LYRA Calibration now based on First Light Day

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1. Initial Problems

The first major calibration attempt is described here:
http://solwww.oma.be/users/dammasch/IED_20090616_Calibration_Methods.pdf
It was based on the idea of simulating the expected LYRA output with the aid of the response curves measured in the laboratory and a small set of solar spectra observed by other space instruments from solar maximum (incl. X-flares) to solar minimum. It was assumed that the relationship between solar input and LYRA output simulated before launch could be used for calibration, once that LYRA was in space. Unfortunately, this was not the case. There were three difficulties:

(1) LYRA nominal spectral intervals were defined for each of the four channels. Channel 1 (Lyman-alpha) was supposed to be around the H I (121.6 nm) line. But the detector-filter combination was also responding to other spectral intervals such that its "purity" - defined as the ratio between nominal signal and total signal - was only around 30%. Since the total signal – with approx. 70% coming from near ultraviolet or even visible or infrared - does not display a high relative variation, not even to flares, a small miscalculation of the expected signal leads to large errors in the estimation of the nominal signal. The same holds for channel 2 (Herzberg). Although in this case the expected purity was higher – around 80% - the surrounding continuum rises vary fast on the long-wavelength side of the nominal interval and therefore, again, small miscalculations of the expected signal can lead to large errors. The response curves of channel 3 (Aluminium) and channel 4 (Zirconium) lead to other complications; since they have a relatively high response in the soft X-ray range below 5 nm or below 2 nm, respectively, their purity and thus their calibration function depends on the strength of the signal, i.e., flare or non-flare situation.

(2) From the very first hours after the covers had been opened, LYRA faced a severe degradation; the signal in some channels fell by 30-50% within the first month alone. Therefore, it was not possible in the long range to compare and calibrate LYRA with other instruments without taking the degradation into account. This, in turn, meant that the degradation had to be separated from the solar variation.

(3) It was originally planned to measure the dark currents on a regular basis, immediately before the covers were opened for solar observations. This implicitly assumed that the dark currents stay constant during the time of observation, which – as it turned out – they do not. In fact, the dark currents for some channels were highly dependent on the on-board temperature, which in turn changed with the spacecraft's orbit around the Earth, and with on-board variations like the operation of other components. In other words, the dark currents had to be estimated continuously, without actually being able to measure them, covers being open.

One intermediate approach to fight the degradation problem was to compare LYRA to other instruments (TIMED/SEE and SORCE/SOLSTICE) on a day-to-day basis. This was soon given up for various reasons: The values of the other instruments were not immediately available, the degradation could not effectively be separated from the solar variation, the calibration functions appeared to vary over time, and – generally – such a high dependency on other instruments was not desired.

2. Possible Solutions

In order to solve the problems mentioned above, several assumptions have to be made.

(1) Instead of arbitrarily defining nominal intervals, the effective spectral intervals as measured in the laboratory tests must be used. Calibrated values for the initial "nominal" intervals have to wait until later, i.e., when more

experience with the instrument's behaviour has been gained. As soon as this will be the case, new data products for the nominal (or other) spectral intervals can be designed if necessary. In the new approach, the effective intervals were defined as follows: 190 – 222 nm for channel 2; 17 – 80 nm plus X-ray below 5 nm for channel 3; 6 – 20 nm plus X-ray below 2 nm for channel 4. Channel 1 is more complicated, since the diamond detectors in heads 1 and 2 behave differently in their response than the silicon detector in head 3. Details will be described below in Section 5.

(2) Instead of comparing LYRA with other instruments, the degradation must be calculated by internal means. This may be done with the help of the two spare units, heads 1 and 3, which so far have only been used for calibration campaigns. Their covers have only been opened for a few hours in all of 2010, while head 2 has been observing the Sun almost continuously since it saw First Light. Therefore, head 2 has experienced major degradation (up to 99%) while heads 1 and 3 have only seen minor, e.g. 10-30%, loss. Channel 3-4 has seen no apparent loss at all and could thus be used as a reference for the shorter-wavelength channels 2-3 and 2-4. Unfortunately there is no reference for the longer-wavelength channels 2-1 and 2-2, so the best that can be delivered currently is a flat line in the long temporal development, with the chance of observing significant variations in the short temporal development, at least in the first months.

