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# GYRO MISALIGNMENT AND SCALE FACTOR ERROR DETERMINATION IN MARS ORBITER MISSION

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This paper deals with the precise estimation of onboard gyros misalignments and scale factor errors using the Star Sensor measurements as exercised in Mars Orbiter Mission. Single axis maneuvers were performed on spacecraft body to get the observability of cross coupling terms as well as asymmetry components independently for each motion. This is a novel approach to determine critical parameters within the accuracy as provided by Star Sensor data for both the selected and non-selected gyro channels. Improvement in attitude accuracy was observed after the obtained results from calibration exercises were translated to spacecraft.

## INTRODUCTION

Mars Orbiter Mission is India's first Interplanetary Mission launched in November, 2013 and aimed to reach MARS in September, 2014. A series of orbit maneuvers were performed prior to its insertion into the hyperbolic heliocentric orbit towards mars. During maneuver operations and also on its way to mars, the precise knowledge of spacecraft's position and attitude is very crucial for efficient fuel usage and radio link with earth respectively. The attitude of the spacecraft is determined using its star-trackers and gyroscopes. There are two star-trackers mounted on the body. Each of them provides the spacecraft attitude in inertial frame. One of the factors which influence the attitude accuracy is the knowledge of the sensor mounting angles. The basic assumption being made in the calibration process is that Star-Tracker-2 mounting is the reference and then the relative mounting of Star-Tracker -1 with respect to Star-Tracker-2 is found. The same assumption is continued for gyro-calibration. This paper deals with the determination of gyro parameters like scale factors, its asymmetry and the misalignment errors using Star-Tracker-2 determined filtered attitude and gyro measured filtered attitude. The filtered outputs from both sensors are compared to derive the errors. The maneuvers are planned such that it provides the observability of each axis scale factor and misalignment errors independently considering the attitude constraints to be satisfied with respect to payloads. The Star sensor updates to gyros are stopped just before the maneuver starts. Total of six maneuvers were performed for the selected channels with each maneuver lasting for around about 25 minutes. The paper is divided into two parts. The first part describes the methodology of performing maneuver and estimation of residual errors. The second

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part discusses about the results of the calibration exercises. The non-selected gyro channels were also calibrated.

## SINGLE AXIS MANEUVER TO ESTIMATE SCALE FACTOR AND MISALIGNMENT ERRORS

The equation governing the kinematics is

$$d(q)/dt = 1/2[\omega_b(t)]\otimes q(t) \tag{1}$$

Where $q(t)$ is the quaternion representing the attitude of the spacecraft with respect to ECI ( inertial) frame and $[\omega_b(t)]\otimes$ is a 4x4 matrix comprising of the angular velocity of the spacecraft and is given by

$$[\omega_b(t)]\otimes = \begin{bmatrix} 0 & \omega_z & -\omega_y & \omega_x \\ -\omega_z & 0 & \omega_x & \omega_y \\ \omega_y & -\omega_x & 0 & \omega_z \\ -\omega_x & -\omega_y & -\omega_z & 0 \end{bmatrix} \tag{2}$$

These rates are calculated based on the incremental angles given by the gyros. The measured angular rate vector $\omega_{gm}$ is related to the true angular rate vector $\omega_b$ (in spacecraft body coordinates) by

$$\omega_{gm} - b_g = [SF]\times[M]\times\omega_b \tag{3}$$

Where, $b_g$ is the gyro bias, $[SF]$ is the diagonal scale-factor error matrix and $[M]$ is the non-orthogonal misalignment matrix.

The body attitude in Inertial frame measured by gyros is based on Equation (1) and is derived by using body rate as given in Equation (3). The error quaternion between the star-tracker measured attitude and gyro measured attitude at any instant is given by

$$\Delta q(t) = q_{bg->b} = q^*_{I->bg}\otimes q_{I->b} \tag{4}$$

Where, $q^*$ represents quaternion conjugate and $\otimes$ stands for quaternion multiplication. These error quaternions are converted to corresponding Euler angles which provides the angular error in 3-axes as $\Delta x,\ \Delta y,\ \Delta z$ in degrees respectively. The basic principle lies in getting these errors when the spacecraft is held inertial i.e. with zero rates on the platform after performing a fixed amount of rotation. During inertial hold, the filtered output of Star Tracker and gyros are compared as shown in Equation (4). The cumulative effect of gyro scale factor errors and misalignment errors, at the end of the maneuver over a single axis, is resulted in terms of angular errors. The observed errors are then used to derive scale factor and misalignment error. Typical rate profile and errors observed during the calibration exercise of yaw, roll and pitch axis are shown in

Figures 1, 2 and 3 respectively. Figures 1 and 2 shows the complete scenario for one axis calibration, while Figure 3 displays the errors after negative rotation along pitch.

