IAA-AAS-DyCoSS1-04-07

ON GROUND CALIBRATION OF TETRAHEDRON GYRO PACKAGE FOR ATTITUDE DETERMINATION

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This work presents the on ground calibration of a gyro package composed of four fiber optic gyros in a tetrahedron configuration. In this work the on ground calibration is performed with a 3-axis turn table covering the work range of the chosen gyros. Analysis covering both the uncalibrated and calibrated accumulated attitude determination error are shown. An Allan variance analysis is performed in order to detect the main sources of noise and to improve the mathematical model. The calibration procedures developed in this work could be used in tests of an in-house tetrahedron geometry of the FOG unit that will fly in next Brazilian missions.

INTRODUCTION

This work shows the on ground calibration of gyro packages composed by four fiber optic gyros in a tetrahedron configuration, for use in on-board attitude determination system. Gyros are mostly used in Attitude Control Systems[1] (ACS) of artificial satellites when high accuracy requirements are present. It also avoids the need of an accurate torque model (including perturbing and control torques), as the dynamical Euler equations are described by simple kinematic equations. If a good on ground calibration is performed beforehand it is expected that the attitude determination due to gyro performance is nearly optimum. On the other hand, tetrahedron configuration of the gyros represents a good compromise between cost and redundancy, as a single axis failure is easily dealt with by such configuration.

In this work the on ground calibration is performed using a high accuracy 3-axis turn table covering the work range of the chosen gyros. The turn table was oriented so as to compensate Earth's rotation in its inner gimbal, so bias can be estimated precisely for each individual gyro. Linearity can also be estimated with this arrangement, by comparison of the gyro outputs with the

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commanded inner gimbal speed. For the attitude determination test, the same turn table is excited so that its motion represents the attitude motion on a satellite. A representative case of a geo-pointed mission in LEO (Low Earth Orbit) with a period of around 100 minutes is exercised.

Analysis covering both the uncalibrated and calibrated accumulated attitude determination error are shown. An Allan variance analysis is performed in order to detect the main sources of noise, so gyros behavior knowledge can be improved. The calibration procedures developed in this work could be used in tests of an in-house FOG-IMU that will fly in next Brazilian missions.

DESCRIPTION OF EXPERIMENTAL SETUP

A high precision 3-axis turntable, model Contraves 53M2/30H with angular position and velocity commanding capabilities was used to generate precisely most of the data. It is powered by a very stable no-break and power supply equipment. It is also isolated against vibration and local effects by mounting and fixing the turntable base on a sismic block.

Table 1 below shows the characteristics of the turntable, and Fig.1 shows the gyro package attached to the table of the inner axis. On the left the gyros are in its normal position and on the right the gyros are upside-down, meaning a 180° rotation of the intermediate axis.

Table 1. Characteristics of the 3-axis turn table CONTRAVES 53M-2/30H

Type	External Axis	Intermediate Axis	Internal Axis
Maximum Axis Rate	500 °/s	750 °/s	1000 °/s
Inertia	Maximum 115 ft-lb-s^2	Maximum 25 ft-lb-s^2	Maximum 3 ft-lb-s^2
Peak Torque	600 ft-lbs	160 ft-lbs	90 ft-lbs
Continuous Stall Torque	300 ft-lbs	80 ft-lbs	45 ft-lbs
Peak Acceleration	4.8 rad/s^2	6.4 rad/s^2	15 rad/s^2
Position Accuracy	0.2376 arc sec	0.8101 arc sec	0.6346 arc sec

The electronic unit of the gyros provides 4 digital RS-422 interfaces, one for each gyro. The wiring goes from the turntable to the outside world through the slip-rings.

