Cage instability of XMM-Newton’s reaction wheels discovered during the development of an Early Degradation Warning System

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ESA’s XMM-Newton space observatory, the flagship of European X-ray astronomy, is after it’s launch in 1999 the most powerful X-ray telescope ever placed in orbit. The mission originally designed for a 10 years lifetime is planned to be operated long into this decade since spacecraft and instruments are operating admirably without major degradation. Therefore recently a system called XMM Early Warning System (XEWS) is developed to perform near-real-time trend analysis of spacecraft parameters in order to detect early degradation of components. This will enable the mission to perform early counter measures in case degradation is detected. During the development of XEWS it has been spotted that one of XMM-Newton’s reaction wheels shows since 2008 non-periodic friction increase during stable pointing. We present an analysis of all four reactions wheels since the start of the mission identifying the periods of increased friction and giving some possible causes and cures for this effect that is as well know as “cage instability” and describe the impact on operations. Additionally a comparison with the wheels of ESA’s INTEGRAL spacecraft which is using effectively the same Attitude and Orbit Control System will be presented.

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I. ESAs high energy astrophysical observatories XMM-Newton and INTEGRAL

ESA is operating within its Horizon 2000 programme two major astrophysical observatories in the high energy regime of X- and Gamma-rays. The goal of these missions is to unveil the hot and violent universe with an unprecedented accuracy in terms of spectral and imaging detection capabilities. Both missions have originally been planned for a mission lifetime of less than a decade but operate still without major degradation and are facing a very high scientific demand.

XMM-Newton was launched in December 1999 on the Ariane 504 rocket from French Guyana. As a cornerstone mission of Horizon 2000 it observes the hot X-ray universe with objects like neutron stars, black holes or active galaxies and has the largest X-ray collecting area of an X-ray observatory ever launched. The three-axis stabilized and 3.8 tons heavy spacecraft with a pointing accuracy of one arcsec consists of three main sections: A seven meter long telescope tube, a squarish service module also carrying three telescopes at its forward broader end and the focal plane assembly housing the detectors at its other extremity. Its pair of solar panels has a 16-metre span. XMM-Newton was ingested in to a highly elliptical orbit with a perigee around 20,000 km and an Apogee of 120000 km and a southern inclination of 40 deg. This highly eccentric orbit has been chosen for two reasons. First, the XMM-Newton instruments need to work outside the radiation belts surrounding the Earth. Second, a highly eccentric orbit offers the longest possible observation periods - less interrupted by the frequent passages in the Earth's shadow that occur in a low orbit. In addition, the orbital period of XMM-Newton is exactly two times the Earth rotation period to maintain optimal contact between XMM-Newton and the ground stations tracking the satellite. This allows XMM-Newton data to be received in real-time and for it to be fed to the Mission Control Centres. Note that XMM-Newton has no onboard data storage capacity, so all data is immediately down-linked to the ground in real time.

INTEGRAL has been launched in 2002 by a Russian Proton rocket from Baikonur, Kazakhstan and is effectively using the same satellite bus as XMM-Newton, however improving the design in various details. The payload provides a combination of imaging and fine spectroscopy over a very wide range of wavelengths from gamma ray to optical. INTEGRAL operates as well on a high elliptical orbit having an apogee of 150 000 km and a perigee of 2000 km with a northern inclination of 51.6 deg.

II. XEWS

After operating XMM-Newton for 10 years in orbit having survived a failure of an antennae switch in 2008 we felt the necessity to develop a system that should be able to spot degradation of components before a failure actually happens. As well encouraged by the fact that the possible mission lifetime currently limited by its fuel reserves to 2020 may be extended significantly by a new Attitude and Orbit Control System mode, we started in 2009 to develop the XMM Early Warning System XEWS.

The Mission Control System (MCS) itself is not primarily constructed to serve this need of component degradation detection, since it concentrates on live analysis of spacecraft parameters using a set of Out Of Limits (OOL) that would trigger an alarm in case a parameter exceeds its limits. However it is not able to detect subtle changes. Especially degradation of parameters, which have an orbital evolution and therefore change a lot already during one revolution, can not be spotted. In addition the Mission Control System Archive is packet based such that extraction of various parameters, which are stored in different packages over time bases of years, would require a significant amount of time and a delay in reaction time for counter measures every time an analysis would need to be carried out.