The loss caused by degradation must be corrected by estimating this loss relative to First Light levels and adding it to the current levels, individually for all channels. Correction by addition (as opposed to multiplication) has advantages, because it was observed that degradation is not only a function of exposure time but also a function of wavelength: The loss is highest in the 190-222 nm range and lowest in the 6 – 20 nm range, and there is no apparent loss in the X-ray range, i.e., flares now lead to the same LYRA count rates as they did a year earlier. Furthermore, the longer-wavelength channels display instrumental artifacts that would be exaggerated out of proportion with a correction factor. On the other hand, there are some disadvantages: The variation of EUV components in channel 3 (and to a lesser degree in channel 4) might be underestimated, and the occultation profiles become distorted since they do not drop to zero levels any longer. Details will be described below in Section 4.

(3) The dark currents were measured as a function of temperature in the laboratory before launch, but only in steps of 10 degrees between -40°C and +60°C. Unfortunately, it turned out that the on-board temperature experienced in space was actually between +35°C and +55°C, a range where the functional relationship between temperature and dark current is very much non-linear. So the real relationship had to be tabulated in smaller steps, exploiting several calibration-campaign observations with closed covers, and even some with open covers, when the solar component could be subtracted. Details will be described below in Section 3.

(4) For an absolute radiometric calibration, the (observed) values of the First Light Day – before degradation started – must be compared to the (theoretical) result of LYRA radiometric model simulations, i.e., to the integral of solar spectra observed by other instruments multiplied with LYRA response curves as measured in the laboratory during the pre-launch BESSY campaigns. This comparison cannot be done without the detailed spectrum of the First Light Day (or a similar day) as an input, because a significantly different or even flat spectrum would not lead to comparable results. The comparison then leads to estimates of what LYRA actually observed in its effective spectral intervals. These estimates then have to be extrapolated into the following months with the aid of the observed degradation. The degradation curve itself has to be projected into the future after the most recent calibration campaign, thus there will be regular updates due to these campaigns. Since only one factor per channel can be calculated for the relationship between LYRA count rate and irradiance in physical units, it must be assumed that this relationship is indeed linear – at least in a neighbourhood around the First Light level. Details will be described below in Section 5.

3. Dark Current Subtraction

The task was to estimate the dark currents of head 2 from the on-board temperature near head 2. As a first approach, the values measured in the lab during the "Functional Tests Thermal Vacuum" were taken, see here:

http://solwww.oma.be/users/dammasch/FT_TV_General.xls

The values from the second table, temperature vs. dark currents in kHz, worked fine for low temperature values, like in Dec 2009 and Jan 2010. For the values after April (above 40° C) the difficulties started. It was not sufficient to use a simple linear interpolation between 40° and 50°. So, data were collected from calibration tests: 26 May, 23 Jun, 14 Jul, 11 Aug, 29 Sep, 14 Oct 2010. These tests covered temperatures between 40 and 49 degrees. Later on, the temperature interval between 30° and 40° could be specified by exploiting a long observation on 25 Nov 2010 when covers were accidentally closed, and a campaign on 02 Dec 2010 when eclipse profiles were acquired. Additionally, values from the same set of calibration campaigns were used to estimate the dark currents of head 3 from the temperatures near head 3. The values from November and December have the advantage that the temperatures are cooler (33-39° C) than in the earlier campaigns (40-49° C), due to the eclipse season that started again in November. But so far, LYRA only experienced values up to 50°, the 51° value was extrapolated manually, and the 60° value was taken from the laboratory measurements. This would have lead to a gross over-estimation of dark currents in the case of temperatures up to 52-54° during the bake-out period 25-26 Jan 2011. Since LYRA only delivered a mixture of solar and eclipse values for this temperature domain - and no values with covers closed - it was tried to estimate the functional dependence with these data. Border conditions were such that the minimum value during the eclipses should meet the dark current, and that the new values could be smoothly attached to the values existing below 50° C. The result is not perfect but promising. The table below shows the current values used for the linear interpolation of head2 dark currents in the latest version (BSDG=0.5) of the calibration software “calib_lev2.pro”. Values up to 30° C were taken from the lab measurements, as was the 60° value.

