Simplistic approach of Yaw error estimation in Geostationary spacecrafts: Experience with INSATs

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Abstract: - Geostationary spacecrafts normally use the concept of biased momentum and they are actively controlled in two axes viz. Roll & Pitch. Yaw error is indirectly controlled based on the principle of Kinematic roll-yaw coupling. Micro-pulse maneuvers are carried out frequently to maintain the spacecraft within the orbital control box. Yaw attitude of the spacecraft is disturbed during the course of micro-pulsing due to cross-axis torques. This paper explains a simplistic approach of yaw error estimation using sun sensors mounted on the solar panel of the spacecraft. It also explains how the same sensor can be used to estimate Roll error at different local time conditions of the spacecraft if required. Experience in using solar panel sun sensor for the roll-yaw attitude estimation using this concept is discussed.

***Introduction:* -** INSATs/GSATs are satellites launched by INDIA to serve multiple mission objectives, combining telecommunication, broadcasting, radio networking, weather data relay and meteorological imaging applications. They are placed in Geo-stationary orbits i.e. they revolve around the Earth in a circular orbit with a orbital radius of about 42,000 km in the equatorial plane. Since they are placed in Geo-stationary orbits the orbital period matches with the Earth's rotation period and relatively satellite appears stationary for a user on Earth. This allows the user to satisfy his requirements with fixed i.e. non-steereable antenna terminals.

INSATs/GSATs are 3-axis stabilized with momentum bias about negative pitch axis. To maintain the yaw axis pointed towards Earth, the Roll & Pitch error of the satellite is actively controlled. The Earth sensor does error sensing and wheels are used as actuators to absorb the error. MTCs (Magnetic Torquer Coils) also help in gradual correction of the disturbance torques. Yaw error is indirectly controlled based on the concept of Kinematic Roll-Yaw coupling i.e. conversion of Yaw error to Roll error gradually over $1/4^{th}$ period of the orbit.

***Control criteria:* -** The orbit of ideal geostationary satellite would be exactly along the earth equatorial plane with revolution period equal to earth rotational period. Then the sub-satellite point of such satellite will be on the equator where the satellite longitude meridian crosses. But this ideal geostationary orbit is not there in reality. If a ideal geostationary orbit is established for a satellite it will deviate slowly from its original position. This deviation is due to various perturbation forces acting on satellite. The major perturbations acting on geostationary satellite are

1. Luni - Solar gravitational force.
2. Asphericity of Earth
3. Solar radiation pressure.
4. On-board thruster activity.

Because of these perturbation forces acting on satellite, the sub-satellite point will be displaced. But as per specifications the sub-satellite point should be within a control box of length 0.2° along East West direction and 0.2° breadth along North South direction with Centre of box is at equator. Thus the sub-satellite point of a satellite positioned at 74° East longitude should be within 73.9° to 74.1° along east-west direction or longitudinal direction and ±0.1° North-South direction, i.e. latitudinal direction. As long as the sub-satellite point is within this control box, the satellite will be within the beam width of user antenna which is non-steereable and fixed. Whenever the sub-satellite point touches the edges of the control box the satellite position to be adjusted by imparting some delta-velocity to the satellite. In this way maintaining the satellite within this control box is called the station keeping and imparting delta-velocity is called station keeping maneuver.

Maneuvers: - Station keeping maneuver carried out to correct the satellite position along North South direction is called North-South station keeping (NSSK) maneuver. Similarly if the correction is along east-west direction, then it is called as East - West station keeping (EWSK) maneuver.

Impact of Yaw error: Yaw error on the spacecraft causes beam rotation and it affects users more predominantly in case of shaped beams. Some of the satellites use the concept of frequency reuse with orthogonal polarization. Yaw error on the spacecraft increases the reception of cross-pol components and signal degradation of the intended components at the user terminals. Hence yaw error on the spacecraft has to identified and corrected.

Various methods exist for satisfying this requirement.

