compared to the target speed selected. When the speed is reached then the increase/decrease in the current supplied is stopped.
2. wheel current control - In this mode certain amount of current is specified, so that the wheel speed would increase until all mechanical resistance and back-EMF balance the energy supplied.
3. wheel torque control – In this mode certain constant current is specified and the feedback is the wheel acceleration read by Hall sensor.
4. satellite angular velocity control - In this mode, the gyro reading is used to determine the angular rate of the satellite. When the rate is reached then the current increase/decrease to the wheel is stopped using proportional control system.
5. satellite angle control - In this mode, the target angular rate is set to be zero. Therefore, the attitude when the mode is commanded is regarded to be angle zero. From this angle, one can set another angle value, which will be executed by ACS by integrating the angular rate reading from the gyro with respect to time. The control system uses proportional and differential system.

The electronics communicate with the gyro at 76800 baud and with the wheel at 38400 baud, both in asynchronous mode. It communicates with the PCDH using the 4 bytes protocol.

3.1. RW performance test

The reaction wheel performance is tested using the wheel speed mode, in which plus and minus 100 (the low limit of control hardware) and plus and minus 5000 (80% of maximum) RPM is assigned and current consumed in the operation is read. The test is done in three different environment, i.e. - 20, 22 (room temperature), and 30°C, to check the wheel performance variation with respect to temperature. Each reading is repeated five times so that the reading fluctuation can be observed. The result of the test is as follows.

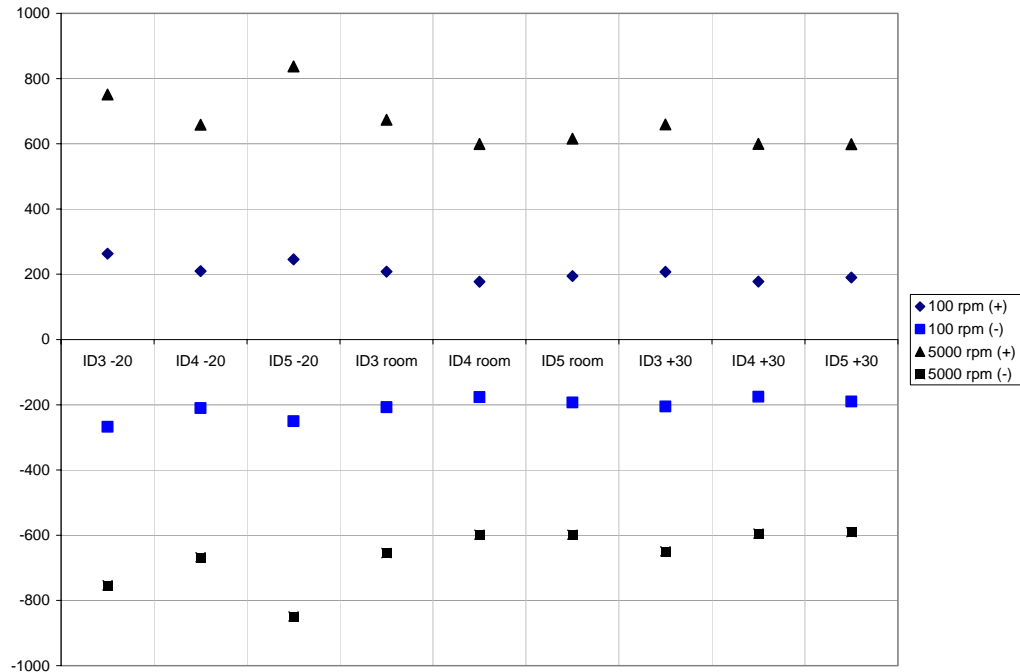


Figure 6. Mean wheel current consumption (mA) on Sept 04 test

Table 2. Current consumption reading spread

	Half spread (%)	Half spread (%)
	100 rpm	-100 rpm
ID3	0,1802	-0,11
ID4	0,1635	-0,08
ID5	0,1669	-0,31
	5000 rpm	-5000 rpm
ID3	0,4985	-0,72545
ID4	0,2728	-1,00057
ID5	0,6549	-0,17873

The tests results show that the power consumption trends are not varied with RPM. They are, however, seems to be affected by temperature. At low and room temperature, wheel ID 4 consumes the least amount of energy for the same rpm, while at high temperature; wheel ID 4 and ID 5 consumes almost the same amount of energy. Wheel ID 3 consumes the highest amount of energy at room and elevated temperature, while at low temperature; wheel ID 5 is indicated to consume the highest. These mean that the friction source in wheel ID 5 is temperature dependent,

which most probably came from the grease on the bearing. Meanwhile, the friction source of wheel ID 3 and ID 4 is more to the manufacturing precision (contact surface, magnet on the motor etc). Wheel ID 4 is indicated to have the most efficient and stable performance.

The reading noise is very small, as the reading statistics shows that the are mostly below 0,5%.