**Figure 1. Yaw axis calibration with yaw rate followed by error along yaw, roll and pitch.**

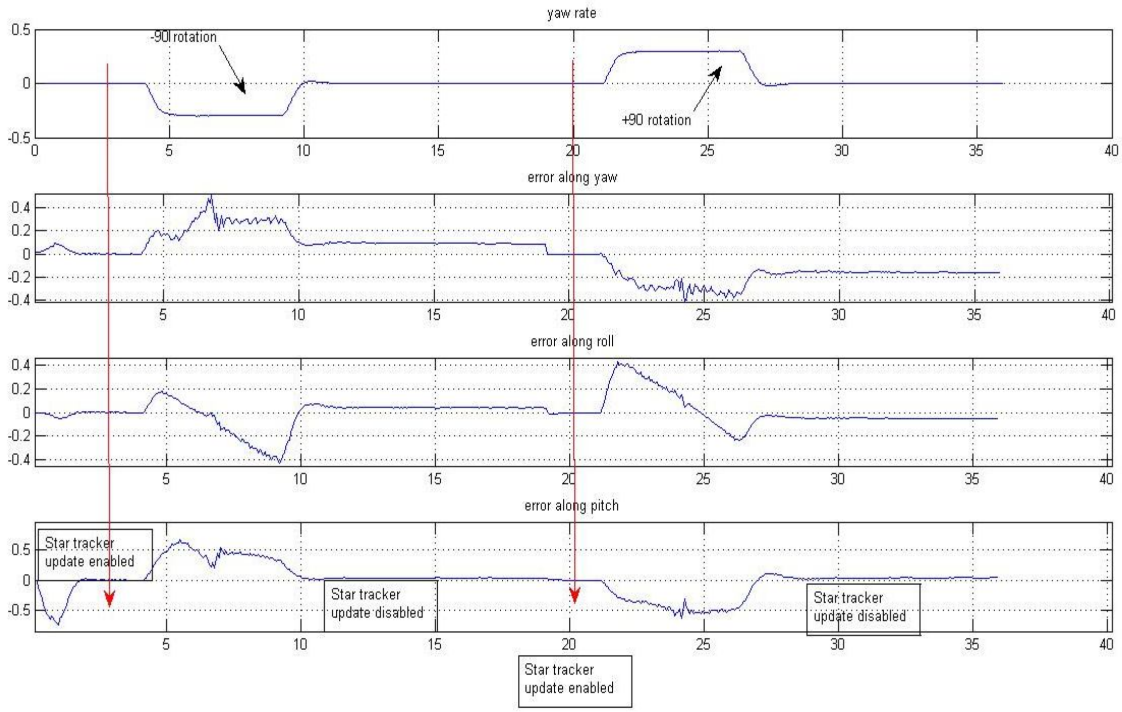



**Figure 2. Roll axis calibration with roll rate followed by error along yaw, roll and pitch.**

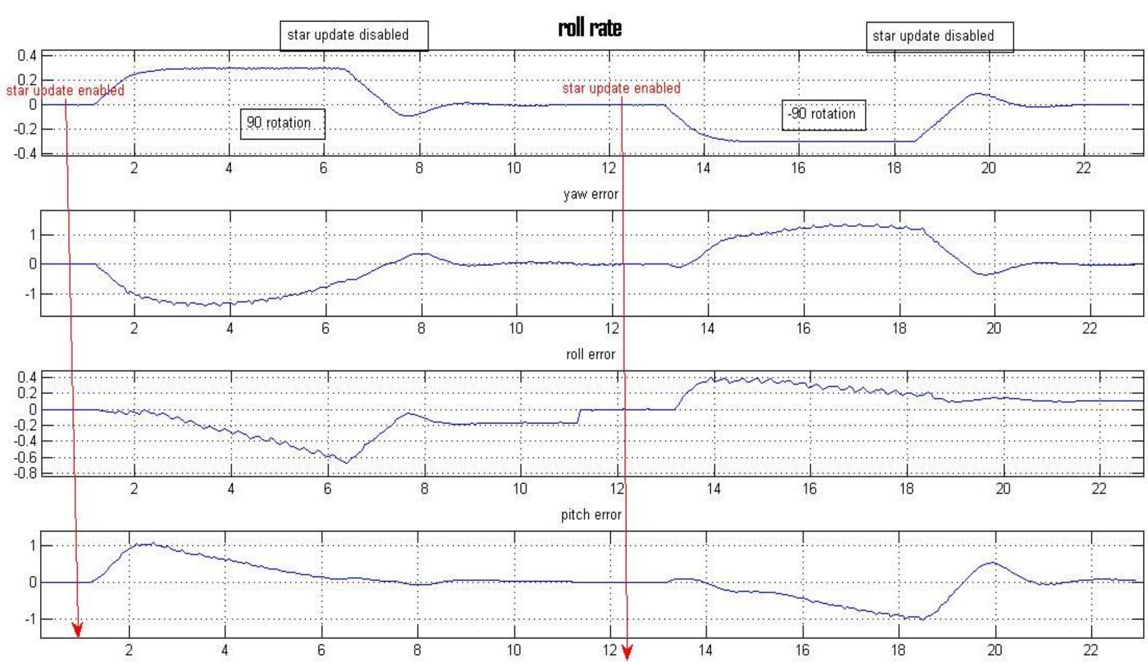
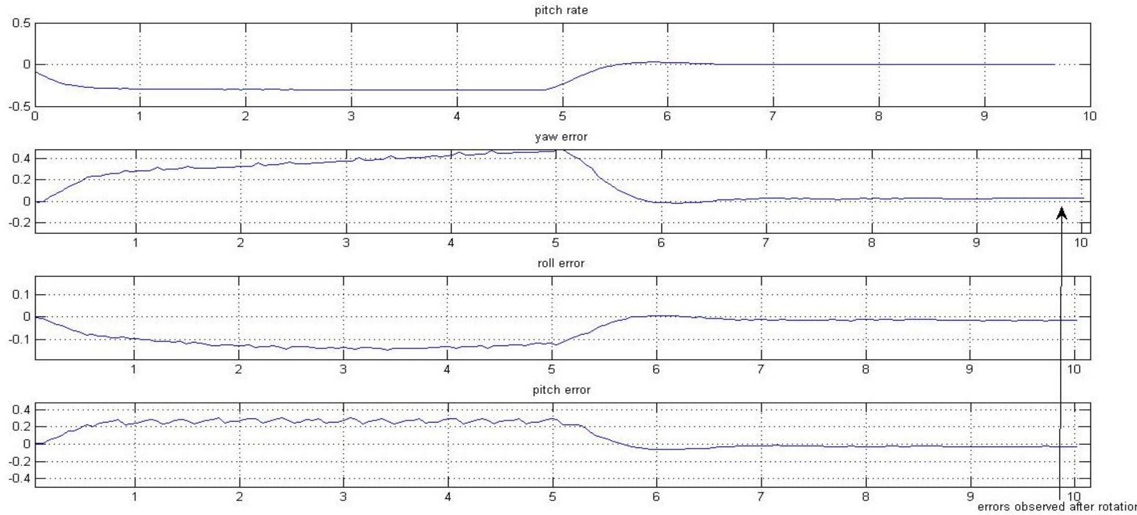


**Figure 3. Pitch axis negative rotation calibration with pitch rate followed by error along yaw, roll and pitch.**




## GYRO CALIBRATION RESULTS FOR MARS ORBITER MISSION

Total of six single axis maneuvers were performed for selected channels of Gyroscope Assembly. The residual scale factor and misalignment errors observed on the spacecraft are listed in Table 1.

**Table 1. Residual scale factors and misalignments for selected channels.**

| Spacecraft Axis | Residual Scale Factors ( ppm-parts per million) |
|---|---|
| Positive Yaw Axis | -1712 |
| Negative Yaw Axis | -1000 |
| Positive Roll Axis | -1795 |
| Negative Roll Axis | -1157 |
| Positive Pitch Axis | -2154 |
| Negative Pitch Axis | 233 |
| | |
| Non-Diagonal Misalignment Terms | Misalignment angle in arc-seconds |
| mc12 | 133 |
| mc13 | 0 |
| mc21 | -124 |
| mc23 | 0 |
| mc31 | 0 |
| mc32 | -56 |