Figure 1. Contraves 3-axis turntable with inner table at 0º(left) and 180º (right)

TETRAHEDRON FOG UNIT

With the aim of designing a gyro package with failure detection capability, a minimum redundancy is desired, and therefore 4 fiber optic gyros are needed. One of the most adequate geometrical solid is the tetrahedron. This solid was designed for nesting the gyros and is basically aluminium metal built according to Fig. 2. The package is powered by stabilized 28Volts nominal power supply, and the interface with the PC allows the readings and archiving of the gyro data. The electronics uses a Sigma-Delta type 24bits ADC (Analog Digital Converter) at 2KHz sampling rate[2]. The gyro signals are made available via request from the onboard computer. The individual digital gyro data are delivered through a RS-422 port, and at most 100Hz sampling rate if synchronously requested. A small circuitry by means of a micro-controller PIC16F873 from Microchip® manages the communication of all 4 gyros digital data with a USB interface. Customized software coded in Labview® (National Instruments) allows the data to be stored in TDMS format (MS-Excel® compliant) containing basic information of time tags and gyro measurements. For this experiment a high sampling rate is not necessary and a lower one for each gyro was set.

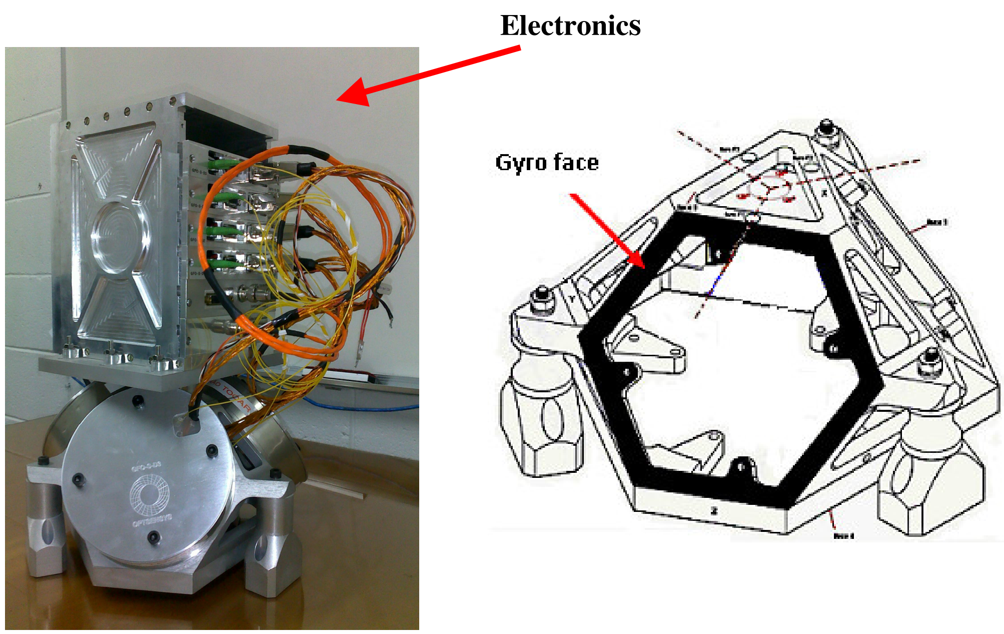

Figure 2. Tetrahedron gyro package.

The unity is a laboratory model (prototype) and intended to characterization of the FOGs. As such the experiment herein has the objective of measuring the main performance characteristics of the unity, providing valuable feeback to the manufacter for the development of qualification and flight models. The Table 2 shows the measured factory characteristics of the delivered unit.

Table 2. Provided factory data sheet of the gyros

Gyro	Model	Scale Factor (V/°/s)	Bias (V)
1	SD02	0.0798	+0.0002
2	SD04	0.0625	-0.0006
3	SD03	0.0905	-0.0004
4	LME02	0.0518	-0.0006

To have an idea of the importance of the calibration, a quick look on Table 2 shows that a bias of around 0.0001V translates to something around 0.001°/s to 0.002°/s or more which would accumulate an error between 6° and 12° for a typical 100 minutes orbit of LEO satellites. An accurate scale factor can also overcome minor misalignment problems.

The geometry of the tetrahedron in which the gyros were installed are shown if Fig. 3. As shown the whole gyro package with respect to the analytical trihedron XYZ (Fig. 3) presents a separation angle among them of $\alpha = 54.736^\circ$.

