7THE REACTION WHEEL BIASING STRATEGY FOR THE XMM NEWTON TELESCOPE

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ABSTRACT *– ESAs XMM NEWTON is a three-axis-stabilised observatory-type satellite in a highly eccentric 48-h-orbit. Its principal attitude actuation device is a set of four reaction wheels in an all-skewed configuration. The purpose of this presentation is to describe the strategies and considerations that lead to the selection of operational wheel speed profiles that don't violate operational constraints and allow uninterrupted scientific observations.*

KEYWORDS: XMM, Reaction wheel, External Torque Estimation, Biasing

INTRODUCTION

ESA's XMM Newton is a space observatory equipped with dedicated instruments to observe astronomical sources at X-ray wavelengths. The telescope is build into a 10 m long spacecraft body that weighs about 3.8 tons. Power is provided by solar panels that have a 16 m span. (fig 1)

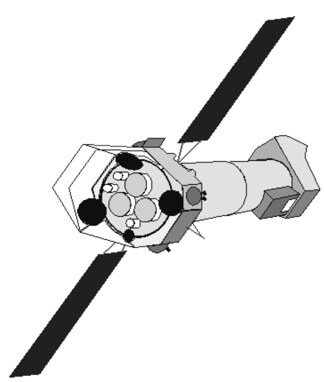

Fig. 1. The XMM Newton Spacecraft

This high-energy radiation can only be observed from outside the earth's radiation belts that reach up to about 40000 km. To keep the satellite above this altitude for long periods and to provide good coverage to the principal ground stations in Kourou (French Guiana) and Perth (Australia), the satellite has been put into a high excentricity, 48-hour orbit with an apogee over the southern hemisphere (Fig. 2) by an ARIANE 5 launcher on 10 December 1999. This orbit allows allocation of astronomical observations during 92% of the time. This is crucial to have a high scientific return.

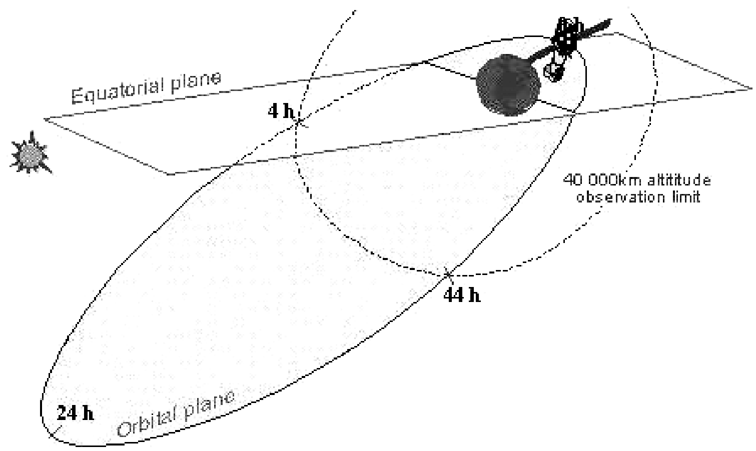

Fig. 2. The XMM NEWTON Orbit

To fulfill the strict pointing precision requirements to the astronomical observations that usually last for many hours, the Attitude and Orbit Control System (AOCS) uses a reaction wheel assembly as primary actuator. The transfer of angular momentum between the assembly and the spacecraft can be controlled with high accuracy and guarantees pointing errors of less than 0.25 arcsec.

The four wheels (one spare) are mounted in an all-skewed configuration and deliver a maximum torque of 0.2 Nm. This is sufficient for attitude slews at a speed of up to 90 deg/h. The operation of these wheels is constraint by certain mechanical and operational limitations that must be considered in mission planning process.

Due to the permanent exposure to external torques, angular momentum is accumulated in the wheels and needs to removed from time to time. This is done by firing hydrazine thrusters that are installed on the spacecraft service module and deliver compensation torques during the adjustment of wheel speeds. These bias manoeuvres are time consuming and should be planned such that have minimal impact on scientific operations.