Yaw error- Estimation:

1. ***GYROs:*** GYROs/DTG are provided on the satellite to get rates & angles information during different modes of operation. Nominally they are kept OFF in view of limitations of life. When required they need to be turned ON about 4 to 5 hours to allow for temperature stabilization. It is to be noted that gyros have the inherent property of drift, which is sensitive to temperature and hence calibration needs to be carried out and drift rate compensation values has to be uplinked for making it ready for measurement.

2. ***Slope to Yaw conversion:*** As already mentioned Yaw error gradually gets converted to Roll error (Ref Fig 1). This is based on the equation,

$$T_x = H_y \omega_z$$

Where, T represents torque,

H the momentum,

ω the rate in the third axis.

The spacecraft body yaw error at any given time can be estimated from rate of change of yaw momentum.

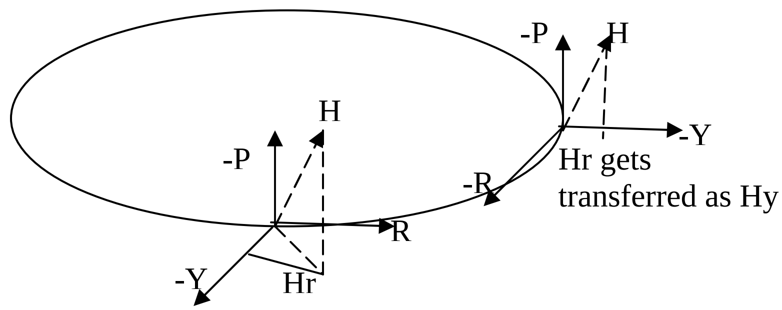


Fig1 Yaw error to Roll error conversion

Spacecraft Body Yaw Error (Ψb-err) = tan-1 (Δ(MW1-MW2) Speed / min * 68 * sin (20) / 60 * 6000) / (7.22 * 10-5 * Hpitch)

For INSAT-3E, with Hpitch ~= 98 Nms,

Ψb-err = 0.54 deg per rpm of Δ(MW1-MW2) Speed / min.

This indicates yaw error reflects as a continuous yaw torque and this creates roll error that gets absorbed by the wheels. This implies Wheel speed (Yaw component) slope is a measure of the yaw error. It is discussed earlier that MTCs provide a gradual correction of the disturbance. The correction provided by MTCs varies with the duty cycle. This component of correction also needs to be accounted in the computation of yaw error. This makes the computation cumbersome.

3. ***Use of Sun Sensors for yaw error estimation:*** There are many Sun Sensors in INSATs/GSATs among which some are body mounted and some are mounted on the solar panel. Two photocells triangular in shape are placed such that at zero error conditions equal areas of both the cells are illuminated. At other angles dissimilar areas are illuminated. This implies that error is proportional to the difference of current generated by the two cells. Some of the sun sensors are mounted to measure the sun angle in the roll-yaw plane and some are mounted to measure the declination i.e. angle with respect to roll-yaw plane. Sun sensors mounted on solar panel (Termed Dec.SPSS) to measure the declination of the Sun, is used on most of the occasions for yaw error estimation (Ref fig 2). This is because, body mounted sensors are available for a limited period due to field-of-view (FOV) restrictions. Whereas Dec.SPSS is available all the time as solar panel keeps tracking sun. Deviation in Dec.SPSS reading with reference to Sun's declination at noon & midnight SLT, is attributed to roll error & at 6 AM & 6 PM SLT to yaw error and a combination of these errors at other periods.

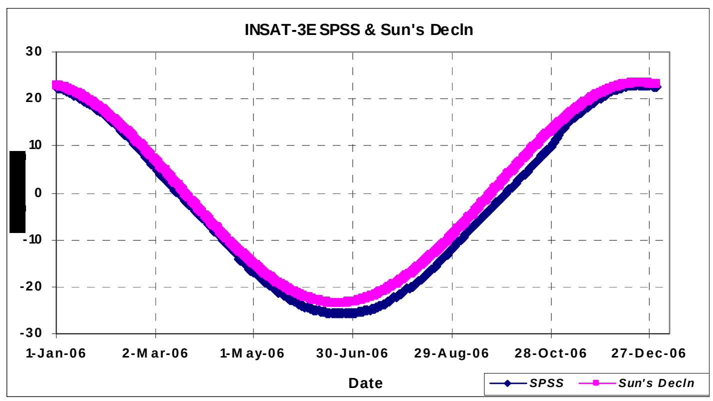


Fig 2

Applications & Experience on-orbit: The above discussed concept is used on different occasions during on-orbit control of INSATs/GSATs.