![Diagram](image)

Figure 1: The XMM Early Warning System provides easy access to daily spacecraft monitoring and detects non nominal behavior of components
XEWS is making use of modern storage and data analysis systems developed by ESOCs Future Studies Section in combination with various data analysis scripts using idl® as baseline developed by the Flight Control Team (FCT). Figure 1 describes the setup of XEWS. The core of XEWS is a MySQL database that has been populated with all spacecraft housekeeping data since the beginning of the mission, however already extracted in parameter values. This has been done using the MUST® software. The import of spacecraft data into the MySQL-MUST database for new live data is continued as well on a near-real-time basis. The MUST database can be accessed using various interfaces, graphical as well as automated scripts. Since the total number of S/C parameters is of the order of 15000 it is not possible to monitor every individual parameter on a regular basis. However we provide on a regular basis plots of the evolution of a subset of parameters, which are transferred automatically to a web site and can be checked if needed.

In order to detect non-nominal behavior, however, we use on top the NOVELTY® system that can detect even for temporally variable parameters changes to their global behavior. NOVELTY analyses all spacecraft data on a regular basis and outputs a list of non-nominal behavior cases. This list is checked by XEWS web based scripts and a warning is sent to the Flight Control Team. Having received a warning any FCT member can immediately check on a web page the flagged parameter evolution over the last week/month/year. In case further analysis is needed the MUST database can now be used for detailed analysis.

One step further is the “Intensive Care Section (ICS)”: has a parameter been identified to be non-nominal it enters the ICS. Here special data analysis scripts, tailored to the individual case, perform daily analysis with a plot output to the web and an email trigger in case a certain health measure parameter exceeds a limit.

During the development of XEWS we spotted a strange behavior of one of our four reaction wheels. First thinking of a S/W feature in our system it turned out that one respectively two of the XMM-Newton reaction wheels show a non-nominal behavior already since 2008, respectively 2012 that was not spotted by the standard out off limit system of the Mission Control System.

![Figure 2: Example of a set of parameters that are automatically plotted on a regular basis for a weekly, monthly and yearly evaluation](image-url)
III. The XMM-Newton Reaction Wheels and their usage in AOCS

A. General description of XMM-Newton’s AOCS

The Attitude and Orbit Control System (AOCS) provides 3-axis stabilisation during all modes. The AOCS architecture is formed around the Attitude Control Computer (ACC), running the software for mode control and the attitude and thrust control laws. The AOCS uses the Star Tracker and Fine Sun Sensor to provide the absolute reference. The star tracker is a small telescope with 3 deg on Z and 4 deg on Y field of view and a thermoelectrically cooled CCD detector. The Fine Sun Sensors deliver pitch and roll information and their field of view is ±45° per sensor. Reaction wheels are the primary actuators for attitude control. Any 3 out of 4 reaction wheels can be used for active control, each one with a net torque of 0.2 Nm and 40 Nms momentum capacity. The reaction wheel that is not used for active control usually is off and is used as cold redundancy unit.

During eclipses, the roll reference from the sun sensor is obviously not available, so it is replaced by rate information from a gyro. The star tracker continues to supply pitch and yaw reference. Whilst eclipses generally occur at low altitude where radiation levels are high, it is expected that without special measures, single event upsets may frequently disturb the star tracker output. Therefore the star tracker has memory error detection and correction and uses sophisticated software filters to avoid loss of its guide star. Also, the redundant computers have memory error detection and correction as a precaution against the radiation environment.

B. The Reaction Wheel Unit

The RWU, made by MMS Stevenage, consists of a Wheel Drive Electronics (WDE) and 4 Reaction Wheel Assemblies (RWA’s) plus the four brackets, which support the RWA’s at the required orientation relative to the spacecraft axes.

The WDE is a four channels transformer that converts MACS Bus commands from the AOCS computer into individual wheel currents as well as relaying back individual wheel status data. All four channels of the WDE are contained within a single enclosure but with the individual channels are electrically and mechanically isolated from each other to prevent the propagation of faults. A Reaction Wheel Assembly is a high inertia flywheel driven by a brushless DC motor that converts wheel current demands from the WDE into reaction torques, which are used to control spacecraft attitude. The rotor is contained within an evacuated enclosure to allow testing of the unit on the ground and also to provide protection of the bearings against contamination. The heart of the RWA consists of 2 angular contact bearings and an oil-impregnated reservoir, to provide lubrication for the lifetime of the RWA. The lubricant is oil type KG80. A bearing heater mounted in the shaft core is provided to control the temperature of the bearings. 11)

The baselined reaction wheels have the following characteristics:

a) 40 Nms nominal momentum capacity,

b) 0.235 Nm net torque capacity at zero speed,

c) Viscous friction increasing linearly from 0 at zero speed to ±0.035 Nm at maximum speed.