4. Test on the RW-Gyro Interaction

The test on the interaction of reaction wheel and gyro is done using an air bearing platform. The platform is used to make test subject float on thin film of air, resulting into very small friction in the vertical rotational axis, in which the wheels and gyros axis are placed. To make the test subject able to further rotate without any constraint, the data communication system is done via LAPAN-TUBSAT PCDH and TTC (wireless). The test set up is as shown in figure 7.

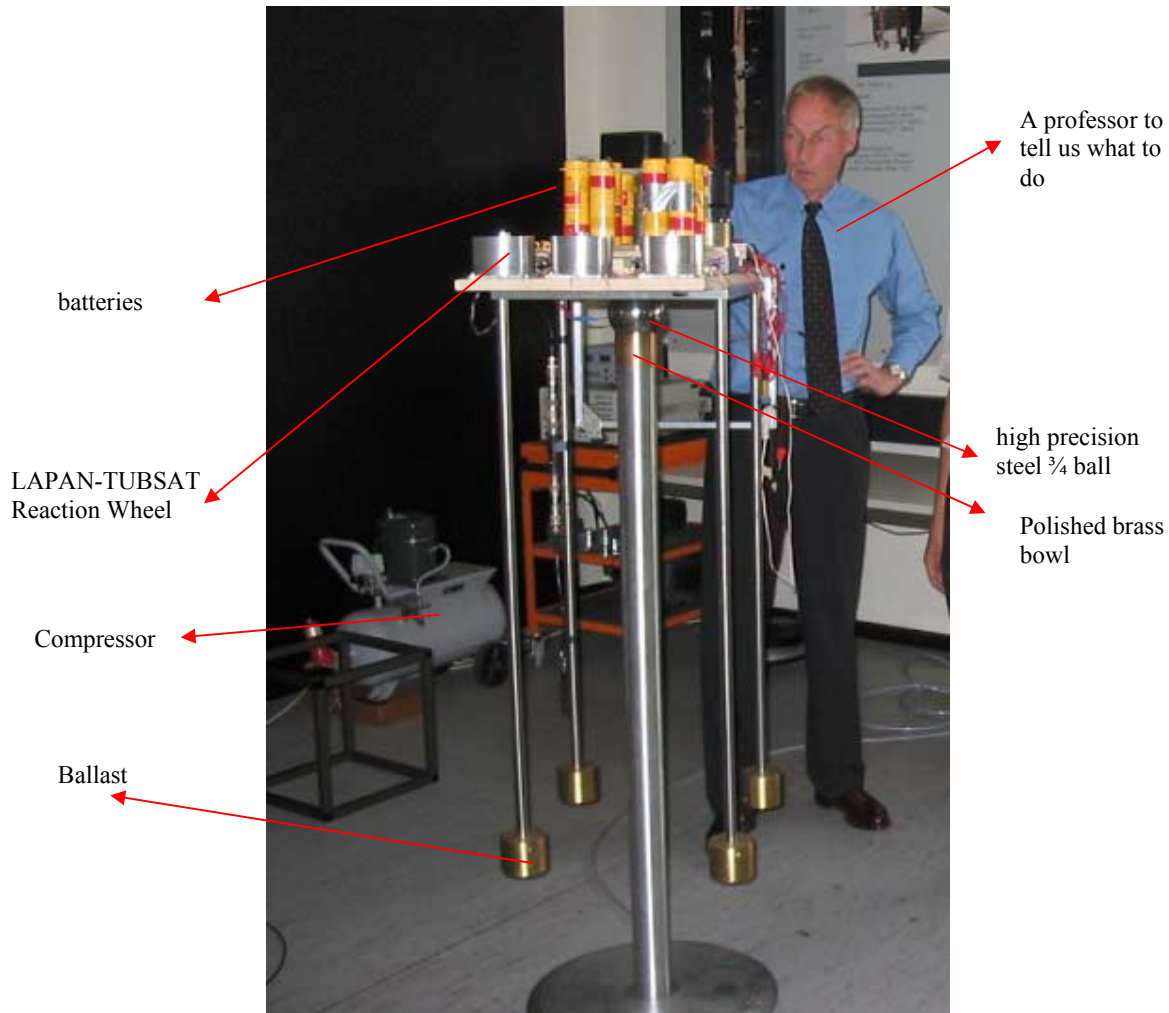


Figure 7. LAPAN-TUBSAT ACS on air bearing facilities

4.1. Angle Control Mode Test

For the test, a laser pointer is added to the platform so that the change in the platform's orientation can be observed easily by looking at laser beam spot on the laboratory's wall.

