XMM-Newton Calibration Technical Note

Seasonal pulse profile distortions in the EPIC-pn timing observations of the Crab pulsar

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1 Introduction

This technical note contains information on the investigation that was carried out in order to find a suitable explanation for the distortions in the pulse profile of the Crab pulsar observed in the routine calibration observations performed with EPIC-pn in Timing mode during the Autumn season.

2 Seasonal distortions in the pulse profile of the Crab

The Crab pulsar is observed twice yearly with EPIC-pn in both Timing (TI) and Burst (BU) modes as part of the routine observations to calibrate the XMM-Newton relative and absolute timing capabilities. These observations are typically performed ∼6 months apart around February-March, and August-September. In what follows we will label these periods as "Spring" and "Autumn", respectively.

These calibration observations were processed using SAS 15.0 and CCFs as of September 2015 (with the exception of the ObsIDs 0611183001, 0611183101, and 0611183201 which used CCFs as of March 2016) using the following call:

```
epproc timing=YES burst=YES srcra=83.633216667 srcdec=22.014463889 withsrccoords=yes
```

Here the X-ray loading correction `runepreject=yes withxrlcorrection=yes` is implied through the `withdefaultcal=yes` setting. No selection was made based on the XMM-Newton orbital phase.

Pulse profiles for each observations were made with the XRONOS tool `efold`, and their plots were normalized to the inter-pulse minimum. A summary of the calibration observations used can be found in Tables 1 and 2.

It has been observed that the pulse profile of the Crab observed in TI mode shows systematic differences between the Spring and Autumn observation, whereas in the BU mode data no significant differences are seen between both epochs. The TI mode Spring observations are very

Table 1: Observation log of the calibration observations of the Crab taken in Timing mode.

Mode	Revolution	ObsID	Exposure (s)	Season	Comments
Timing	0056	0122330801	22579	Spring	
Timing	0411	0153750401	9034	Spring	
Timing	0698	0160960201	28299	Autumn	
Timing	0700	0160960301	10208	Autumn	
Timing	1048	0160961001	5028	Autumn	
Timing	1049	0160961201	5029	Autumn	
Timing	1140	0160961401	5012	Spring	
Timing	1249	0412590201	5053	Autumn	
Timing	1325	0412590601	5059	Spring	
Timing	1414	0412591101	5021	Autumn	
Timing	1504	0412591501	7654	Spring	
Timing	1600	0412592001	6057	Autumn	
Timing	1687	0412592501	4562	Spring	
Timing	1797	0412593101	3654	Autumn	
Timing	1872	0611180201	3658	Spring	
Timing	1964	0611180501	5662	Autumn	
Timing	2058	0611180801	3163	Spring	
Timing	2150	0611181001	5391	Autumn	
Timing	2150	0611181101	4257	Autumn	
Timing	2236	0611181401	5660	Spring	
Timing	2329	0611181601	4105	Autumn	
Timing	2419	0611181801	4957	Spring	
Timing	2515	0611182001	6499	Autumn	
Timing	2607	0611182201	4698	Spring	
Timing	2713	0611182401	15924	Autumn	
Timing	2788	0611182601	5497	Spring	
Timing	2879	0611182801	5499	Autumn	
Timing	2969	0611183201	6754	Spring	
Timing	2969	0611183001	6884	Spring	NRCO
Timing	3065	0611183401	17658	Autumn	

Table 2: Observation log of the calibration observations of the Crab taken in Burst mode.

