Measurement and prediction of the performance of a satellite based antenna pointing mechanism and controller
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1. SUMMARY

For the ENVISAT mission with the Polar Platform (PPF), an earth observation programme funded by the European Space Agency (ESA), the Ka-Band Subsystem (KBS) will transmit data from the on-board sensors to earth via a Geostationary satellite of the Data Relay Satellite System (DRS). In this inter-satellite inter-orbit communication link, the KBS Antenna points in “open loop” towards a DRS satellite with high accuracy and maintains track as the PPF continues in its low earth orbit. An outboard assembly (OBA), comprising a 0.9 metre parabolic Antenna attached to its pointing mechanism (APM) is mounted on a mast which is deployed once the PPF is in orbit. The Ka-Band microwave transmitter, which feeds the Antenna via waveguides, is housed inboard together with the Antenna pointing control hardware. The drive selected for the antenna pointing mechanism includes a stepper motor attached to a gearbox. Optical encoders were chosen to provide absolute position feedback for the pointing control system. The Antenna and Antenna Pointing Mechanism assembly is shown in Figure 1. The mechanical performance of the antenna pointing system (APS) associated with pointing accuracy, pointing stability and disturbance torques imparted to PPF have been predicted and correlated with measurements performed on an Engineering Model (EM) of the APS. This was then used to predict the characteristics and performance of the Flight Model (FM). It was not feasible to perform the verification solely by terrestrial test methods because of the influence of the earth’s gravitational field. A judicious combination of test and analytical methods was required to prove the mechanical performance. Linear flexible and non-linear control/rigid body dynamics models (with connection stiffnesses) of the APS and its associated pointing mechanism drive and antenna pointing controller (APC) have been developed. Zero-g terrestrial test arrangements were developed to enable system identification to be undertaken to derive the values of physical parameters characterising the gearbox.
2. **MAIN SYSTEM REQUIREMENTS**

The KBS OBA will operate in weightless conditions. The specifications for pointing accuracy and disturbance torque are given below:

Pointing accuracy (degrees):  
- Random component: 0.054 (2 \( \sigma \))
- Uncompensatable Bias: 0.066 (max.)
- Max. Variation over 1 orbit: 0.043 (peak)

Generated disturbance torque at the spacecraft centre of mass: peak value to not exceed 0.06 Nm below 1 Hz.

The above performance must be achieved for a reference day test trajectory, based upon the data extracted from typical Data Relay Satellite trajectories (as seen by PPF).

A subset of this reference day trajectory is shown in figure 2, and contains the typical tracking and handover trajectories for which max. angular speed and acceleration are in the order of 2 °/s and 0.015 °/s\(^2\) respectively.
3. APM TECHNICAL DESCRIPTION

The Antenna Pointing Mechanism (APM) motorgears are arranged in a "elevation over azimuth" configuration allowing an antenna pointing range of -30 to +90 degrees in elevation and -165 to +165 degrees in azimuth. The motorgear design is the key to the pointing and disturbance torque performance. A stepper motor (with 200 steps over 360 degrees and a 64 microstep capability) was attached to a gearbox with a reduction ratio of 100. Pre-loaded bearings were employed on the input and output shafts. Fomblyn lubrication was selected for all bearings, including those in the gearbox.

The selected reducer is of the "Harmonic Drive" type and consists of the following components (see Figure 3):
• Circular spline (CS), a rigid ring with an internal toothed rack which has two teeth more than that on the flexspline.

• Flexspline (FS), a flexible, thin walled cylindrical cup with external teeth of marginally smaller pitch diameter than the CS. The FS is fitted inside the CS.

• Wave Generator (WG), a narrow ball bearing assembly fitted into an elliptical structure which is plugged inside the flexspline pressing the teeth of the FS at each end of the major axis to the corresponding teeth on the CS. As the WG rotates through one full revolution, the FS moves one tooth, resulting in 100:1 reduction gearing.