tmp	-40	-30	-20	-10	0	10	20	30	
dc1	6.84	6.67	6.80	6.97	6.74	6.66	6.60	7.42	
dc2	6.25	6.29	6.29	6.33	6.35	6.37	6.38	6.39	(from lab)
dc3	6.18	6.21	6.23	6.25	6.26	6.27	6.29	6.33	
dc4	6.17	6.10	6.26	6.38	6.51	6.63	6.73	7.12	

tmp	34	35	36	37	38	39	40	41	42	43	44	
dc1	7.60	7.70	7.80	8.00	8.40	9.10	9.80	10.5	11.0	12.0	13.0	
dc2	6.50	6.50	6.50	6.50	6.50	6.50	6.50	6.50	6.50	6.50	6.50	(from
dc3	6.42	6.44	6.46	6.49	6.53	6.56	6.62	6.68	6.75	6.83	6.92	space)
dc4	7.60	7.80	8.00	8.30	8.60	9.00	9.40	9.90	10.5	11.2	12.0	

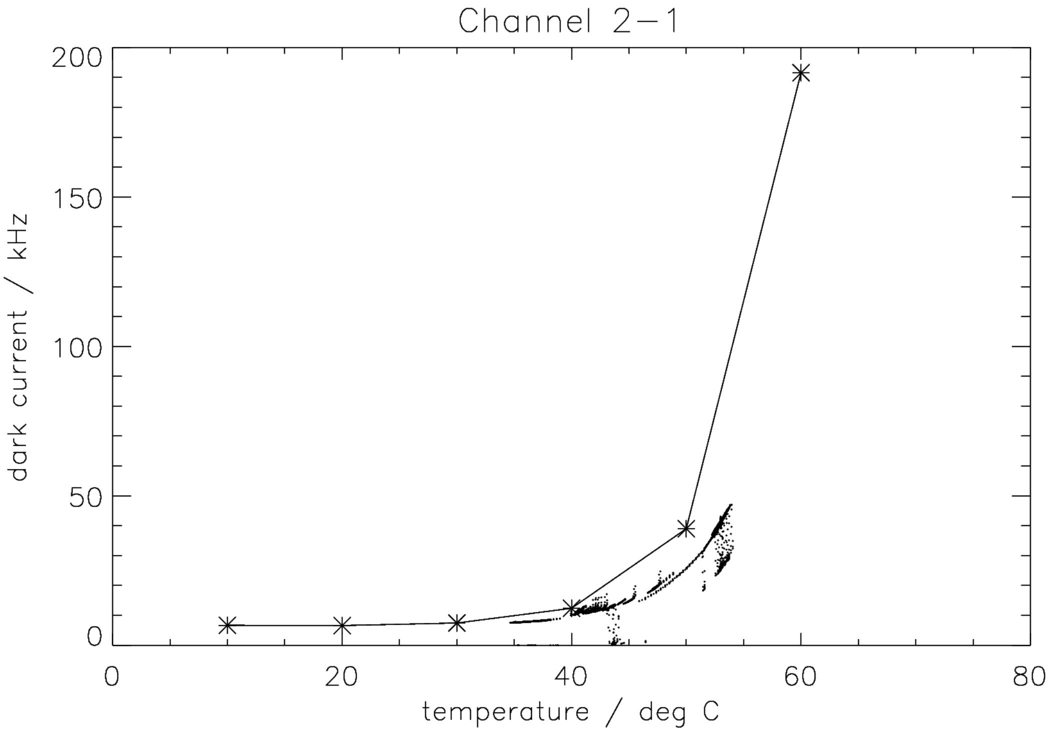
tmp	45	46	47	48	49	50	51	52	53	54	55	
dc1	14.5	16.0	18.0	20.0	22.0	25.0	29.0	33.0	37.0	43.0	53.0	
dc2	6.50	6.50	6.50	6.50	6.50	6.50	6.50	6.40	6.40	6.40	6.40	(from
dc3	7.05	7.20	7.40	7.60	7.80	8.10	8.40	8.80	9.20	9.70	10.5	space)
dc4	13.0	14.4	15.9	17.4	19.5	22.5	25.0	29.0	33.0	37.0	43.0	