Mode	Revolution	ObsID	Exposure (s)	Season	Comments
Burst	0234	0135730701	10000	Spring	
Burst	0874	0160960401	14717	Autumn	offset
Burst	0874	0160960601	3985	Autumn	offset
Burst	0955	0160960701	8227	Spring	
Burst	0955	0160960801	5024	Spring	
Burst	0955	0160960901	8224	Spring	
Burst	1049	0160961101	5033	Autumn	
Burst	1138	0312790101	42525	Spring	
Burst	1138	0312790201	5028	Spring	offset
Burst	1138	0312790401	7802	Spring	offset
Burst	1140	0160961301	5001	Spring	
Burst	1140	0160961501	6703	Spring	
Burst	1249	0412590101	6403	Autumn	
Burst	1249	0412590301	8853	Autumn	
Burst	1325	0412590701	8860	Spring	
Burst	1414	0412591001	13206	Autumn	
Burst	1414	0412591201	13405	Autumn	
Burst	1504	0412591401	21704	Spring	
Burst	1504	0412591601	20204	Spring	
Burst	1600	0412591901	5804	Autumn	
Burst	1600	0412592101	15391	Autumn	
Burst	1687	0412592401	18910	Spring	
Burst	1687	0412592601	18234	Spring	
Burst	1797	0412593001	10204	Autumn	
Burst	1797	0412593201	6420	Autumn	
Burst	1872	0611180101	9704	Spring	
Burst	1872	0611180301	19204	Spring	
Burst	1964	0611180401	8203	Autumn	
Burst	1964	0611180601	14740	Autumn	
Burst	2058	0611180701	6204	Spring	
Burst	2058	0611180901	14307	Spring	
Burst	2150	0611181201	7956	Autumn	
Burst	2236	0611181301	5808	Spring	
Burst	2236	0611181501	19007	Spring	
Burst	2329	0611181701	20185	Autumn	
Burst	2419	0611181901	19301	Spring	
Burst	2515	0611182101	15070	Autumn	
Burst	2607	0611182301	16371	Spring	
Burst	2713	0611182501	22263	Autumn	offset
Burst	2788	0611182701	15217	Spring	
Burst	2879	0611182901	18944	Autumn	
Burst	2969	0611183101	10779	Spring	
Burst	3065	0611183301	8802	Autumn	