• Elliptical Ball Bearings fitted onto the WG maintain the deformation of the FS.

Figure 3: Sketch of gearbox illustrating its principle of operation

4. VERIFICATION APPROACH

Pointing and disturbance torques tests were performed on an EM APM which has significantly different design characteristics to the Flight Model (FM). The behaviour of the FM had to be predicted using best engineering estimates of key physical parameters normally obtained by test.
For these reasons, the approach to the verification of the pointing and disturbance torque performance was based on combined test and analytical methods. It was thus essential to derive test methods which provided insight into the torque harmonics created by the motorgear, so that pointing and disturbance torque characteristics could be correlated with the mathematical model parameters.

4.1. Tested Configurations

Four different test configurations were devised, using the EM APM:

1. APM attached to a mass dummy of the ATA with a very small out-of-balance characteristic, but representative inertia changes with elevation angle and an elevation inertia about 25% of the actual ATA. (Configuration 1)

2. APM attached to the ATA, operated at high elevation angles with no gravity compensation device fitted to the ATA. (Configuration 2)

3. As configuration 2 but with a gravity compensation device consisting of a bungee attached at one end directory above the azimuth rotation axis and at the other to the ATA. (Configuration 3 was not suitable for disturbance torque tests as the fluctuation in torque induced by the compensation device are potentially much greater than the expected disturbance torques, but the effect on pointing performance is small.)

4. APM attached to the ATA with an elevation angle of zero degrees, with the ATA supported above its CoG location by a bungee. Operation of the KBS was restricted to the azimuth axis, and could only be used over the -12 to 12 degree azimuth range. (Configuration 4)

4.2. Mathematical Models

For each of the test configurations, a mathematical model of the control system and the APS structural masses and inertias connected by the torsional stiffness of the motorgear in azimuth and elevation was developed. This is the control/structure model. This resulted in four mathematical models:

- Model 1. EM APM and ATA mass dummy
- Model 2. EM APM and ATA
- Model 3. FM APM and ATA mass dummy
- Model 4. FM APM and ATA
4.3. First Verification Step (Configuration 1)

Configuration 1 was used to assess many different trajectories for both pointing and disturbance torque measurements. Although the configuration is not representative of the geometric characteristics of the actual APS, it did allow many other parameters to be investigated such as stick-slip characteristics of the motorgear, harmonic content of the motorgear torque spectrum, stiffness of the motorgear gearbox and influence of the cable drum on disturbance torque and pointing performance. It also permitted the control algorithm of the APC to be checked for the parameters associated with this particular mass and geometric set-up. Open and closed loop tests were undertaken for both pointing and disturbance torque. The measurement of pointing performance was achieved using a commercially available device robotic measurement system.

Disturbance torque measurement required the design and manufacture of a special purpose 6 dof force and torque transducer, capable of resolving torques as low as 0.002 Nm in the presence of a static torque of 25 Nm, i.e. a resolution of 1 in 12500. It was not possible to devise such a sensitive transducer, but a resolution of 5000 was achieved with a strain gauge device.

Mathematical Model 1 was used in conjunction with the results of pointing measurements in 'configuration 1' to perform non-linear system identification procedures to obtain the values of parameters controlling the performance of the EM gearbox. This analysis demonstrated that the following parameters were critically influencing the performance of the EM OBA under open loop control:

a. Stick-slip characteristics of the gearbox at tooth passing frequency
b. Stiffness of the flex-spline of the gearbox
c. Damping of the gearbox
d. Cogging torque due to the stepper motor elements
e. Resistance torque changes caused by two per revolution fluctuations in the torque required to turn the gearbox

Having identified the values of these parameters, the control structure model was modified and used to predict the disturbance torque and pointing performance of the EM OBA. The disturbance torque was predicted at the interface with the torque transducer. In order to relate this torque to that measured during the disturbance torque tests, the following activities were performed:
1. The Finite Element Model (FEM) of the EM APM attached to the mass dummy was modified to include the measured stiffnesses of the torque transducer. These were obtained from a modal survey test undertaken during the disturbance torque tests with the ATA mass dummy. The predicted torques at the interface with the torque transducer were applied to the FEM and the forced response calculated to determine the resulting torque as measured by the torque transducer with the EM OBA attached to it.