The first test is to measure the system accuracy. The test was done by commanding the wheel drive electronic to angle control mode. The system then damps all rotation and uses its last orientation as its zero degree orientation. After that, the system is commanded to change its pointing direction to 90° orientation. After the system reached steady state, the telemetry is read. The deviation of actual angle that reads by telemetry is between $90,106 - 90,080^\circ$. It is to be noted that, the platform is inertially

fixed, while the Earth (and therefore the laboratory) rotates with respect to the inertia reference (and therefore to the platform). Therefore, the orientation of the platform is observed to drift slowly around the room. This was observed through laser beam spot on the wall.

The second test is to observe the transient time of the system. The test was done by asking the system to rotate the platform -360° . The transient time recorded is 1,5 minutes.

4.2. Angular Velocity Control Test

The tests are done to check the control system's accuracy. The first test was done by commanding the system to angular velocity control mode, and set the angular velocity value to 0. As the system steady

state, the telemetry reading shows the actual angular velocity of 0,02 °/s, which is a non-zero number. It means there is steady state deviation. This happen because only proportional control (Kp) is applied, which mean that the actual angular velocity never go value zero since wheel speed never go zero value.

The second test was to keep the angle drift zero (observed on the laser point in the room) using angular velocity mode, which mean to assigned a value to compensate Earth's rotation. Iteration was done on the value of angular velocity assigned to get the laser pointer stay at one point on the wall.

Table 3. Angular rate to compensate drift

Angular rate (°/s)	Drift of the laser pointer
0	To left
-0.02	To right
-0.01	To left
-0.015	To right
-0.013	Almost none

The compensation value is not the same as the Earth rotation rate normal at Berlin since reading error has contribute on the small value reading as well as the existence of other disturbance that may influence the drift, such as vortex in the air bearing platform and magnetism.

4.3. Angular momentum transfer

The objective of this test is to demonstrate the angular momentum transfer between the reaction wheel and the platform. The experiment procedure can also be used to measure the inertia of platform, or if the satellite already in orbit to measure the inertia of the satellite.

The angular momentum of the system is expressed by equation (1) above. If the system has non-zero angular momentum, and one of the angular velocity of the platform is equal to zero, then the whole angular momentum is of the system absorbed by the wheel. Mathematically can be expressed as

$$H = I_r \cdot \omega_r \quad (2)$$

Once the angular momentum is calculated (since the inertia of the wheel can be calculated), the wheel can be stopped, so that the angular momentum can be absorbed by platform. Once the wheel stopped, the inertia of the platform can be calculated from

$$I_p = H/\omega_p \quad (3)$$

Therefore, the procedure of the platform's inertia measurement is as follows

1. Introduce angular momentum by speed up the wheel and hold on the platform
2. Put ACS on angle mode so that $\omega_p = 0$, read the wheel speed
3. Set $\omega_r = 0$ so all of angular momentum can be absorbed by platform, read the gyro output

The results are :

Table 4. Wheel RPM

wheel rpm	initial wheel speed (rpm)		
	500	1000 (1)	1000 (2)
sample 1	329.64	624.96	1170.62
sample 2	312.94	619.76	1134.58
sample 3	317.78	593.88	1126.95
mean (rpm)	320.12	612.87	1144.05
mean (deg/s)	1920.72	3677.2	6864.3

Table 5. Platform's angular rate

gyro (deg/s)	Initial wheel speed (rpm)		
	500	1000 (1)	1000 (2)
sample 1	0.574	1.045	1.93
sample 2	0.458	1.046	1.95
sample 3	0.387	1.054	1.89
mean (rpm)	0.473	1.048	1.927

Since the inertia of the wheel is 0,00088 kg m², the angular momentum and inertia of the platform are :

Table 6. Platform's inertia

	initial wheel speed (rpm)		
	500	1000 (1)	1000 (2)
H	1.690	3.236	6.041
I platform	3.573	3.087	3.134

The average platform inertia is 3,265 kg m²

5. Conclusions

From gyro test, it is concluded that compared with the vendor specification that mentions the error to be less than 3 °/hr, the gyro error in the test is very small (10% from the limit). The result would be used as reference for the performance of the gyro in the future as the similar test is to be done after the satellite integration, environmental test, and transportation, to check for performance degradation.

The gyro test also found that the quantization/ minimum resolution of the angular rate is 0,000954, confirming the maximum designed reading of 8°/s (5 rpm) angular rate of the satellite read by WDE every 256 ms.

From the reaction wheel test, it is concluded that wheel ID 4 is the best wheel from the three wheels tested. Therefore, the wheel would be assigned to the satellite Y axis, which will have the heaviest duty on the satellite momentum bias attitude control mode. The result would be used as reference for the performance of the gyro in the future as the similar test is to be done after the

satellite integration, environmental test, transportation, and in orbit, to check for performance degradation. The test also found that the wheel RPM reading noise is very small.

From the gyro-wheel interaction test, it is concluded that the system performed as designed, as three of the most important function of the system have been checked. The test also shows that the angle control mode has better accuracy performance than the same function done using angular rate control mode with assigned zero rate.

6. References

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