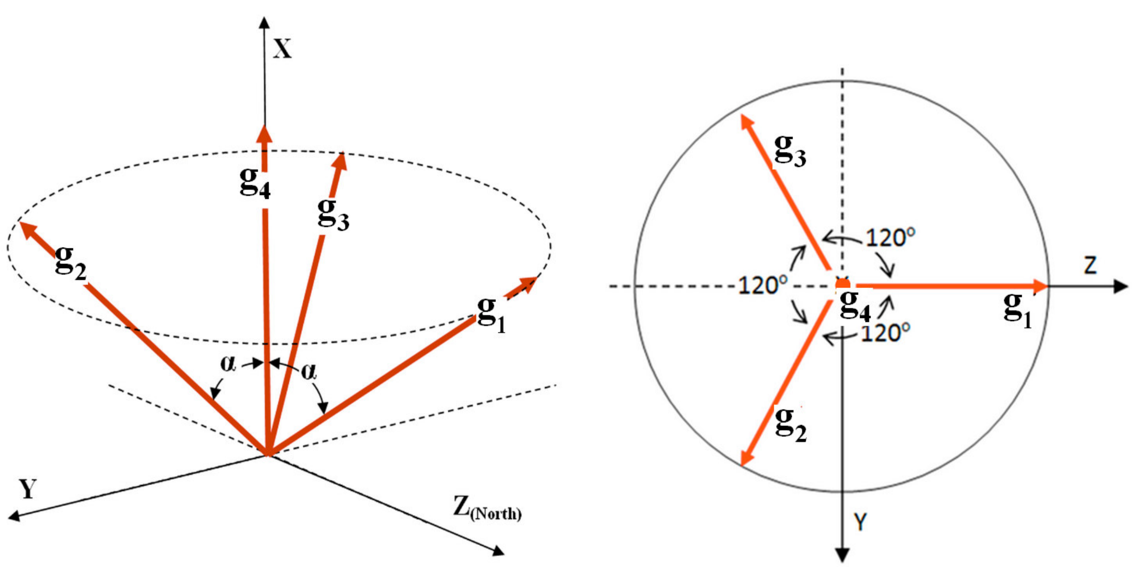

Figure 3. Axes orientation wrt XYZ, α = 54.736°

FOG UNIT CALIBRATION

This calibration procedure was first presented by (Ref. 3), applied to an IMU (Inertial Measurement Unit) composed of 3 accelerometers and 4 FOG gyros mounted tetrahedrically. Because gyro errors are translated to accumulated error on attitude determination of artificial satellites, one mitigates them by estimating biases, scale factors, and misalignments, on ground. So, in this essay a four fiber optic gyros package, attached on the faces of a tetrahedron are excited and characterized. The calibration makes use of a high precision 2-axis turn table exciting each analytical trihedron axis in turn and estimulating other mixed axis-coupling conditions. The collected data are processed by the procedure which follows with the objective of estimating the main sources of error (individual biases and scale factors, and misalignments of the unity).

According to Fig. 3, Eq. (1-2) states the nominal matrix **H** which relates and projects the 4 individual gyro readouts onto the XYZ main axes (X pointing up, Z to north):

$$\mathbf{g} = \mathbf{H}\boldsymbol{\omega} \quad \text{or} \quad \begin{pmatrix} g_1 \\ g_2 \\ g_3 \\ g_4 \end{pmatrix} = \begin{bmatrix} 1/\sqrt{3} & 0 & \sqrt{6}/3 \\ 1/\sqrt{3} & \sqrt{2}/2 & \sqrt{6}/6 \\ 1/\sqrt{3} & -\sqrt{2}/2 & \sqrt{6}/6 \\ 1 & 0 & 0 \end{bmatrix} \begin{pmatrix} \omega_x \\ \omega_y \\ \omega_z \end{pmatrix} \tag{1}$$

If the contrary is needed one uses the pseudo-inverse matrix **H***, which is the least squares solution of (1):

$$\boldsymbol{\omega} = \mathbf{H}^*\mathbf{g} \quad \text{or} \quad \begin{pmatrix} \omega_x \\ \omega_y \\ \omega_z \end{pmatrix} = \begin{bmatrix} \sqrt{3}/6 & \sqrt{3}/6 & \sqrt{3}/6 & 1/2 \\ 0 & \sqrt{2}/2 & -\sqrt{2}/2 & 0 \\ -\sqrt{6}/3 & -\sqrt{6}/6 & -\sqrt{6}/6 & 0 \end{bmatrix} \begin{pmatrix} g_1 \\ g_2 \\ g_3 \\ g_4 \end{pmatrix} \tag{2}$$