2. The control/structure model was modified to include the stiffness of the torque transducer and the resulting torques extracted from the model. This model was also employed to study the stability of the controller when the KBS OBA was mounted on the torque transducer.

Acceptable correlation was obtained from the open loop tests. It was also established that the performance of the system under closed loop control was virtually identical to that observed during the open loop tests with the ATA mass dummy. This completed the test and analysis sequence for the EM APM attached to the ATA mass dummy.

4.4 Verifications with 'Configuration 2'

At this stage, the control/structure model was modified by replacing the ATA mass dummy with the real ATA (Model 2), and new control coefficients established for this 'configuration 2'. Again pointing and disturbance torque calculations were performed to compare with measured data (References 4.10 - 4.18). Since only a limited number of trajectories can be evaluated by test, the selection of these trajectories was a carefully considered activity.

Trajectories were selected which explored the boundaries of the performance envelope of the KBS OBA and which would initiate particular physical phenomenon. In particular the following characteristics were to be investigated:

1. Pre-pointing trajectories which exhibit maximum speed of the APS in elevation and azimuth to produce maximum disturbance torques associated with out-of-balance and gyroscopic effects and to maximise the influence of the “two per rev.” torque fluctuation of the gearbox.

2. Tracking trajectories which exhibit minimum speed of the APS in elevation and azimuth to initiate stick slip behaviour by operating in very low motor torque regimes.

3. Large changes in elevation angle so that natural frequency shifts during operation are generated.
4. Motor speed sweep trajectories to pin-point high frequency harmonics associated with tooth passing frequency and stepper motor cogging torques.

5. Stop trajectories.

6. Handover scenarios.

The test data from these trajectories were used to verify the control/structure model. The FM motorgear characteristics were then substituted into the control/structure model (Model 4) and the FM APS performance predicted. This required the estimation of the same key parameters identified on the EM motorgear. This model was then used to predict the APS performance during a typical day’s operation.

5. SIMULATION MODEL

The model has been built using the “MatrixX” CACSD package. The general simulation scheme is shown in Figure 4 below. The model contains 10 blocks, of which the most important are:

- the block “apc” which models the controller,
- the block “motor_har_az” which models the motor/gearbox for azimuth,
- the block “motor_har_el” which models the motor/gearbox for elevation,
- the block “apm_s” which models the kinematics and dynamics of the APM,

![General simulation scheme](Figure 4: General simulation scheme)
The inputs of the total simulation model "control" are:

* the desired azimuth and elevation positions (rad)
* the desired azimuth elevation velocity (rad/RTC, RTC = Real Time Cycle)

The outputs for the total model are:

* the antenna azimuth and elevation position (rad)
* the filtered reaction torques (Nx, Ny, Nz) (Nm)
* the filtered reaction forces (Fx, Fy, Fz) (N)

Since the most critical element appeared to be the gearbox, we will describe the key characteristics used to represent the motor torque harmonic behaviour.

1. **Motor torque**: The torque \( T_{\text{gross}} \) as generated by the motor without losses is calculated as follows:

\[
T_{\text{gross}} = T_{\text{max}} \cdot \sin(\beta \cdot NN - K_{\text{angle}} \cdot \theta_r)
\]

with \( T_{\text{max}} \) the maximum torque of the stepper motor, \( \beta = \pi/64 \), \( NN \) is the desired position of the motor (corresponds to the position of the magnetic field), \( K_{\text{angle}} = 100 \) and \( \theta_r \) is the position of the motor.