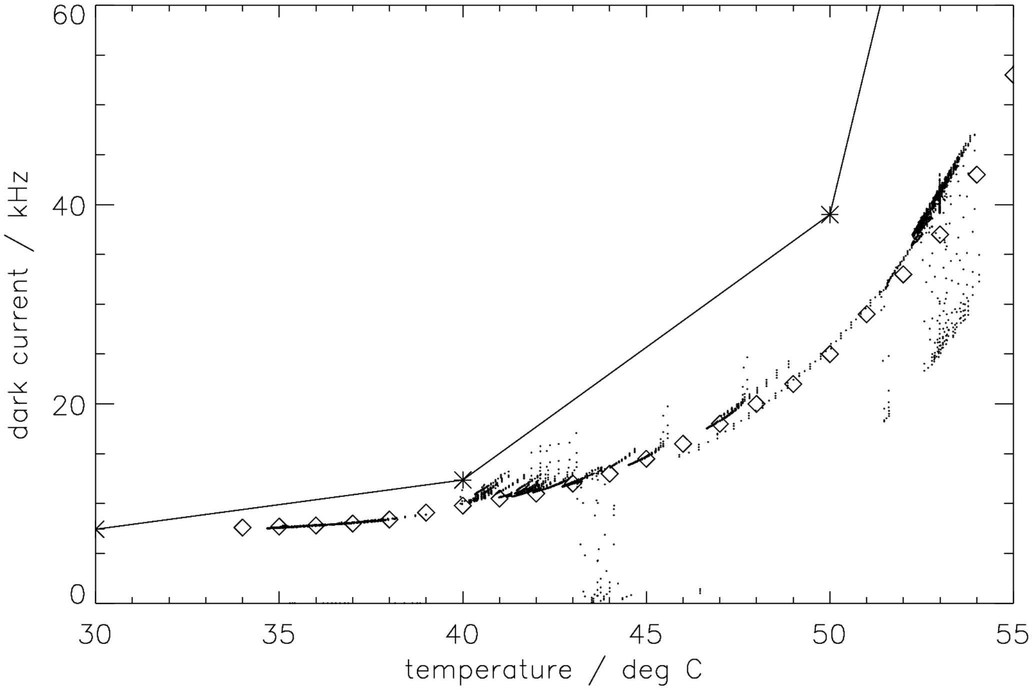
tmp	60	
dc1	191.60	
dc2	6.39	(from lab)
dc3	21.31	
dc4	169.45	

tmp = temperature in degree C
dc1(,2,3,4) = dark current of channel 2-1(,2,3,4) in kHz

As an example, the dark currents of the Lyman-alpha channel of head2 are shown here in the figure below: The upper image shows the overall situation of channel 2-1, the straight lines connect the values from the lab FT_TV (asterisks). The small dots are the dark current measurements from the calibration tests. The lower image shows the specific situation between 35 and 55° C. The diamonds denote the values that were selected (manually) to substitute the old ones for the interpolation. Obviously, the dark currents for channel 2-1 were slightly over-estimated in the thermal-vacuum test of 29 Jun 2009, as were the dark currents of channels 2-3, 2-4, and 3-1. The other measurements could be almost exactly confirmed. Especially, it could be confirmed that the dark currents of channels 3-3 and 3-4 indeed decrease with rising temperature.