The manufacturing quality plays a fundamental role in errors arising from misalignments. The "as built" package must have such misalignments estimated, meaning in this case a correction to the nominal **H** matrix. Additionaly it is desired to obtain the best scale factor and bias estimates, leaving to the user the task of dealing with the remaining noises (random walk, white noise, etc.). The proposed equation is:

$$\mathbf{K}\mathbf{g} = \tilde{\mathbf{H}}\boldsymbol{\omega} + \mathbf{b} + \boldsymbol{\eta} \tag{3}$$

where **K** is a diagonal scale factor matrix, **g** is the vector with the raw gyro outputs in Volts, **b** is the vector with the biases, and $\boldsymbol{\eta}$ is the vector representing the remaining noise assumed white gaussian. If one designs a sequence of positions and rotations wisely one can estimate the parameters accordingly. Table 3 shows a sequence of 16 positions/rotations in a 2-axis turntable which allows collecting data needed for the parameters estimation. It is seen that two-by-two sequences of opposite rotations on the turntable are commanded.

Table 3. Rotation sequence for 2-axis table (w=6º/s; C=w cos30º, S=w sin30º)

Sequence	Inner axis	Outer axis	X-axis	Y-axis	Z-axis
1	+w	0°	+w	0	0
2	-w	0°	-w	0	0
3	+w	+180°	+w	0	0
4	-w	+180°	-w	0	0
5	0°	+w	0	+w	0
6	0°	-w	0	-w	0
7	+180°	+w	0	+w	0
8	+180°	-w	0	-w	0
9	+90°	+w	0	0	+w
10	+90°	-w	0	0	-w
11	-90°	+w	0	0	+w
12	-90°	-w	0	0	-w
13	+30°	+w	0	+C	+S
14	+30°	-w	0	-C	-S
15	-30°	+w	0	+C	-S
16	-30°	-w	0	-C	+S

Therefore, by subtracting them in pairs (two-by-two) the effects of earth rotation and constant bias terms are eliminated[3], resulting:

$$\mathbf{K}\ \Delta\mathbf{g} = 2\tilde{\mathbf{H}}\boldsymbol{\omega} + \boldsymbol{\eta}^* \tag{4}$$

As **K** is assumed diagonal with explicit elements given by $K_i, i = 1,\ldots 4$ one arrives at:

$$\Delta\mathbf{g} = 2\begin{bmatrix}\omega_x & \omega_y & \omega_z\end{bmatrix}\begin{bmatrix}\tilde{h}_{ix} / K_i \\ \tilde{h}_{iy} / K_i \\ \tilde{h}_{iz} / K_i\end{bmatrix} + \boldsymbol{\eta}^* \tag{5}$$

where $i = 1,\ldots 4$, $\tilde{h}_{ij}$, $j = x, y, z$ is the *ij*-th element of matrix $\tilde{\mathbf{H}}$, and $\begin{pmatrix}\omega_x & \omega_y & \omega_z\end{pmatrix}$ assumes the positive values of the Table 3 for the given two-by-two 8 sequences. The least squares solution for such system is:

$$\begin{bmatrix}\tilde{h}_{ix} / K_i \\ \tilde{h}_{iy} / K_i \\ \tilde{h}_{iz} / K_i\end{bmatrix} = \boldsymbol{\Omega}^{\#}\ \Delta\mathbf{g}_i \tag{6}$$

where $.^{\#}$ means the pseudoinverse matrix, and $\boldsymbol{\Omega}$ and $\Delta\mathbf{g}$ are given explicitly by:

$$\boldsymbol{\Omega} = 2\begin{bmatrix}\omega_x(1) & \omega_y(1) & \omega_z(1) \\ \vdots & \vdots & \vdots \\ \omega_x(8) & \omega_y(8) & \omega_z(8)\end{bmatrix}, \quad \Delta\mathbf{g}_i = \begin{bmatrix} g_i(1) - g_i(2) \\ g_i(3) - g_i(4) \\ \vdots \\ g_i(15) - g_i(16)\end{bmatrix} \tag{7}$$