2. **Cogging torque**: The cogging torque \( T_{\text{cog}} \) is calculated as follows:

\[
T_{\text{cog}} = t_{\text{cog}} \cdot \sin(200 \cdot \theta_r + \phi_{\text{cog}})
\]

with \( t_{\text{cog}} \) the amplitude of the cogging torque and \( \phi_{\text{cog}} \) is the phase of the cogging torque.

3. **Motor friction**: The motor friction \( T_{\text{motfric}} \) is calculated as follows:

\[
T_{\text{motfric}} = \text{motfricpar} \cdot \dot{\theta}_r
\]

with \( \text{motfricpar} \) the motor friction parameter and \( \dot{\theta}_r \) is the velocity of the motor.

4. **Dynamic friction**: The dynamic friction \( T_{\text{dyn}} \) in the gearbox elliptical bearings is calculated as follows:

\[
T_{\text{dyn}} = (T_{\text{dyn}0} + T_{\text{dyn}1} \cdot \sin(2 \cdot \dot{\theta}_r + \phi_{\text{dfric}}) \cdot \text{SIGN}(-\dot{\theta}_r)
\]

with

\[
T_{\text{dyn}0} = \text{dyn0par} \cdot \text{MIN}(\text{ABS}(\dot{\theta}_r) / \text{dynvel},1)
\]

\[
T_{\text{dyn}1} = \text{dyn1par} \cdot \text{MIN}(\text{ABS}(\dot{\theta}_r) / \text{dynvel},1)
\]
the phase of the dynamic friction, dyn0par and dyn1par are the parameters of the dynamic friction, dynvel is the saturation velocity, MIN() is the minimum function, SIGN() is the sign function, ABS() is the absolute value function. This dynamic friction is a position dependent saturated viscous friction.

5. Static friction: The static friction ($T_{stat}$) in the gearbox elliptical bearings is calculated as follows:

$$T_{stat} = T_{stat0}$$

with $T_{stat0}$ the static friction parameter.

This static friction is however only present if $2 \cdot n \cdot \pi - \delta < 200 \cdot \theta_r + \phi_{statric} < 2 \cdot n \cdot \pi + \delta$ with $n$: any integer number, $\delta$ is half of the stiction angle, $\phi_{statric}$ is the phase of the static friction. The static friction is a position dependent Coulomb friction.

6. Damping and stiffness of the gearbox: The torque contribution ($T_{sdhds}$) due to the structural damping and the stiffness of the gearbox is calculated as follows:

$$T_{sdhds} = fsv \cdot (\dot{\theta}_r / R - \dot{\theta}_t) + Ka \cdot (\theta_r / R - \theta_t)$$

with $R$ the transmission ratio of the HD, $\dot{\theta}_t$ is the velocity of the antenna and $\theta_t$ is the position of the antenna.

6. POINTING PERFORMANCE (REFERENCE DAY)

Results of the pointing tests were used to confirm the simulation model, which was then updated to represent the FM APS. The reference day trajectory was divided into 9 parts and simulated. Table 1 summarises the 9 simulation sections, and presents the pointing performance for each. The Azimuth/Elevation pointing errors PDF for Section 1 is provided in Figure 5.

The results in table 1 show that the system is predicted to always be well within the test specification of 44 mdeg (95%, on each axis). This simulation was performed with parameters considered to be worst case for the flight version of KBS.
## Table 1: Summary of Reference Day Pointing Simulation Results