CONSTRAINTS ON WHEEL OPERATIONS

Each of the reaction wheels has a mass of 6.95 kg and a diameter of 365 mm. They are very well balanced and run on bearings with extremely small friction. The units are actuated by a brushless motor. To protect the sensitive components from mechanical damage, the following operational constraints must be met:

- The individual wheels have a limited speed and therefore a limited momentum storage capability. The bearings are designed and tested to speeds of up to 4000 RPM. Nevertheless, the AOCS checks the speeds against an operational limit of 3900 RPM.
- Low wheel speeds can cause stiction that may result in attitude jitter and mechanical damage. Nevertheless, in realistic operational scenarios it is unavoidable to stop the wheels occasionally and change they spin direction. To minimize mechanical stress caused by stiction, these zero crossing shall be made such that the wheels are decelerated and accelerated quickly. Therefore, the AOCS checks that the speeds of the individual wheels are never under 120 RPM for more than 630 sec.

If any of these two constraints is violated, the wheel speeds are automatically adjusted in an automatic momentum dump (AMD). Hydrazine thruster firings are triggered to compensate for the resulting torques on the satellite body. During a scientific observation, this is undesirable because a slight attitude disturbance is unavoidable in such a manoeuvre. If an AMD would be triggered during a slew or the subsequent attitude stabilization phase, the satellite would automatically be put in a thruster controlled safe mode that guarantees the survival of the spacecraft by keeping the solar arrays pointing to the sun. Such an automatic mode transition calls for a subsequent lengthy reconfiguration that disrupts scientific work for several hours.

For increased safety against such disruptions, it was decided not to allow the wheelspeeds to go below 400 RPM during stable pointing phases.

BIAS MANOEUVERS

During nominal operations, the speed of the individual wheels is permanently changing due to attitude slews and the effect of external torques. Since the attitude sequence during one orbit is dictated by the position of the desired observational targets and the attitude the satellite assumes during the perigee passage, the only way to influence the wheel speed profile is to explicitly command the wheels to spin at a certain rate in a so called momentum bias manoeuvre.

The time before and after the perigee passage is not usable for scientific observation since the radiation environment is to strong below an altitude of 40000 km. To make good use of these hours, mission planning tries do as many of the satellite "housekeeping" tasks as possible during that time. Consequently, bias windows are typically allocated before the slew from the perigee safe attitude to the first observational target and after the slew back to the perigee attitude.

To make operations as fuel efficient as possible, it is tried to use the unavoidable delta-v effect of the thruster firings for orbit maintenance. To do so, biasing operations are preferably done in either of the two bias windows, depending on the desired orbit change. The preferred window typically changes every few weeks.

Typically, only one biasing opportunity, either shortly before or after perigee, is used to select the wheel profile or the entire revolution. This one bias manoeuvre must be used to ensure safe wheel speeds over the next 48 hours.

TYPICAL WHEEL PROFILES

Figure 3 shows a typical profile for all three wheels over one revolution. Some typical features are visible:

- Long periods of many hours of astronomical observations during which the satellite is "starring" at a source without changing its attitude. In such periods, external torques (mainly caused by solar radiation pressure on the asymmetrical satellite body) gradually change the total angular momentum and therefor the individual wheel speeds.
- Sudden changes caused by large slews from one attitude to the next. In these periods, the total inertial angular momentum of the wheel system doesn't change much, but the distribution over the individual units changes significantly since their inertial orientation is changed rapidly with the moving spacecraft.