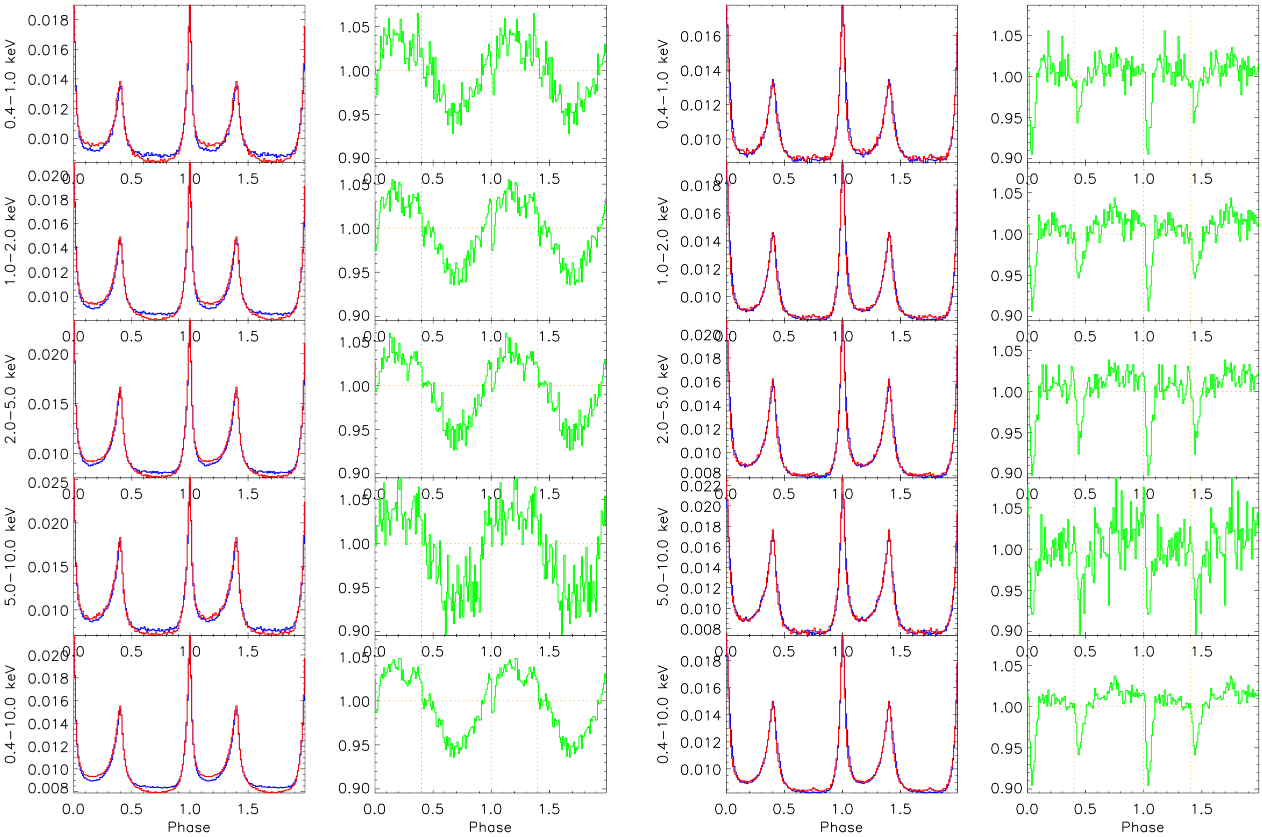

Figure 1: Pulse profiles and ratios of the TI (left panel) and BU (right panel) observations of the Crab taken in the Spring (blue) and Autumn (red) seasons. See details in the text.

similar to the BU mode profiles, as expected, but the Autumn TI mode profiles are anomalous, showing an excess in counts in some of the valleys between peaks and a deficit of counts in others, as shown in Figs. 1 and 2.

Fig. 1 shows the pulse profile in TI and BU modes for the Spring and Autumn season observations, as well as the normalized ratios between seasons for each mode for different energy ranges. In these ratios each pulse profile is normalized by the total number of counts, which is proportional to the overall exposure time, so that only distortions in the shape of the profile are highlighted. The observed anomaly is thus clearly seen in the normalized ratio TI Autumn/TI Spring, with deviations of ∼5% of the former with respect to the latter. The pulse profiles BU mode in Autumn and Spring are virtually the same. Likewise, in Fig. 2 we show the ratio between modes in a given season, with similar results as in Fig. 1: significant deviations are seen in the ratio TI Autumn/BU Autumn, while none are found in the TI Spring/BU Spring ratio.

3 Investigation of the pulse profile anomaly

In order to find an explanation for the origin of the pulse profile anomaly in the Autumn observations of the Crab in TI mode, we investigated different possibilities described below.

3.1 Change in position angle

Because of the observing constraints, the Spring and Autumn observations are rotated in position angle (PA) by 180 degrees. Given the asymmetry in the physical extent of the nebula, its