Further details as well as the effect of dark-current removal can be found in the report
http://solwww.oma.be/users/dammasch/IED_20110208_LyraDarkCurrentsTemperatures.pdf





4. Degradation Correction

Values for LYRA heads 1, 2, and 3 were used from the following calibration campaigns: 06, 07, 11, 12, 13, 15, 28, 30 Jan, 02, 20, 24 Feb, 03, 10, 17, 18, 24 Mar, 22 Apr, 03, 26 May, 23 Jun, 11, 15 Jul, 11 Aug, 22 Sep, 15 Oct, 04 Nov, and 24 Nov 2010, more or less simultaneously taken for all three heads, making it 27 data points which were manually selected. The dark currents of heads 2 and 3 were estimated and subtracted. This report concentrates on heads 2 and 3, because this is an attempt to estimate the degradation of head 2, partially by comparing it to head 3. It can be observed that the development of the LYRA channels' output is a function of the time that these channels were exposed to solar radiation (i.e., the time during which the covers were open). Heads 1, 2, and 3 show a similar development if one considers the first, say, fifty hours of sunlight exposure. But only head 2 was almost continuously open and exposed since 06 Jan 2010.

The development of the long-wavelength channels *-1 (Lyman-alpha) and *-2 (Herzberg) is dominated by instrument degradation, while the development of the short-wavelength channels *-3 (Aluminium) and -4 (Zirconium) is dominated by solar variation. According to PMOD/WRC observations with earlier instruments, there is a physical reason for this: The degradation is caused by condensation and UV-induced polymerization of outgassing molecules on the filter surface. The resulting layer absorbs longer wavelengths more than shorter wavelengths, thus ch*-4 is affected the least.

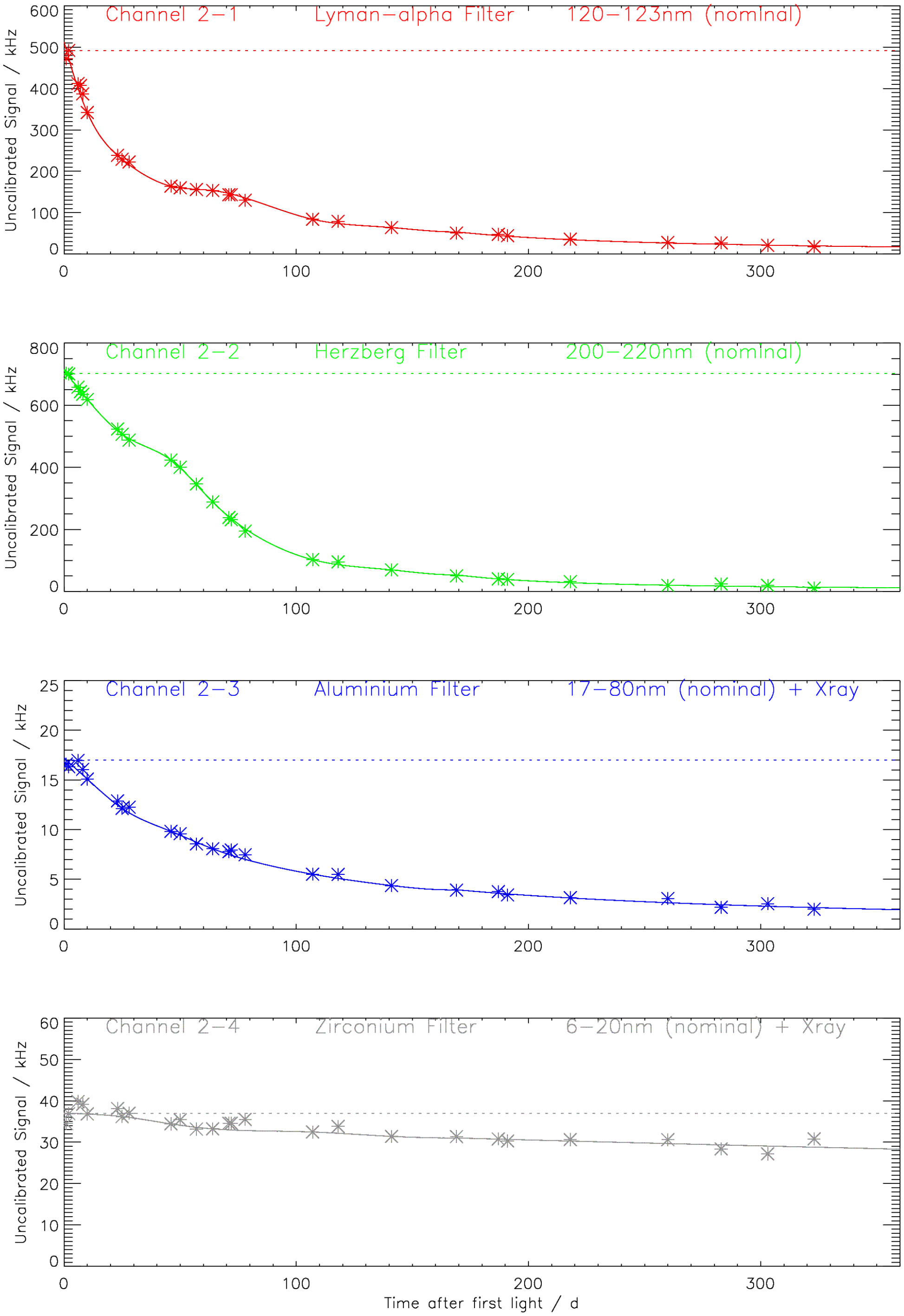
To remove the solar variations, channel 2-3 can, for example, be divided by channel 3-3 to result in an almost smooth line. The same holds for ch2-4/ch3-4 or ch2-4/ch1-4. Also, ch*-3 can be divided by ch*-4 to result in a smooth line (i.e. without solar variations). In the end, ch1-4 and ch3-4 appear to be straight; they show no decline in their first forty, fifty hours of exposure, and can thus be used as a reference. Accordingly, ch2-3 and ch2-4 are corrected by a normalized ch3-4; as a result, channels 2-3 and 2-4 are smoothed, and their degradation can be fitted more easily.