The numbers in parenthesis represents the 16/2=8 sequence pairs.To calculate the misalignments and the scale factors the constraint of unit vector for each column of **H** matrix must be used:

$$\left(\tilde{h}_{ix}\right)^2 + \left(\tilde{h}_{iy}\right)^2 + \left(\tilde{h}_{iz}\right)^2 = 1 \tag{8}$$

Afterwards the biases may be obtained by:

$$\mathbf{Kg} - \tilde{\mathbf{H}}\boldsymbol{\omega} = \mathbf{b} + \boldsymbol{\eta} \tag{9}$$

If the noise $\boldsymbol{\eta}$ is zero-mean with identical standard deviation then the bias **b** is simply computed by:

$$\mathbf{b} = \frac{1}{16}\sum_{j=1}^{16}\left(\mathbf{Kg} - \tilde{\mathbf{H}}\boldsymbol{\omega}\right) \tag{10}$$

The turntable rotation **w** disappears when summed up in pairs (two-by-two) the 16 sequences. The Earth rotation effect, $\boldsymbol{\omega} = \left(\Omega_e \sin\phi,\ \ 0,\ \ \Omega_e \cos\phi\right)$, still remains in the measurements, where Ω_e is the earth rotation rate and ϕ is the geodetic latitude of the turntable:

$$\mathbf{b} = \left(\frac{1}{16}\sum_{j=1}^{16}\mathbf{Kg}\right) - \tilde{\mathbf{H}}\boldsymbol{\omega} \tag{11}$$

CALIBRATION RESULTS

The turntable was used to carry out the calibration essay, and the FOG unit was fixed to the inner dish according to the axes established in Fig. 3. The sequence of 16 rotations as stated in Table 3 was applied. The nominal angular velocity used was 6º/s, therefore a single revolution takes 60s. Care was taken to get enough data for each individual sequence covering at least 60s. To each sequence, the mean value and standard deviation of the mean was computed and used to yield the calibration results. The calibration procedure of Eqs. 6-10 was applied and the results are shown in Table 4. The differences with respect to factory settings are also presented. The scale factors and biases agrees to some extent when individual gyros results are compared.

Table 4. In-house calibration and differences wrt factory data

Gyro	Model	Scale Factor (V/°/s)	Scale factor difference (V/°/s)	Bias (V)	Bias difference (V)
1	SD-2	0.0730	-0.0068	0.0002	+0.0000
2	SD-4	0.0785	+0.0160	0.0004	-0.0010
3	SD-3	0.0880	-0.0025	0.0002	+0.0006
4	LME-02	0.0775	+0.0257	-0.0003	-0.0003

On the other hand, the estimates of the elements of the **H**-matrix shows the difference with respect to the nominal values given in Eq. (1). The estimated $\tilde{\mathbf{H}}$ matrix absorves the misalignments with respect to the designed structure shown in Fig. 3 and Eq. (1). Table 5 shows both the nominal and the estimated $\tilde{\mathbf{H}}$ matrix.

Table 5. Nominal and estimated transformation matrix H

H nominal	*x*	*y*	*z*
1	0.57735	0	0.81650
2	0.57735	0.70711	-0.40825
3	0.57735	-0.70711	-0.40825
4	1	0	0
$\tilde{\mathbf{H}}$ estimated	*x*	*y*	*z*
1	0.55526	-0.00146	0.83167
2	0.42638	0.78516	-0.44914
3	0.51389	-0.74179	-0.43088
4	0.99999	-0.00094	0.00065

In other words, recalling Eq. (3) $\mathbf{Kg} = \tilde{\mathbf{H}}\boldsymbol{\omega} + \mathbf{b} + \boldsymbol{\eta}$, an angular velocity on X-axis of 6°/s and zero on both Y and Z axes (first sequence of Table 3), neglecting Earth rotation, should nominally read $g_4 \cong 0.0518 \times 6 \times 1 - 0.0006 \cong 0.3102$ V, whereas using the estimated $\tilde{\mathbf{H}}$ matrix one arrives at $\tilde{g}_4 \cong 0.0775 \times 6 \times 0.99999 - 0.0001 \cong 0.4649$ V. The measured value is $g_4^m = 0.4663$. It depicts a troublesome difference if factory settings are used in conjunction with the nominal **H** matrix.