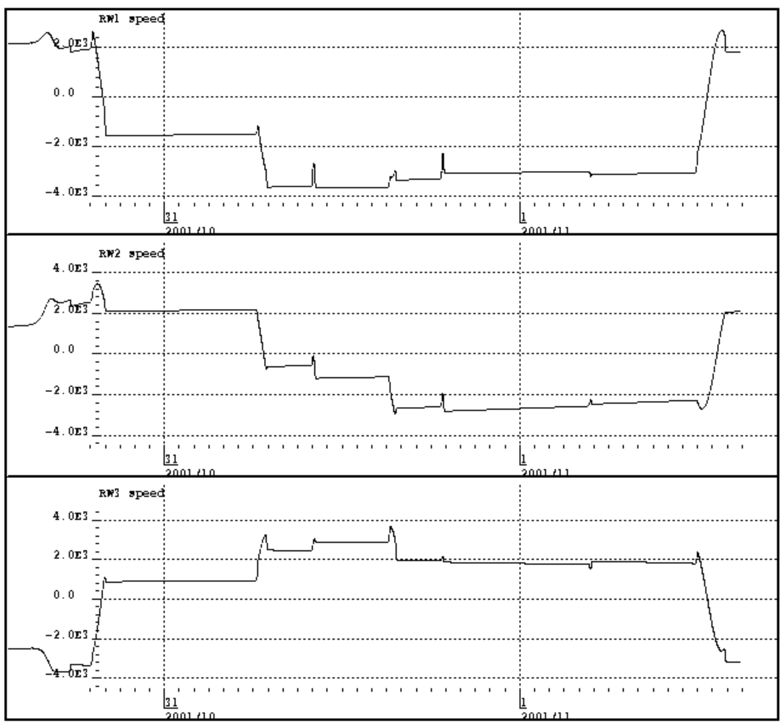

Fig. 3 The wheel profile over an entire orbit

Other important features are visible in the enlarged view of the wheel profile around perigee (fig.4). It shows the perigee passage, the subsequent small bias manoeuvre and the first large slew in the new orbital revolution.

Close the earth, the gravity gradient torque gets stronger and dominates over the radiation torque. This is visible from the strong continuous variation in all three wheels.

After perigee, a small bias manoeuvre shows as a sudden variation in all three speeds.

The last obvious feature in this graph is the first large slew of the beginning revolution. It shows as a considerable speed variation in all three wheels. It is possible to distinguish three phases of the slew:

- The acceleration phase, in which angular momentum is transferred from the wheels to the satellite body. Wheel one shows a large increase of several hundred RPM.
- The coast phase, the shows as a large but continuous change in the speeds. In the profile of wheel one, this shows as a sudden drop after the acceleration and long staedy drop, including a zero crossing.
- The deceleration phase, in which angular momentum is retransferred back to the wheels.

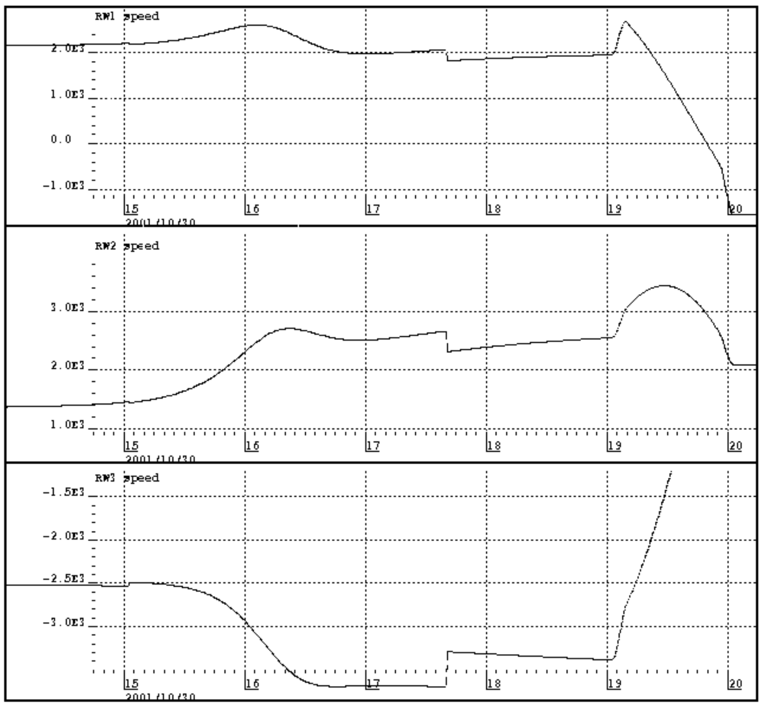

Fig. 4 The wheel profile around perigee

WHEEL SPEED PREDICTION

In order to select an acceptable profile by commanding the appropriate biasing manoeuvre in the preferred window before or after perigee, one has to predict the speeds of the individual units at any time of the revolution. Based on these predictions, good profiles can be identified.