The development, especially in ch2-1 and ch2-2, shows phases of different degradation velocity. After day 80, the degradation seems to have stabilized, though. Therefore, only the last data points, representing the calibration campaigns up to 24 Nov 2010, were used for a fit to estimate the future development. This fit uses a function of the type 1/(a+b*time); this appears to be quite a stable approach. The degradation trend in the first half year (day 1 – day 169 after First Light) is fitted with a spline function through some manually selected data points. This is done because there is no apparent mathematical function for the initial degradation; it seems to happen in various phases, and the physical processes behind it (polymerization and emergence of contamination layers on the filters' surfaces) are not known well enough. The degradation trend for the second half year is fitted with the above-mentioned 1/time function; other functions like negative exponentials will be tested in the future. The result is also a robust estimate for the future behaviour. The two functions described above are concatenated (currently at day 169).

For calibration purposes, the degradation is estimated as the difference between a channel's output at First Light and its fitted or projected curve, and then this difference is added to the measured signal (dark currents already removed). The advantage is that variations in the LYRA channels' output are not exaggerated. Variations in channels 2-1 and 2-2 are basically instrumental artifacts, spontaneous jumps (not yet understood), slow reactions of detectors, unresolved dark current subtractions. Since these channels have lost 96% or 98% of their initial output, multiplying the residual signal with a factor 25 or 50 would blow these jumps out of proportion. - For channels 2-3 and 2-4, the approach has an additional physical reason: their main variation seems to be caused by the solar variation, especially from SXR, and these variations are basically unchanged by the degradation, since the contamination film mainly affects longer UV wavelengths. Thus, a multiplication with a factor would artificially blow up these SXR variations after several months of degradation and lead to wrong results in the end; this was tested in earlier attempts.