Fig. 4 shows the difference between the measurements of the 16 sequences of Table 4 and both the factory settings with nominal **H** matrix (left), and the estimated settings with the proposed calibration procedure (right). Notice the difference in ordinate scales. The right side is around 3 orders of magnitude less than the left side (0.001×0.100). It means that a calibration procedure is mandatory at the risk of damaging extensively the interpretation of the tetrahedron FOG unit readings irreparably.

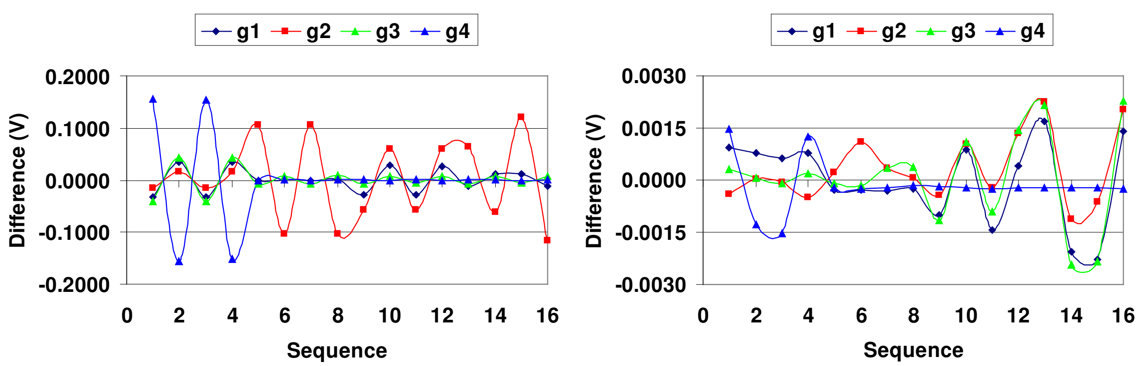

Fig. 4 Difference between factory/nominal settings and estimated for the 16 measurements sequences.

CHARACTERIZATION USING ALLAN VARIANCE

For this characterization the tetrahedron unit was aligned as per Fig. 3. Then data were collected with the unit at rest, statically, for a time span of 2 hours without interruption. The data of each individual gyro was analyzed[4,5] and, for the 2 hours period, only a signature of angle random walk appeared consistently. The quantization was not very stable, and bias unstability was not very explicit. The rate random walk was barely observed and the rate ramp did not show up at all. The most observed characteristic was the angle random walk at the 10^{-5} level.

Table 6 shows the summary of the results using Allan variance method for each individual FOG gyro. The Table was prepared using the final plot and is only for indicative purposes. Additional extensive laboratory essays would be required in case more meaningful and accurate figures are needed.

Table 6. Allan variance noise characteristics for tetrahedron gyro unit

Gyro	Model	Quantization	Angle random walk	Bias unstability (0.664B)	Rate random walk	Rate ramp
1	SD-2	6e-5	3e-5	5e-6	NO	NO
2	SD-4	6e-5	3e-5	2e-6	6e-8	NO
3	SD-3	4e-5	3e-5	1e-6	NO	NO
4	LME-02	6e-5	5e-5	3e-6	7e-8	NO

Fig. 5 shows the plot of Allan variance analysis for the gyro LME-02. The software used was ALAVAR version 5.2, authored by Makdissi[6], to obtain the log-log data. The left plot of Fig. 5 shows the Allan variance curve and its ± standard errors. The other plot of Fig. 5 shows the fitted slopes to obtain the noise values, shown in Table 6.