<table>
<thead>
<tr>
<th>Simul. Part</th>
<th>Approximate Time Section(s)</th>
<th>95% Azimuth Error (mdeg)</th>
<th>95% Elevation Error (mdeg)</th>
<th>Max Disturb. Torque (Nm)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 - 1500</td>
<td>6.7</td>
<td>9.9</td>
<td>&lt;0.02</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>1500 - 1800</td>
<td>7.3</td>
<td>5.0</td>
<td>(0.08)</td>
<td>Prepointing</td>
</tr>
<tr>
<td>3</td>
<td>1800 - 4400</td>
<td>4.9</td>
<td>6.0</td>
<td>&lt;0.03</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>4400 - 4700</td>
<td>7.0</td>
<td>7.1</td>
<td>0.06</td>
<td>Prepointing</td>
</tr>
<tr>
<td>5a</td>
<td>4700 - 5800</td>
<td>5.8</td>
<td>12.6</td>
<td>&lt;0.02</td>
<td>-</td>
</tr>
<tr>
<td>5b</td>
<td>5800 - 6600</td>
<td>7.9</td>
<td>8.2</td>
<td>0.06</td>
<td>Prepointing at end</td>
</tr>
<tr>
<td>6</td>
<td>6600 - 9200</td>
<td>5.7</td>
<td>6.6</td>
<td>&lt;0.02</td>
<td>Very slow - no resonances</td>
</tr>
<tr>
<td>7</td>
<td>9200 - 12200</td>
<td>5.5</td>
<td>4.3</td>
<td>&lt;0.02</td>
<td>Very slow - no resonances</td>
</tr>
<tr>
<td>8</td>
<td>12200 - 14600</td>
<td>8.4</td>
<td>7.7</td>
<td>&lt;0.02</td>
<td>Very slow - no resonances</td>
</tr>
</tbody>
</table>

**Figure 5**: Elevation Error/Probability Density Function - Simulation Part 1
7. DISTURBANCES TORQUE TESTS

Four trajectories were used to provide measured data to compare with the disturbance torques predicted by the control/structure model. Three of these trajectories, AESING00, EL089P00 and ACQ600 required no zero-g kit and were trajectories within the mission profile of the KBS. During these trajectories, the stop trajectory mode of the APC was checked.

Only one trajectory was measured with the zero-g kit in place, AL012M00. This trajectory violated the normal operational acceleration limits of KBS in order to achieve the 2 degrees/second maximum speed within the -12 to +12 degrees azimuth range of the trajectory. Subsequent analysis of the measured data from the zero-g kit test indicated that the contaminating forces due to the presence of the bungee support were too large to readily be compensatable. Further work is ongoing to fully explain the effects of the zero-g kit.

Repeatability of the measurements was checked by performing the trajectories up to three times. The measured data was processed into 1 Hz and 2 Hz filtered time history data, as well as unfiltered plots. Estimates of the torques referenced back to the spacecraft CoG were derived from the measured data. It was necessary to use a mass compensation method to remove the effects of the gravity vector and to compensate for cross-coupling terms between torques and forces introduced by the design of the 6 DOF transducer.

A low pass filter set at 0.01 Hz was implemented to remove low frequency fitting errors.

Table 2 lists the disturbance torque test trajectories.

<table>
<thead>
<tr>
<th>TRAJECTORY</th>
<th>MODE</th>
<th>TYPE OF TRAJECTORY</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZPS ATA</td>
<td>- - -</td>
<td>Pseudo-static trajectory - AZ</td>
</tr>
<tr>
<td>AESING00</td>
<td>Acquisition</td>
<td>Combined AZ &amp; EL, close to singularity</td>
</tr>
<tr>
<td>AESTPP00</td>
<td>ACQ Interrupt</td>
<td>As above, with stop trajectory at the end</td>
</tr>
<tr>
<td>EL089P00</td>
<td>Acquisition</td>
<td>Elevation trajectory 70 - 87</td>
</tr>
<tr>
<td>ELSTPP00</td>
<td>ACQ Interrupt</td>
<td>Elevation stop trajectory 70 - 87</td>
</tr>
<tr>
<td>ACQ600</td>
<td>Pre-pointing</td>
<td>Hand-over scenario</td>
</tr>
<tr>
<td>AL012M00</td>
<td>Pre-pointing</td>
<td>Azimuth trajectory +/- 12 degrees</td>
</tr>
<tr>
<td>ALSTPP00</td>
<td>P-P Interrupt</td>
<td>Azimuth trajectory +/- 12 degrees with stop</td>
</tr>
</tbody>
</table>