The disadvantage of this “additive” approach is that possible solar variations in channels 2-1 and 2-2 (and maybe, due to longer-wavelength contributions in its 17-80nm spectral interval, also in channel 2-3) may be underestimated in the end. This problem must be solved later on. Another disadvantage is that the eclipses in the first season decrease down to zero level, whereas eclipses in the second season decrease only down to the level that is added for degradation correction. This problem must be solved by treating the eclipses separately (and storing them into extra FITS files, as was originally planned).

Further details as well as the effect of the degradation removal can be found in the reports
http://solwww.oma.be/users/dammasch/IED_20101203_DegradationFit_Update.pdf
and
http://solwww.oma.be/users/dammasch/IED_20101209_LyraDegradationCorrection.pdf

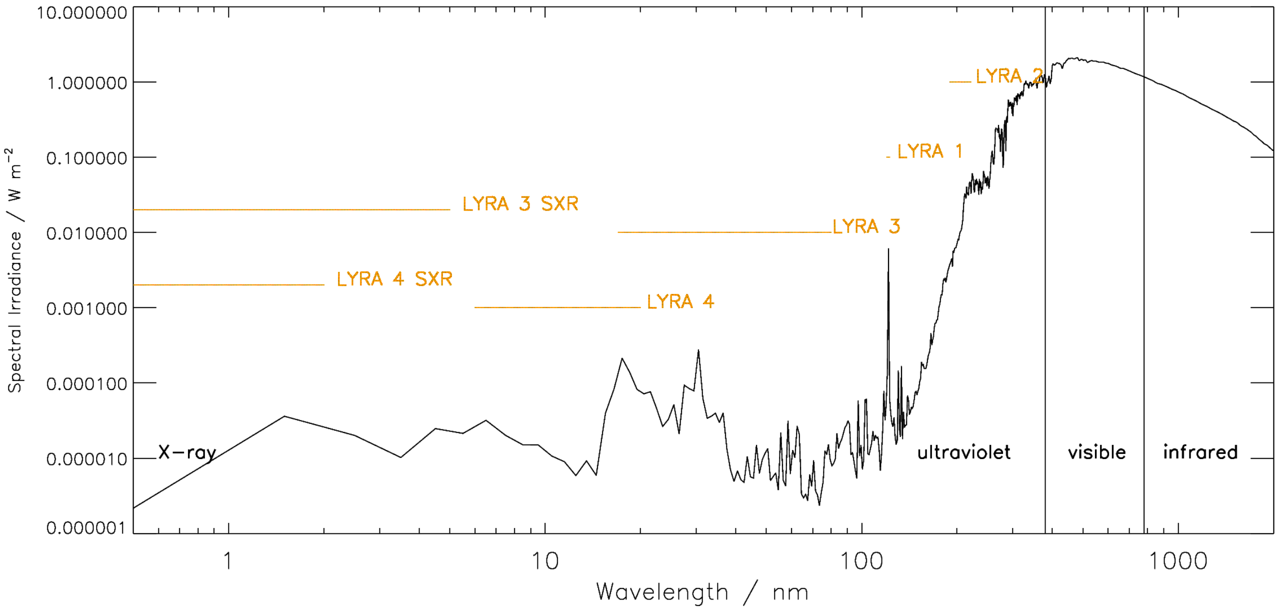


5. Conversion to Physical Units

It must be stressed that the LYRA response functions were only in part measured in the laboratory (BESSY campaigns in 2006-2007, with an emphasis on the nominal spectral intervals); in part they were interpolated to cover gaps, and in part they were extrapolated to spectral intervals that could not be observed in the synchrotron. These extrapolations into longer-wavelength regions – based on producers' measurements, separately for their filters and detectors - were subsequently tested (and, if necessary, corrected) by exposing LYRA to visible light under controlled conditions (Davos campaign). Thus, different parts of the LYRA responsivities have a different degree of reliability.