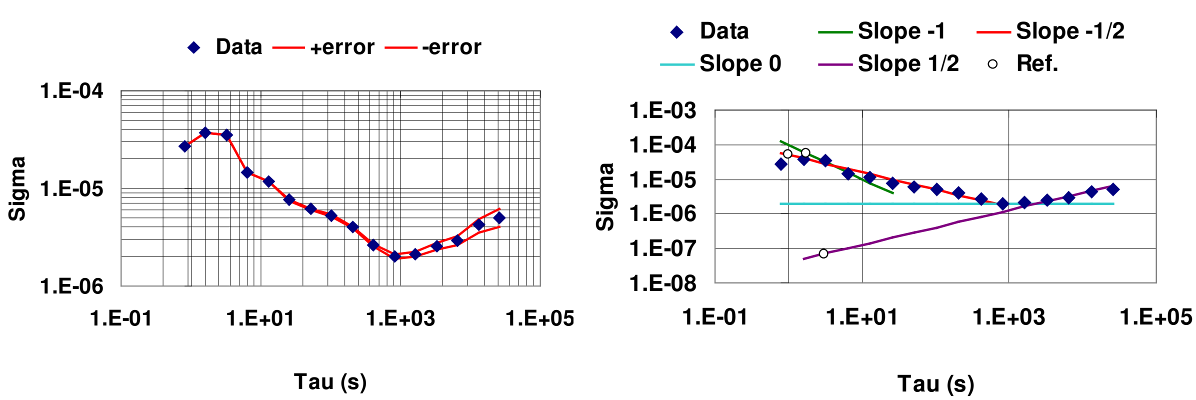

Fig. 5 – Allan variance analysis for gyro LME-02

EXPERIMENT OF ATTITUDE DETERMINATION

A typical geo-pointed LEO (Low Earth Orbit) satellite has an orbit with period around 100 minutes. For remote sensing missions, near polar and sun-synchronous orbits are required. Basically an Attitude Control System (ACS) is in charge of keeping actively the earth-pointing attitude. In this situation, nominally the roll and yaw gyro readings should be around zero, and the pitch-axis gyro should read the angular velocity of the orbit, i.e., around 0.06º/s or 0.001rad/s.

For a representative test to emulate an attitude determination using gyros, the turn table was commanded so that its motion ressembles the actual attitude motion. It started from the local tangent plane aligned to NED (North-East-Down) system, that is, roll-pitch-yaw zeroed. Then for at least 100 minutes the turn table was rotated with angular velocity of 0.06º/s equivalent to one orbit revolution. The setup was to have gyro data at around 8 samples every 10s (sampling time of 0.8s), a bit more than 1Hz rate. We collected around 7500 single data for each gyro corresponding to more than 100 minutes of continuing motion of the turntable.

Fig. 6 shows the plot of data from gyros 3 (SD-3) and 2 (SD-4). It is clearly seen that an orbit span time is covered. Thus the expected attitude angle at the end of 100 minutes should be 360º, exactly one cycle. The attitude angle was computed by simply using the raw gyro rate data times the stepsize (simple Euler integration). Neither effort was made to de-noise (smooth) the data through e.g. any low-pass filter or similar, nor outliers (unless those clearly out of scale) were discarded. The only effect compensated for was the Earth rotation. As the exact attitude of each gyro is known at any time instant, the earth rotation vector was intentionally discounted from the raw data.

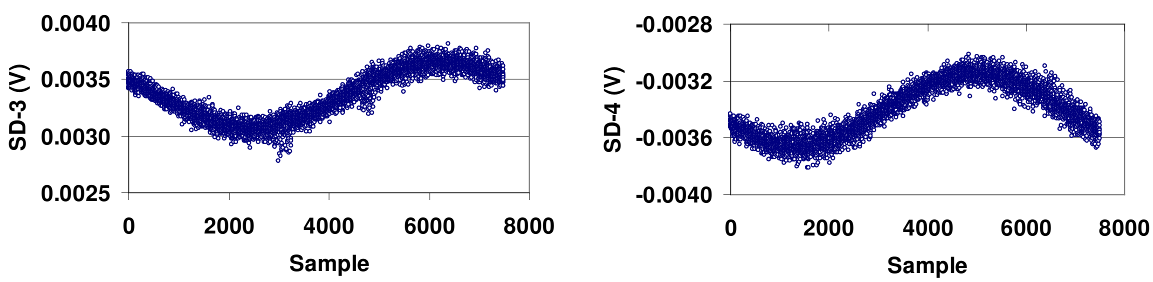

Fig. 6– Typical data from gyros g3 (SD-3) and g2 (SD-4) for one orbital period.