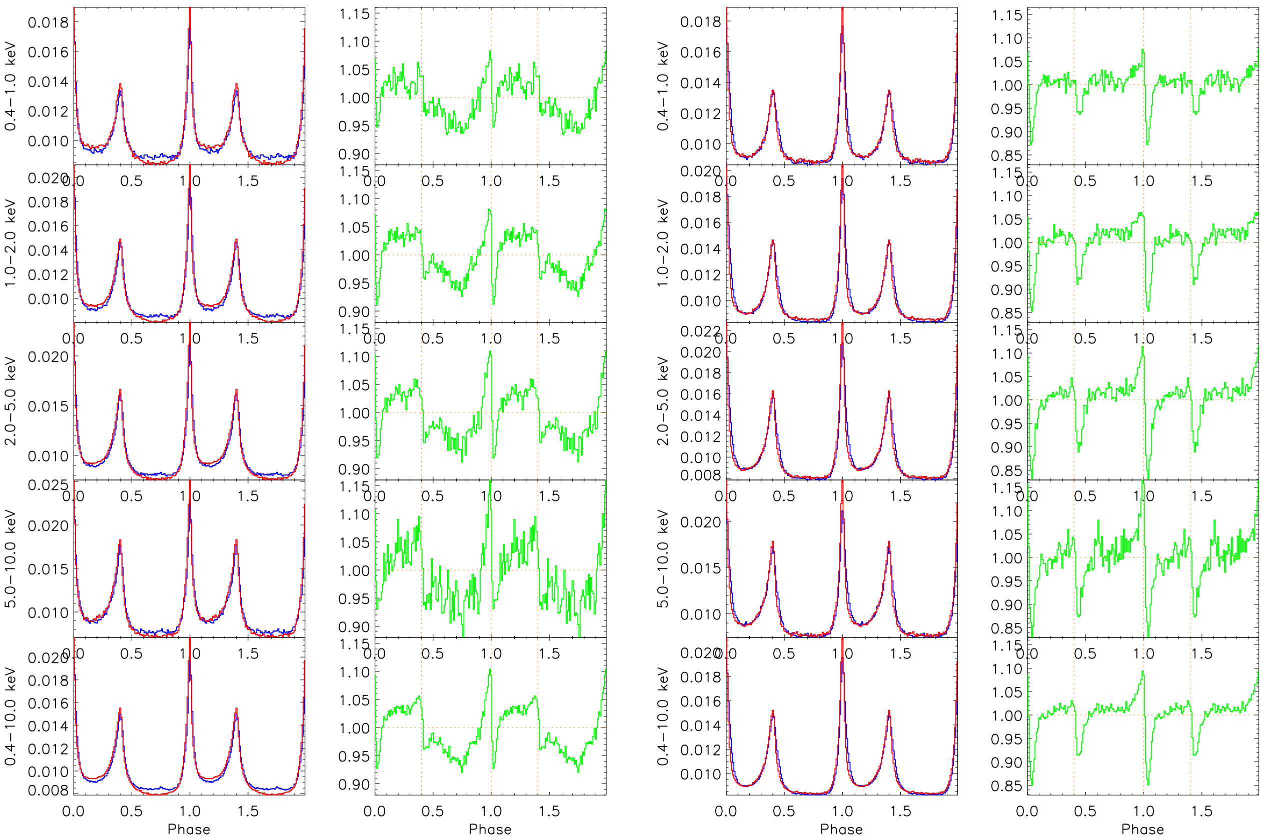

Figure 2: Pulse profiles and ratios of the observations of the Crab taken in the Autumn (left panel) and Spring (right panel) seasons in both TI (red) and BU (blue) modes. See details in the text.

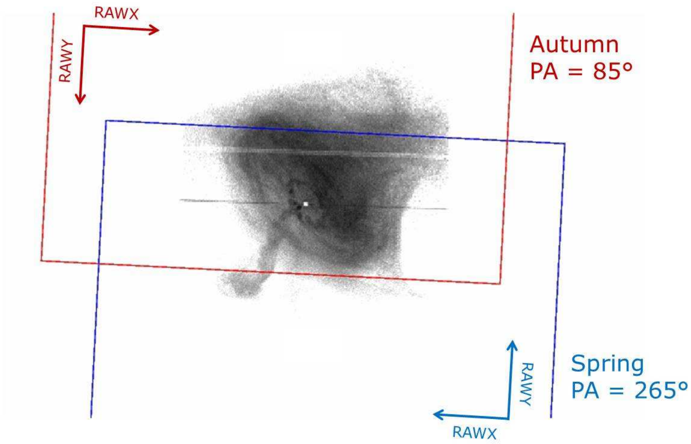

Figure 3: EPIC-pn field of view (FOV) in the Spring (blue; PA = 265 degrees) and Autumn (red; PA = 85 degrees) observations of the Crab.

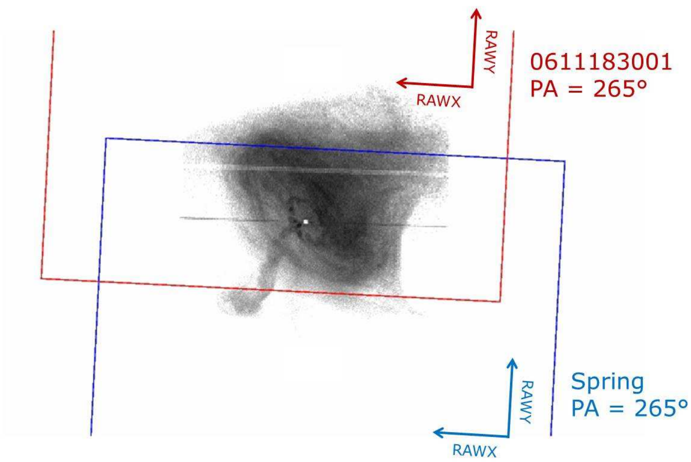

Figure 4: EPIC-pn field of view (FOV) in the regular Spring observations (blue; PA = 265 degrees) and in the NRCO observation in Spring 2016 (red; PA = 265 degrees) of the Crab.

coverage within the detector will differ between these two seasons (see Fig. 3). In principle it would be possible to determine whether the differing pulse profile is due to the varying coverage by replicating e.g. the autumn coverage in the spring.

To this end an additional TI mode Non-routine Calibration Observation (NRCO) was performed in Spring 2016 with a pointing offset in order to obtain an identical coverage as in the Autumn observations, but with the PA constrained to that of spring (ObsID 0611183001). The pointing offset resulted in the source not being located at the nominal aim point, but close to the readout of the detector (see Fig. 4).