Table 2 : List of trajectories
Pseudo-static trajectories (AZPS_ATA) were used to provide static force and torque measurements for the APS in a high elevation mode. From these measurements it was possible to establish the following:

1. Confirmation of the transducer calibration
2. CoG position of the combined APS, ATA and Moving part of APM
3. Determination of the orthogonality of the APS test set-up w.r.t. the torque transducer
4. The feasibility of using a mathematically generated gravity compensation based on KBS mass and CoG data. The result of which are reported below:

The torques about the x and y axes, $T_x$ and $T_y$, are related to the CoG positions of the APS and the moving masses of the APM and ATA. The equations of these torques as a function of the elevation and azimuth angles of the tested trajectories were defined. Figure 6 plots the results of the calculation of $T_x(t)$ for the EL089 trajectory. These predictions should be compared with the raw data obtained from the test (Figure 7).
The masses in the torque functions are varied in a multi-degree of freedom curve-fit using the measured torques and encoder angles to derive values which best fit the measured data. The obtained 'static' torque function is then subtracted from test data to eliminate the effects of gravity.

8. DISTURBANCE TORQUE RESULTS

8.1. Measured

Only the results of trajectory EL089 is presented in the paper. Figure 8- is the measured torque around X-axis (Tx) from the torque transducer, compensated for the effects of gravity and low pass filtered below 1 Hz. These data have also been filtered above 0.02 Hz to remove systematic curve fitting errors introduced by the process used to remove the torque fluctuation due to operation of the KBS APS in the earth's gravitational field. This phenomenon has been checked by improving the curve-fitting on the EL089 trajectory and recalculating the compensated and filtered data. The low frequency contribution reduced from 0.02 Nm to 0.01 Nm.

![Compensated and band-passed filtered torque about x-axis for trajectory EL089.](image)

The low frequency filtered torques and forces obtained from the analysis method were used to calculate torques at spacecraft CoG. The results are presented in Table 1.

8.2. Predicted

The predicted forces and torques at the torque transducer have been applied to the FEM of the KBS APS mounted on the torque transducer.
Figure 9 shows the predicted torque about the x-axis for trajectory EL089. This is to be compared with Figure 8.

All results showed that the predicted torques are pessimistic compared with the measured compensated data and their characteristics are similar to those observed during the tests.

8.3. Lessons learned

The following conclusions were drawn from the test and analysis campaigns:

- the gravity vector induced torques introduce significant low frequency torque variation despite the extremely small angular changes of the KBS OBA during trajectories.
- the proximity of the fundamental resonance of the KBS OBA (on the torque transducer stiffness) to the low pass filter frequency introduces filter errors.
- measurement errors caused by the use of the encoder output to create the gravity compensation terms are the 20% of the magnitude as the torques being measured.
- torques at the torque transducer, as predicted by the computer model, are pessimistic compared to those measured during the test. Also, predicting torques at S/C CoG from the measured torque data produces assumes that the torque fluctuations are produced by the motorgear and fed through to the ATA.
- cross-coupling terms introduced by the torque transducer render the force data unreliable.
- rig induced forces are dominating the measured torques with the zero-g kit attached to the KBS OBA.
• measurement noise (after filtering the data) is the same order of magnitude as the measured data for some of the trajectories.

The following improvements to the test procedure are necessary to ensure that the FM disturbance torque measurements are more reliable:

• dedicated test to measure harness (cable drum) contribution
• measurements only with the ATA mass dummy
• measurement of rotational accelerations
• alignment measurements to established inclination of KBS OBA to vertical
• no switching of ADC on azimuth encoder
• test on APM on its own to determine its CoG

9. CONCLUSION

It has been possible with a combined test and analytical approach to determine the disturbance torque and pointing performance of satellite based antenna pointing system.