The wheels are mounted on the spacecraft service module in a tetrahedral configuration with the axis of symmetry along the spacecraft X-axis. Each wheel is canted at 60° to the spacecraft X-axis with one wheel in each of the +X+Z, -X+Y, -X+Z and -X-Y quadrants. 10)
IV. Wheel cage instability

A. Detection and typical cage instability case

During summer 2011 an anomalous behaviour was noticed on one reaction wheel of XMM-Newton: the current of RW1 sometimes during stable pointing showed a jump, with increased value of drawn current. Afterwards a cross check was made with the commanded torque. The commanded torque (ACC control “last commanded torque value”) showed the same behaviour of the current, it matched that pattern and confirmed the anomaly.

A typical example is the cage instability on DOY 202-203 (2011) where the S/C was in stable pointing, while performing a long observation (from 2011-07-21 | 01:59:45 to 2011-07-22 | 15:36:25). The torque and the current

![Figure 4 Upper panel: commanded torque of all three reaction wheels during a stable pointing (blue: RW1, green RW2, yellow RW3. The jumps in torque indicate that the RW1 is entering cage instability. Lower panel: The temperature of RW1 stops cycling when the wheel enters cage instability state and increases without heater power added to the system](image-url)
had several jumps to higher level. The nominal torque request has an average around 0.02 Nm while during the jumps the torque increases up to 0.038 Nm, for the same speed conditions. The same was seen on the Reaction Wheel LCL current with the nominal current level being in average at 0.53 A and during the jumps increasing up to 0.80 Amps. The reason for these jumps is a sudden increment of the bearing friction level. It has a small impact on the pointing only during the change in the friction level which is compensated within few ACC control cycles (every control cycle is 0.5 sec) by means of an increased value of the commanded torque and consequently of the commanded current. When the S/C is in stable pointing the commanded torque has to compensate the friction and the external torques, which give a long-term contribution and it is some orders of magnitude lower then the friction. We can approximate then the value of the ACC commanded torque with the value of the friction of the wheel. The friction and consequently the commanded torque during stable pointing vary with the wheel speed. The spacecraft does not have an on board friction estimator, so there is no direct telemetry of friction, but only for commanded torque. On top of that during nominal operations the reaction wheel unloading and the slews produce peaks of torque, typically at maximum torque (0.23 Nm). That’s why this problem was not easy to spot and was spotted much later then the original occurrence: it was masked by the maneuvers and by the wheel unloading.

We have noticed as well an increase in the RW1 temperature, which seems to be correlated to the jumps. The explanation is that the increased friction level heats up the wheel and therefor a temperature increase can be seen. During the anomaly the heater switches off and it does not cycle anymore, because it does not need to heat anymore. Whenever the friction goes back to nominal levels the temperature decreases and the heater starts to cycle again.

![Figure 5: Impact of cage instability on the pointing accuracy](image)

Upper: a spike on wheel speed while entering (left) and exiting (right) cage instability – amplitude 4 rpm
Lower: impacts on the guide star position (y-coordinate) while entering (left) and existing (right) cage instability – amplitude: 2.7 arcsec

The effects on the pointing during the change in friction are a peak in RW1 speed of 4.5 rpm and a consequent peak in the position of the Guide Star Y coordinate of 13 CCD units (around 3.2 arcsec, for the case of 2011-07-21 | 12:21:30) (See Figure 5). The ACC detects the increased error on the Guide Star and its control loop commands a higher level of torque, which increases the RW1 speed. The attitude is stabilized within 5 minutes. And the control loop becomes stable with a higher torque and current. This situation lasts until the friction level goes back to nominal values (the anomaly can sometimes last for hours), and when it returns nominal again the change of friction causes a small de-pointing, similar to the one described above. The described problem does have impact only on Y
Guide Star position, meaning that it causes a Yaw movement, but it has no impact on Z Guide Star position (no movement in Pitch).

At the end of the anomalous friction increment, there is a jump of the torque and current back to nominal values. The effect on the wheel speed described before is now inverted: the RW1 speed has an overshoot, with a peak on the opposite direction with respect to the previous one of the order of 4 rpm. In Figure 5 upper panel we show the wheel speed from 13:20h to 15:20h and the peak is marked. The effect is more evident in Figure 5 lower panel, which shows the Guide Star Y coordinate and its jump due to the return to nominal friction levels. In this case the effect on the pointing is an offset of 11 CCD units, meaning 2.7 arcsec.