Due to the similar coverage of the remnant in this NRCO and Autumn observations, the expectation was for the NRCO to replicate the autumn pulse profile, if the differing coverage of the nebula was the source of the pulse profile anomaly. However, the resulting NRCO profile was more similar to the spring profile than to the autumn profile (see Fig. 5). While this would suggest that the different nebula coverage between seasons is not the main cause of the differing pulse profiles, a caveat described in Sect. 3.2 may prevent us from entirely ruling out this explanation.

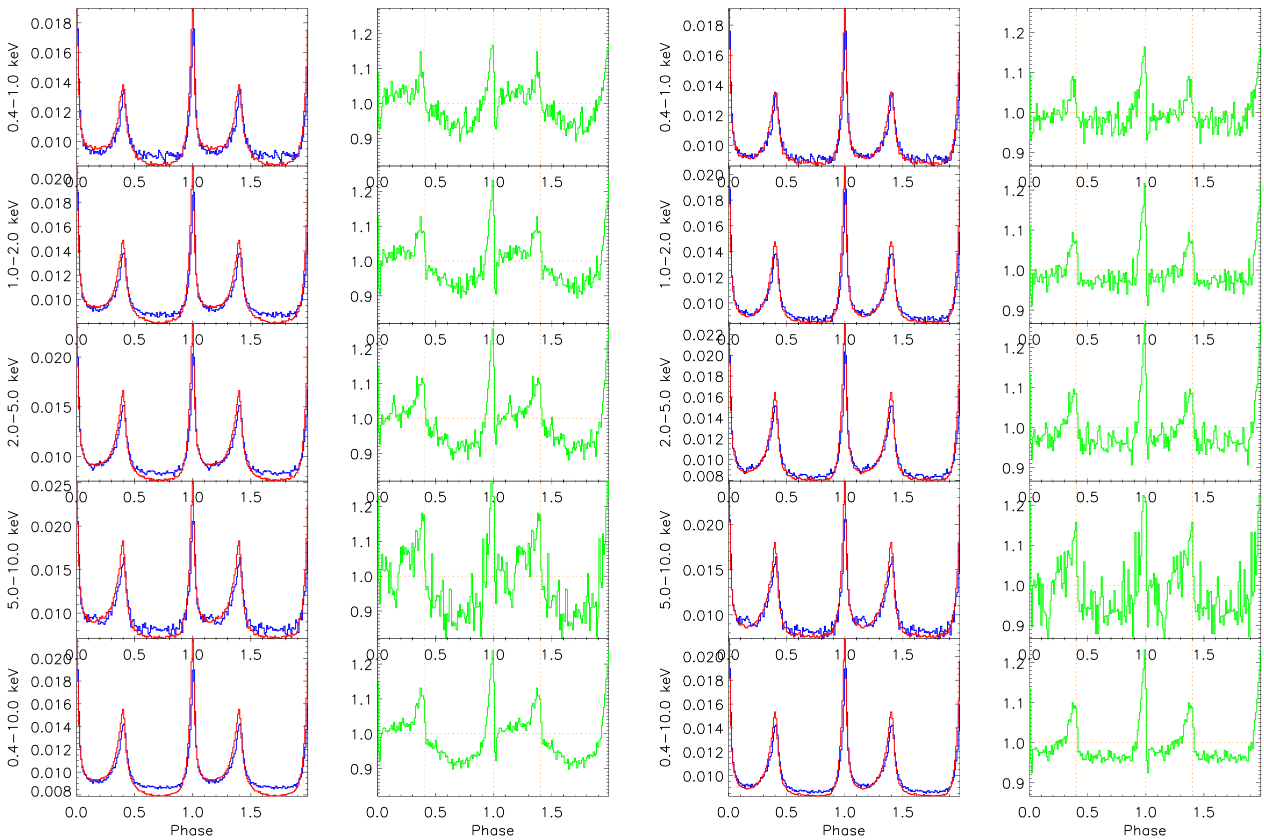

Figure 5: Pulse profiles and ratios of the observations of the Crab taken in TI mode in the Autumn (left panel) and Spring (right panel) (both in red) compared to the NRCO in Spring 2016 (blue).