1. *Wheel-speed excursion control:* INSAT-3E has an additional SPSS in north solar panel, for measuring roll /

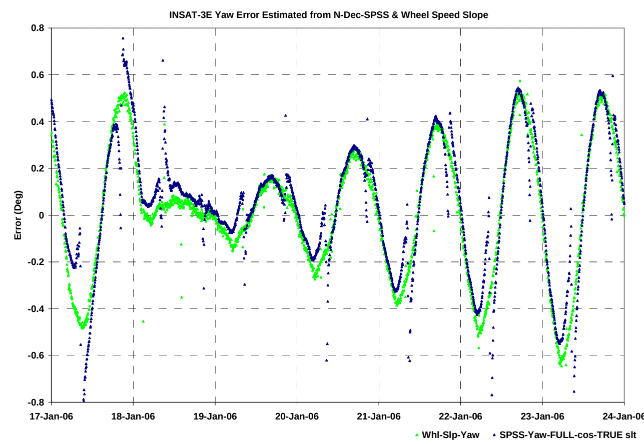
yaw error. As roll error is always maintained at zero using Earth Sensor, at noon & midnight SLT it is assumed that Dec.SPSS reads sun's declination (to eliminate any fixed offset/bias). Hence, at these points, north Dec.SPSS data are taken and propagated, for considering sun's declination. From this dec. SPSS data, yaw error is estimated, after accounting for the sun's declination, cosine effect over the orbit, Solar Panel offset and equation of time. Yaw error estimated from wheel speed slope is compared with Dec. SPSS derived yaw error. If the yaw momentum build up is left un-dumped, the peak yaw momentum observed at Noon or Mod-night SLT will be transferred to peak yaw error at 6 AM or 6 PM SLT. Hence, the peak yaw error is a function of peak yaw momentum stored and vice-versa is also true. i.e. if yaw error is left un-corrected the excursions experienced by wheels also increases. Wheel speed excursions are controlled within limited band (Ref fig. 3 & 4).

Estimation of yaw error 6 hours in advance helps in excursion control.

2. *Drift-rate control due to NSSK:* Drift-rate observed on a satellite post-NSSK depends on the yaw error at the time of firing.

Expected Drift Rate (Δ D) = Δ V * sin (θ) / 2.83,

where,



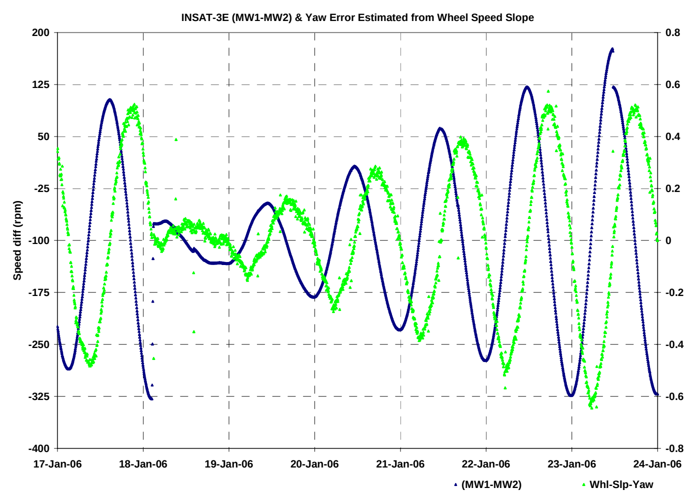


Fig 3 & 4

Δ V – North-South Δ V imparted using S1S2 / N3N4 thruster pair, in m/s.