B. Background on cage instability

Cage instability as well called “retainer instability” is a major cause of bearing failure in control moment gyroscopes, momentum wheels, and reaction wheels. It is a well-known phenomenon with bearings of rotating systems running in marginally lubricated regimes. The instability is caused by too much or too little oil and consists in a chaotic vibration of the cage (ball bearing retainer). The case of XMM-Newton, after many years in orbit can only be due to reduction in oil quantity. The mechanism of bearing cage instability triggers a series of events, which are consequences of lack of oil: the initial vibration causes increased friction, which is directly readable in telemetry as jump in commanded torque to the wheel. As we showed in the previous paragraph the bearing in this condition runs hotter, as the vibration produces heat. After some times of this vibration regime the oil lubricant gets thinner and gets ejected from bearing as micro droplets. As soon as the oil runs hotter it starts to degrade and the lighter fats boil off. This is a cyclic mechanism, where the oil degrades further until more complex parts boil off, and eventually it may lead to bearing failure.

The retainer or the “cage” for the ball bearings is usually made by a non-metallic cotton based phenolic material. It is initially impregnated with lubricant, but during the lifetime it absorbs a certain amount of oil, leading to oil starvation and triggering the phenomenon of cage instability. The lack of lubricant is also usually a consequence of lubricant breakdown due to chemical deterioration and of lubricant evaporation if the bearing runs at high temperature. The so-called “surface migration” is also possible, when in the bearing a thermal gradient is created and the oil migrates to colder regions.

The bearing cage instability can create the following dynamic conditions: a) Radial instability – consists in a high frequency radial vibration of the retainer and results in abrupt torque variation. Under marginal lubrication condition, this will cause significant torque increase and audible noise, while under excess lubrication it shows sudden reduction in torque. b) Axial Instability – caused by excessive distance between rolling element and retainer pocket. c) Position instability – occurs when retainer oscillates between its mean position of running and the races. Occasionally the retainer moves in the radial direction and rubs against the race. This results in a periodic change in friction torque.

C. Statistical analysis

We performed a statistical analysis to detect when the cage instability actually started and to measure if it gets stronger over time. For this we retrieved from the MUST database the parameters for the commanded torque since 2005 and filtered out periods where the AOCS system performs slews or Reaction Wheel Biases, since these data points would hide the cage instability effect. (It is not expected to see any onset on cage instability effect while a wheel is changing its speed.) For every month we sorted torque data for every wheel into a histogram, where a wheel without cage instability will show a Gaussian-like distribution of torque values with a maximum at the most frequent torque value. A wheel that suffers from cage instability will show a second peak centered on the torque value that is needed to keep the required wheel speed during stable pointing. Figure 6 shows two cases for such an analysis, where the first case from March 2006 is not showing cage instability and the second case of November 2011 a strong case of cage instability. Appendix B shows the full analysis for every month between 2000 and 2011. It can be clearly seen that the second peak starts to appear in 2008 and is present since then for RW1. For RW2 we see only little effects of the order of 5% since 2011.
To clearly determine the onset of the cage instability we fitted a Gaussian profile to every monthly distribution for wheel 1 and determined the maxima and centroids of the Gaussian fits as well as the integral below the individual curves. Plotting now the ratio of these 3 parameters for the non cage instability and the cage instability peaks gives a clear indication of the onset of the effect and two additional measures: the ratio of the maxima, respectively the ratio of the integral of the two peaks translates into the amount of cage instability, whereas the ratio of the centroid of the peaks determines the strength of the cage instability effect, or the amount of additional torque that is needed to stay at the same speed. Figure 7 summarizes the full analysis from 2005 to 2011. The ratio of the integral seems to be a more reliable figure, since the fits are sometimes not accurate enough when the cage instability peak is not separated clearly. However our aim is not to measure the cage instability abundance to a high accuracy, rather to determine trends. For this reason we show both the ratio of the maxima and the ratio of the integral in Figure 7.

A further analysis has been carried out by repeating the above but on a yearly not monthly histogram basis. This results in better statistics to determine the abundance of cage instability per year. Figure 8 shows the distribution of torques for wheel 1, 2 and 3 depicted in yearly graphs since 2006. The amount of cage instability determined from the ratio of the integrals of the torque distribution peaks is printed on the plots as ratio.