Fig. 7 shows the orbit angle evolution in terms of nominal, and using both calibrated and factory settings. The left side plot shows that at the 100 minutes the angle integrated by the gyro using factory settings resulted in 467°, whereas the calibrated curve obtained 362°. The right plot shows how the error accumulates along the time for the calibrated unit. If plotted the factory differences along time would be out of scale. The difference between calibrated and nominal attitude at the end showed a drift of 2°. It is almost linear only in interval 2500-6000s, and the drift shows behavior typical of random walk noise effects. The linear part shows a residual drift bias of 2.5°/h. Although this error level is quite manageable more experiments are under way to fine tune the calibration procedure aiming at minimizing such error. In a typical attitude maneuver situation of 10 minutes the gyro-only attitude determination system would still provide accuracy within 0.4° level, taking into account the constant 2.5°/h drift.

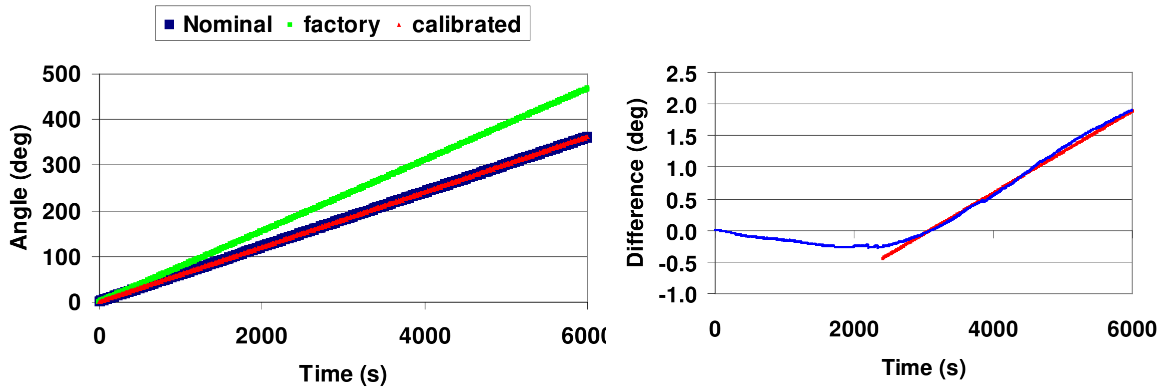

Fig. 7 – Nominal, factory, and calibrated gyro attitude computation (left); and error accumulation of calibrated gyro (right).

CONCLUSION

This work presented several facets of on-ground calibration of a gyro package composed of four fiber optic gyros in a tetrahedron configuration. A high precision turntable is the paramount device to achieve fruitful results. First the individual scale factors, biases, and a **H** matrix representing the projection of the 4 gyros into an analytical XYZ trihedron is estimated in a least squares sense. It was proposed a procedure with a suited rotations sequence to excite all the gyros and axes so as to allow them to be computed. As the estimated **H** matrix is different from the nominally designed matrix, most of this difference can be attributed to misalignments of the structure which nests the individual FOGs. A short Allan variance analysis is performed showing that the noises other than the quantization and angle random walk ones are less important. Then an attitude determination using the FOGs unit was emulated, covering an orbit period of 100 minutes, very representative of common LEO missions. It is shown that if factory nominal settings are used, the accumulated error in one orbit can arrive at an unacceptable error of 107°. However by using the estimated parameters from the ground calibration, the accumulated error was of 2°, clearly depicting the beneficial effects of calibration.

In conclusion, the calibration procedures developed and applied in this work could be used in assessment of an in-house FOG tetrahedron unit that further should be flight-qualified. Enhancements can be done in order to take into account the noise level when taking measurements of the sequence of rotations. To avoid jeopardizing the mission, techniques to quickly detect and isolate single failures in such tetrahedron geometry are being evaluated[7], so as to reconfigure the software to recover almost promptly.

ACKNOWLEDGMENTS

Our thanks to Optysensis Ltd. through Dr. Osni Lisboa who kindly made available the FOGs unit, Dr. P.G. Milani and MSc. Eng. W. Einwoegerer for helping with the laboratory and turntable commands, Eng. Andre Corsetti from Compsis for Labview® interface fixing, and FINEP (Brazilian Foundation for Studies and Projects) through Project SIA-Fundep 11382*3 for sponsoring the co-author Rafael H. Siqueira scholarship.

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