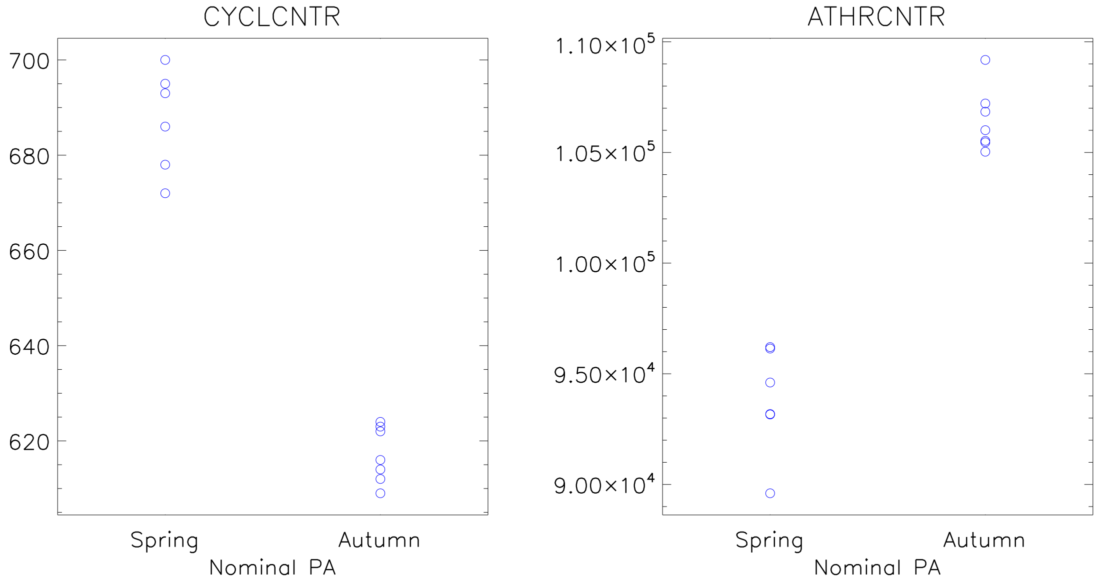

Figure 6: CYCLCNTR (left panel) and ATHRCNTR (right panel) values for TI mode observations performed in Spring and Autumn, respectively.

3.2 Housekeeping parameters

We also investigated the behaviour of some housekeeping parameters, looking for seasonal dependence that may explain the abnormal profiles. For this we investigated the following counting cycle report housekeeping parameters:

- CYCLCNTR: Number of rejected read-out cycle counters
- ATHRCNTR: Cumulative ATHR counters

Both parameters showed a seasonal dependence in TI mode (see Fig. 6). For BU mode, the instrument does not in general enter into counting mode and hence these parameters are not recorded.

For TI mode, the CYCLCNTR parameter shows systematically higher values in the spring configuration with respect to those in the autumn, whereas the ATHRCNTR shows the opposite behaviour.

Additionally the following event header keywords were also investigated:

- FIFOLOSS: Exposure loss due to FIFO AUX2 overflows
- FIFOOVER: Number of FIFO AUX2 overflows
- FIFODEFI: Number of FIFO AUX2 deficiencies

In Fig. 7 we show the evolution of FIFOOVER and FIFODEFI throughout the different calibration observations up to spring 2016 (FIFOLOSS is not shown as it is a scaled version of FIFOOVER). As expected, TI mode observations are subject to a substantial number of FIFO overflows, almost three orders of magnitude more than the number of FIFO overflows in BU mode. The number of FIFO deficiencies has the same behaviour as the FIFO overflows, being both parameters anti-correlated.