θ - Absolute Body Yaw Error, in deg.

Therefore, in 3E for Δ V thruster pair S1S2 (South face thrusters) with average Δ V of 5.25 m/s (from OD results), the expected drift rate (Δ D) per deg. of yaw error, is -0.0324 deg/rev.

Similarly, for Δ V thruster pair N3N4 (North face thrusters) with average Δ V of –5.00 m/s (from OD results), the expected drift rate (Δ D) per deg. of yaw error, is 0.0308 deg/rev.

INSAT/GSAT satellites have the flexibility to command attitude bias to reduce the attitude offset during Delta-V maneuvers due to the torque imbalance of the thruster pair.

Knowledge of yaw error prior to NSSK is essential in computing the yaw bias to be commanded to target the required maneuver induced drift rate.

3. *Yaw error control post-pulsing:* In case of EWSK if the thruster firing duration is small, then the required delta velocity is given in terms of small pulses in the wheel control mode itself without going to thruster control mode. The pulses of 32ms or 65ms of 2 or 4 thrusters are used. Even for triaxiality control on-orbit mode pulses are used. On some occasions post NSSK if the drift rate is high pulses are issued in on-orbit mode. During on-orbit pulsing it is observed on some occasions that Yaw error gets generated due to the cross-axis components of the thrusters fired during pulsing. With the prior knowledge of the Dec.sensor reading profile on a nominal day and the day of pulsing and since always roll error is maintained at 0 deg the deviation of the profile of the current day can be attributed to yaw error created during pulsing. The absolute quantity of yaw error can be computed also taking the satellite local time into consideration. But, for the operator simple comparison tools are made available and by firing appropriate roll thrusters the profile will be brought back to the nominal day profile thus ensuring the correction (Ref fig. 5).

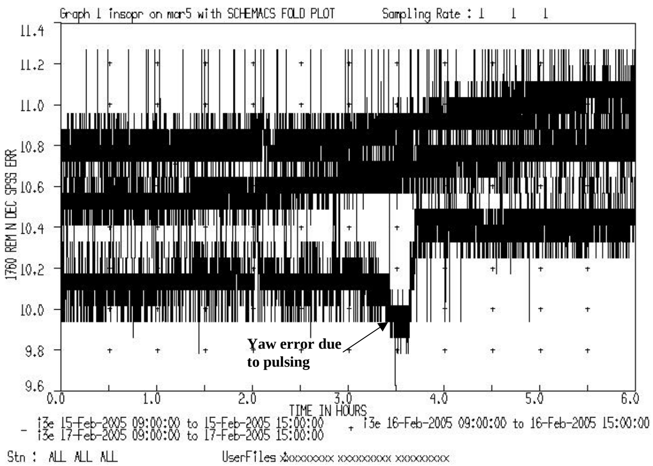


Fig 5

Yaw error estimation during pulsing & during correction process is essential for proper attitude control

4. *Loss-of-attitude recovery:* Satellites experience Loss-of-attitude condition due to malfunctioning or failure of different elements like sensor or actuator or control processor & electronics. In this condition the satellite loses its nominal

orientation and all the user servicesare affected. This is a emergency condition where restoration should be at the earliest. During such contingencies roll & pitch attitude can be restored using earth sensor. Dec. SPSS can be used to estimate yaw error while normalizing the attitude of the satellite.

Limitations: The method discussed above (Yaw error estimation using Dec. SPSS) is difficult to be used close to Noon & Midnight SLT conditions as the sensor reading in sensitive to roll movements of the satellite. Other methods have to be used during these conditions and after crossing these zones the correction can be verified by this method.

Extension of this concept: The concept discussed can be extended to compute roll error in Noon & Midnight SLT conditions in case of Earth Sensor failure contingency in a satellite added with the computation of yaw error in 6 am & 6 pm conditions.

The method discussed above can be fine-tuned and a closed form solution can be obtained where yaw error can be fed to the control system and yaw steering of the satellite is possible in a simple method.

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