The computational process of speed prediction for a certain moment in time can be broken down into the following steps:

1. Calculate the inertial angular momentum of the spacecraft based on the initial wheel speeds
2. Integrate the effect of the external torques on the total angular momentum from the bias up to the time of interest
3. Calculate how the angular momentum at that time distributes over the wheel and the satellite body.

4. Calculate the speed of the individual wheel from its angular momentum

The development of the wheel speeds depends on following factors:

- The selected bias window. This should be selected depending on the desired delta-v effect on the orbit.
- The wheel speeds commanded in the selected bias window. This is the only free parameter to control the profile. It is understood that these initial value must satisfy the above mentioned constraints.
- The attitude sequence. This is defined by the astronomical observation targets and exposure times planned for the revolution. This sequence is defined by scientific mission planners and is not a free parameter for profile planning. It is introduced into the planning process via an interface file that contains the relevant data.
- The external torques. It was found that the only relevant influences are solar radiation and gravity gradient.
- The mass properties (moments of inertia) of the spacecraft body and the reaction wheels.

The last two parameters can be considered as invariable database parameters for this purpose.

External Torque Prediction

The prediction of the external torques acting on the satellite turned out to be the most difficult part of the wheel speed prediction process. The best known contribution **N** stems from the gravity gradient torque. It depends only on the usually well known parameters **I** (the inertia tensor of the satellite) and $\mathbf{R_s}$ (the radius vector to the center of the earth in the spacecraft reference frame). The constant μ is the gravitational constant of the earth.

$$\mathbf{N} = \frac{3\mu}{R_s^3}\left[\mathbf{R_s} \times \left(\mathbf{I} \cdot \mathbf{R_s}\right)\right]$$

As discussed and shown above, it becomes predominant in the parts of the orbit close to perigee.

The second important contribution stems from the torque caused by the force from the interaction of the satellite body with the solar radiation. Therefor, it depends on the relative orientation of the satellite and the sun. This relationship was calibrated by deriving the total torques acting on the satellite by obsersing the change rate of the wheel speeds at different attitudes. The remainder of the total torque after substracting the known gravity gradient effect was then attributed to the solar radiation. After a lengthy calibration process using many different sun-spacecraft orientation angles, this calibration yielded a very reliable prediction model for the radiation torque..

Any other contribution, for example the magnetic torque, is too small to be observable.

Slew Simulation

To asses the transfer of angular momentum between the wheel system and the satellite body correctly, it is necessary to model the cinematics of the slew correctly. For this purpose, a routine simulates the eigenaxis slews of the spacecraft, considering the sinsusoidal ramp phase and the coast phase that is typically longer than one hour.

Finding valid profiles

Once it is possible to predict the wheel speeds for any moment from a given set of initial wheel speeds, it is possible to check whether any given initial state will lead to constraint violation or not. In order to quickly find a valid bias automatically, one can define a cost function that penalizes any threshold crossing. A simplified flow diagram is shown in figure 5. A suitable optimization algorithm can than be employed to find minima of this function. In our case, a simplex routine is used for this purpose.

CONCLUSION

Using the outlined methods to predict the wheel speeds at any time and to identify valid profiles by minimizing a suitable penalty function that assign costs to constraint violations, it was possible to find valid solutions for almost all operational cases. The resulting bias manoeuvres are usually fuel efficient and beneficent for orbit maintenance. Extra bias windows that were originally foreseen around apogee but would have disrupted science operations could be dropped.

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