Similarly, the Gyro correction matrix was determined for redundant channels also by selecting the redundant channels in loop and performing the respective single axis maneuver. While selecting the redundant channels, the maneuvers required for calibration were reduced as some of the channels were already calibrated in the previous selections. The observed residual scale factors are tabulated as shown in Table 2. And the residual misalignments are tabulated in Table 3.

**Table 2. Residual scale factors for all gyros.**

| Axis | DTG | Residual Positive Scale Factors ( ppm-parts per million) | Residual Negative Scale Factors ( ppm-parts per million) |
|---|---|---|---|
| Yaw | DTG#2 | -1712 | -1000 |
| | DTG #3 | -2612 | -603 |
| Roll | DTG #1 | -1795 | -1157 |
| | DTG #3 | -1936 | 253 |
| Pch | DTG #1 | -1719 | -46 |
| | DTG #2 | -2154 | 233 |

**Table 3. Residual misalignments for all gyros.**

| Axis | DTG | Non- Diagonal Misalignment Terms (in arc seconds) | |
|---|---|---|---|
| Yaw | | mc12 | mc13 |
| | DTG#2 | 133 | 0 |
| | DTG #3 | 0 | 90 |
| Roll | | mc21 | mc23 |
| | DTG #1 | -124 | 0 |
| | DTG #3 | 0 | 95 |
| Pch | | mc31 | mc32 |
| | DTG #1 | -67 | 0 |
| | DTG #2 | 0 | -56 |

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