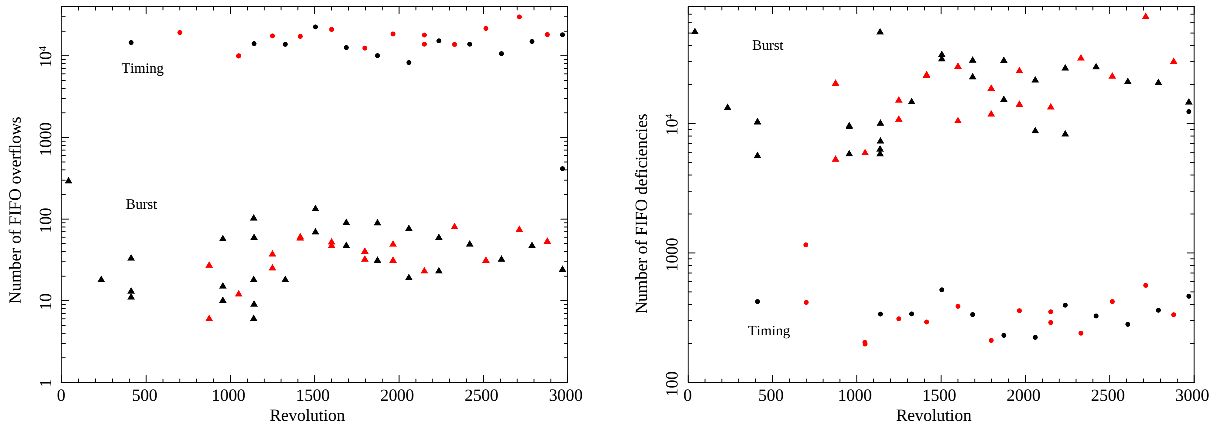

Figure 7: Number of FIFO overflows (left panel) and FIFO deficiencies (right panel) as a function of XMM-Newton's Revolution for observations in TI mode (dots) and BU mode (triangles). The observations performed in Spring are coloured black, whereas those performed in Autumn are coloured red.

At first sight no seasonal dependence is observed, as the number of FIFO overflows in Spring (black symbols in the plot) and Autumn (red symbols) seem to scatter around the same mean value. However, the average number of FIFO overflows in the observations in TI mode taken in Spring is ∼18% lower than those taken in Autumn (14050 versus 17226, respectively). On the other hand, for BU mode exposures the average number of FIFO overflows in both seasons is the same (43 and 41 in spring and autumn, respectively). This is more clearly seen when we normalize the number of FIFO overflows by the exposure time of each observation, as taken from the `EXPOSURE` parameter (see Fig. 8). In this figure it is observed that the normalized number of FIFO overflows is systematically higher in Autumn than in Spring for the observations taken in Timing mode. For the Burst exposures the scatter of the Spring and Autumn observations is similar, with no clear trend in either season.

It is also noted that the NRCO observation of Spring 2016 in revolution 2969, shows a factor of ∼35 fewer normalized overflows than the average for the other calibration observations in TI mode (see Fig. 8), although this has not a measurable effect on the pulse profile. This decrease (and the corresponding measured decrease in flux) is explained by the location of the source in the CCD, closer to the detector readout (see Sect. 3.1). One effect when moving the source towards the Camex (read-out) is that the effective area decreases due to mirror vignetting, but in addition the counts are also spread over a larger region (and thus reducing pile-up in a certain pixel) and therefore also reducing the count rate as some more counts fall outside of CCD4 to `RAWY`<0 than otherwise to `RAWY`>200.

The observed seasonal distortions are most likely produced by these FIFO overflows, that occur more often during the Autumn observations. Their net effect is the loss of counts at different phases of the pulse profile of the Crab which ultimately cause the observed profile anomalies. The explanation for the seasonal behaviour of the overflows lies on the different number of counts gathered on-board due to the different coverage of the nebula between Autumn and Spring.

In Fig. 3, where we can see the different FOV covered by *XMM-Newton* in both seasons, it is shown that during the Autumn observations most of the nebula surrounding the Crab pulsar is within the FOV whereas in the Spring observations a fraction of the nebula is left out. This translates in a difference in the number of counts gathered on board and hence in the measured count rate, which is seen in Fig. 9. Using the Burst mode observations as a proxy for the total number of counts acquired by *XMM-Newton*, one can see that the count rate in the Autumn observations is ∼ 10% higher than that of the Spring observations. Higher count rates mean a