Figure 6: Torque distribution of the three reaction wheels over one month. Black: wheel 1, blue: wheel 2, red: wheel 3. The green and light blue lines are Gaussian fits to wheel 1 data. Left: no cage instability is seen (2006 March). Lower: The second peak shows clear cage instability of wheel 1 during this month. (2010 November)

Figure 7. Evolution of cage instability for wheel 1: the middle panel shows the indicators for the strength of the cage instability (light blue stars), and the abundance (dark blue (peak position ratio) and green (integral-ratio)).
Correlating the needed torques to satisfy a certain wheel speed requirement gives further insight into the cage instability situation. This method can as well be used to detect caging in real time - A clear advantage in comparison to the statistical method. A pure correlation of the wheel speeds with the commanded torques can be used in combination with the theoretically needed torques to produce a certain wheel speed. Subtracting the model torque value from the real one should give a value around 0. Is the value significantly different from that a clear indication for cage instability is given. To verify this method we produced torque wheel correlations subtracting the theoretically required torque from the actual one as a function of wheel speed.

Figure 6 shows the evolution of cage instability over 6 years for wheel 1. The percentage of cage instability varies between 0 and ~24 % (2010).

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Figure 9 shows the evolution of this value over time and clearly indicates cage instability for wheel 1 already as of 2007 and for wheel 2 as of 2009. This method can as well be used to detect live cage instability (see section F).

Figure 7 shows the evolution of commanded minus predicted absolute torque as a function of wheel speed from 2006 until 2011 for wheel 1 (black), wheel2 (blue) and wheel 3 (red). The cage instability shows up as branches. Note the slope offset for wheel3 (red) in 2006-2009 is not due to cage instability and currently under investigation.
D. Short term mitigation

The quickest mitigation for the problem of the bearing cage instability was to switch off the RW1, and reconfigure the AOCS for a different configuration of active wheels (i.e. RW 2-3-4). This was as well the recommendation from industry. A series of activities was performed to evaluate the feasibility of the operation and the impact on the Mission. In parallel a nominal procedure to reconfigure active RW in Thruster Controlled Mode from 1-2-3 to 2-3-4, and two contingency procedures to reconfigure in case of problems during the operation were prepared, reviewed and tested with the simulator. RW4 was initially spun up and checked for 1h and 30min and since the health check of RW4 was ok, ACC Word B was reconfigured to select RW1 inactive and the RW1 LCL was switched off, letting the RW1 drifting down by natural friction. The drift down was performed in TCM, allowing a drift down time of 2h, which included some safety margins. After a reconfiguration of the nominal AOCS parameters, the entry in Inertial Pointing and Slew Mode (IPS) was commanded and the S/C was controlled with the new RW 2-3-4 set.

In order to save fuel, the spin up of RW4 was done using the null-space principle, such that the other wheels compensated for the change in the angular momentum. With this approach the total angular momentum does not change and the thruster actuation in TCM Stage 2 is close to zero.

The new wheels configuration will be kept until the re-lubrication of RW1 will take place (see section E, F).

E. Possible cure

The bearing unit of the reaction wheels is made of steel ball bearings having non-metallic retainers (cages), usually made of phenolic resin filled with cotton fabric. These cages are impregnated, on ground, with liquid lubricant and are the main source of lubrication during the first few years in the lifetime of the bearing. On the other hand they are also the principal lifetime limiting factor of the reaction wheels as soon as due to lubricant loss the well-known cage instability effect occurs. In order to prolong the mission’s life and to preferably avoid this unwanted effect onboard lubrication systems have been developed.

On XMM-Newton a static oil reservoir is foreseen for in-situ lubrication. This reservoir is mounted on the static part of the bearing unit. It consists of a cylindrical porous material reservoir surrounded by an aluminum sleeve. Incorporated into the aluminum sleeve there is a heater that on demand heats up the oil inside the reservoir. Due to the different thermal expansion factors, of aluminum and the porous reservoir, oil is pressed out. The oil gets to the cages and the ball bearings by surface migration and vapor condensation.

When using this method of re-lubrication the heater activation time has to be progressively increased after each operation to press out each time the same quantity of oil from the reservoir.

F. Outlook

Currently we are investigating with industry a strategy for the re-lubrication and further operations of the reaction wheels. We expect to carry out a first re-lubrication exercise in 2012 for RW1 with an evaluation phase of one month. After that time reaction RW2 would be re-lubricated.