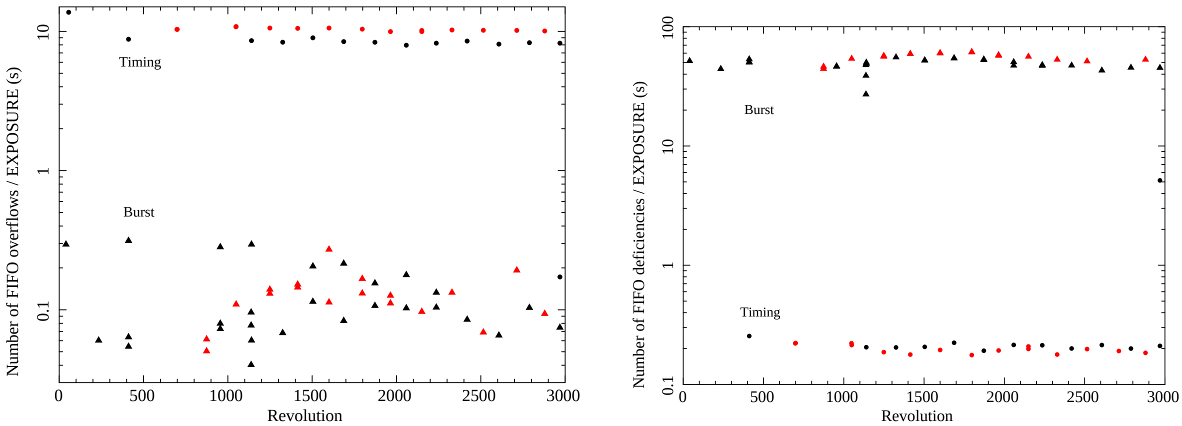

Figure 8: Number of FIFO overflows (left panel) and FIFO deficiencies (right panel) normalized by the exposure time (in seconds) as a function of XMM-Newton's Revolution for observations in TI mode (dots) and BU mode (triangles). The observations performed in Spring are coloured black, whereas those performed in Autumn are coloured red.

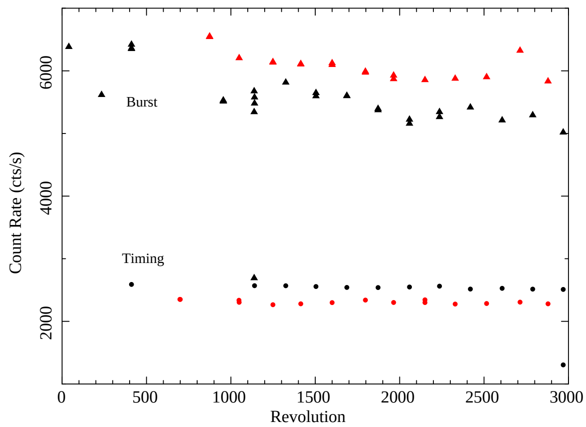

Figure 9: Count rate of the Crab as a function of XMM-Newton's Revolution for observations in TI mode (dots) and BU mode (triangles). The observations performed in Spring are coloured black, whereas those performed in Autumn are coloured red.

higher number of FIFO overflows produced on-board in the Timing mode observations and thus a net loss of counts for the Autumn observations in this mode. The observed seasonal pulse profile anomaly is therefore produced by a combination of the different coverage of the target and the large amount of FIFO overflows produced on-board because an inappropriate setup of the EPIC-pn camera (Timing mode instead of Burst). This effect was effectively washed out in the NRCO observation due to the loss of counts (more than $\sim 40\%$) due to vignetting described above.

While this effect seems to have little effect in the overall timing capabilities of *XMM-Newton* (see EPIC calibration status document, CAL-TN-0018[1]), it stresses the fact that for very bright sources, like the Crab, the preferred setup for the EPIC-pn camera should be Burst rather than Timing mode.

[1] http://xmm2.esac.esa.int/docs/documents/CAL-TN-0018.pdf

4 Summary

We have conducted an investigation in order to explain the seasonal distortion in the pulse profile of the Crab observed in the routine calibration observations in Timing mode performed in the autumn seasons with respect to those performed in Spring and those in Burst mode for both seasons. We looked at the different FOV covered by *XMM-Newton* between both seasons as well as the values of different housekeeping parameters, some of them showing a clear seasonal dependence in the Timing mode observations. In particular, the number of FIFO overflows is systematically higher in the Autumn observations of the Crab taken in Timing mode with respect to the values recorded for the Spring observations. No seasonal dependence is seen for this parameter in the Burst mode observations.

These FIFO overflows are generated on-board because of the large number of counts collected, which cannot be handled appropriately in Timing mode producing a net loss of counts in different phases of the pulse profile and thus creating the observed distortions. The seasonal appearance of this behaviour is due to the different coverage of the nebula surrounding the Crab pulsar. A combination of both effects is the most likely explanation for the seasonal pulse profile anomaly, which seems to have little or no impact in the overall timing capabilities of the satellite. It is therefore stressed that for very bright sources such as the Crab, the preferred instrumental setup for the EPIC-pn camera should be Burst instead of Timing mode.