If the re-lubrication exercise was not fully successful we consider using the above study to define speed ranges that are most probable to show cage instability and avoid those for stable pointing in the mission planning.
Furthermore we are investigating the potential of the new Attitude and Orbit Control System mode\(^5\) that would allow us to slightly change the wheel speed of one of the wheels during stable pointing without the need to stop the observation. This feature could be used to ‘de-cage’ a wheel, which shows cage-instability, since we believe that the chaotic resonance of the cage would be stopped by a little change in speed and the wheel would go back to nominal behavior. This could be done automatically from ground using an algorithm to detect the caging on the basis of the analysis described in section III.C by calculating the theoretical torque and compare it to the actual commanded one. Such an OOL has been already implemented on the Mission Control System and is able to detect a cage instability within some minutes.

G. INTEGRAL

The same analysis has been carried out for INTEGRAL with the result that none of the INTEGRAL wheels shows cage instabilities so far. Figure 11 shows the INTEGRAL case equivalent to Figure 8 for the XMM case.

A plausible reason why the cage instability is present on XMM and not on INTEGRAL could either be the age of the reaction wheels (INTEGRAL wheels are 3 years younger) or the fact that INTEGRAL has more slews and maneuver. So far we see the caging instability only starting during a stable pointing, i.e. during periods where the wheels spin at constant speeds.

\[\text{Figure 9: For INTEGRAL the same analysis as Figure 8 for XMM does not show any indication of cage instability}\]

V. Conclusion

ESA’s X-ray cornerstone mission XMM-Newton is operating in its 13th year. As of 2008 a cage instability is present for wheel one with an mean abundance of \(~20\%\). As of 2011 the effect has been seen as well on wheel two but with a lower abundance of \(~5\%\). Since December 2011 wheel one has been replaced by the redundant wheel four in the control loop awaiting now a re-lubrication procedure that may cure the effect. Investigations are as well underway how to cope with the effect in case the re-lubrication exercise would not be fully successful; an option is to use the statistical analysis of this paper to define operations of the wheels outside the regions of maximum cage instability (below a certain to be defined wheel speed), an other option is to use a delta torque measurement to detect cage instability and future new mode of the AOCS system to perform active de-caging. The first re-lubrication exercises are planned for autumn 2012.

Furthermore the described XEWS system is put in place to detect early degradation of spacecraft components in order to be able to develop counter measures as soon as a small degradation is actually detected.
Appendix A
Acronym List

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<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>ACC</td>
<td>Attitude Control Computer</td>
</tr>
<tr>
<td>AOCS</td>
<td>Attitude and Orbit Control System</td>
</tr>
<tr>
<td>ESOC</td>
<td>European Space Operations Center</td>
</tr>
<tr>
<td>FCT</td>
<td>Flight Control Team</td>
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<tr>
<td>IPS</td>
<td>Inertial Pointing and Slew Mode</td>
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<tr>
<td>MCS</td>
<td>Mission Control System</td>
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<tr>
<td>RW</td>
<td>Reaction Wheel</td>
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<td>RWA</td>
<td>Reaction Wheel Assembly</td>
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<td>RWB</td>
<td>Reaction Wheel Bias</td>
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<td>WDE</td>
<td>Wheel Drive Electronics</td>
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<td>TCM</td>
<td>Thruster Controlled Mode</td>
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<td>XEWS</td>
<td>XMM Early Warning System</td>
</tr>
<tr>
<td>WDE</td>
<td>Wheel Drive Electronics</td>
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The XMM-Newton project is an ESA Science Mission with instruments and contributions directly founded by ESA Member States and the USA (NASA).

References

1) M. G. F. Kirsch et al., these proceedings, Synergy of operations of ESA's high energy astrophysical missions
3) Christoph Winkler, INTEGRAL Overview, Policies and Procedures, Issue 1.0
4) Marcus G. F. Kirsch et al., 2010, SpaceOPS proceedings, XMM-Newton, ESAs X-ray observatory, the Loss of Contact Rescue and Mission Operations ready for the next decade
5) M. Pantaleoni et al., these proceedings,
6) idl data analysis software, http://www.exelisvis.com
8) Martinez-Heras et al. these proceedings, New Telemetry Monitoring Paradigm with Novelty Detection
Appendix B: Overview of monthly histograms

<table>
<thead>
<tr>
<th>Month</th>
<th>January</th>
<th>February</th>
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2000 - 2011