The problem is that – while the "nominal" spectral intervals could be carefully examined – the less reliable spectral intervals beyond, say, 240nm are vast and contain relatively strong irradiance which – integrated - may counteract the spectral rejection intended by the selection of the various filters. This has serious influences, especially on the calibration of the Lyman-alpha channels, as will be shown below.

The core of the LYRA Radiometric Model (LRM) is to estimate the electric current flowing in a certain detector with the aid of a solar spectrum, a spectral response function, and the size of the precision hole. This estimated current must be compared to the count rates as observed and transmitted by the instrument on the spacecraft. The count rate can be converted into the detector's electrical current with the aid of established instrument parameters, like resistance and Voltage-Frequency-Converter (VFC) parameters. The comparison is *not* possible without a given solar spectrum. To avoid the degradation problems, the solar spectrum as observed by two space instruments on LYRA's First Light Day, 06 Jan 2010, was used: Spectral irradiances from 0.5nm to 115.5nm (TIMED/SEE) and from 116.5nm to 2412.3nm (SORCE/SOLSTICE) were concatenated; compare image below. The data can be found on their websites:
http://lasp.colorado.edu/see/see_data.html
http://lasp.colorado.edu/lisird/sorce/sorce_ssi/index.html



The following three tables for the three LYRA heads compare the LRM-simulated values (integral of solar spectrum, times spectral responsivity, times precision-hole area) with the observed values (count rate, minus dark current, times VFC parameter, divided by resistance), all in nA.

Head 1

```
    ch1-1        ch1-2        ch1-3        ch1-4

sim 0.2929 nA   11.28 nA   0.06399 nA   0.1064 nA

obs ~1300 kHz    620 kHz      24.0 kHz     37.5 kHz
dc    -9.0 kHz   -6.6 kHz     -6.8 kHz     -7.2 kHz
VFC,resis. =>          =>            =>           =>
    0.5311 nA   12.78 nA   0.07116 nA   0.1216 nA

diff   +81.3%     +13.3%       +11.2%       +14.3%
```

Head 2

```
    ch2-1        ch2-2        ch2-3        ch2-4

sim 0.1030 nA   12.07 nA   0.05765 nA   0.01542 nA

obs   500 kHz    710 kHz      23.0 kHz      45.0 kHz
dc    -8.0 kHz   -6.5 kHz     -6.4 kHz      -7.5 kHz
VFC,resis. =>          =>            =>            =>
    0.1969 nA   14.81 nA   0.06780 nA   0.01511 nA

diff   +91.2%     +22.8%       +17.6%         -2.0%
```

Head 3

```
    ch3-1        ch3-2        ch3-3        ch3-4

sim 0.3686 nA   9.693 nA    1.0250 nA   0.1082 nA

obs   930 kHz    552 kHz       280 kHz     36.2 kHz
dc   -10.0 kHz   -6.5 kHz     -6.4 kHz     -6.2 kHz
VFC,resis. =>          =>            =>           =>
    0.3807 nA   11.44 nA    1.1400 nA   0.1249 nA

diff    +3.3%     +18.0%       +11.2%       +15.4%
```

Thus, from the three heads, there are three estimates for each LYRA channel output relative to the simulations based on other instruments' spectra. Within sensible limits, an average is calculated.

```
    +81.3%       +13.3%        +11.2%       +14.3%
    +91.2%       +22.8%        +17.6%        -2.0%
     +3.3%       +18.0%        +11.2%       +15.4%
=> ? (0.0%)   => +18.0%     => +13.3%     => +9.2%
```

The question remains: Which irradiance value should this be compared to? Please note that the comparison above is not based on selected spectral intervals but – more or less – on the total spectral irradiance. With dark currents removed, LYRA head 2 observes 492kHz (Lyman-alpha), 703.5kHz (Herzberg), 16.6kHz (Aluminium), and 37.5kHz (Zirconium) on 06 Jan 2010; compare second table above. Dark current levels were observed immediately before opening the covers.

In the case of the Lyman-alpha channel, the irradiance value to be selected is doubtful. Heads 1 and 2 show large differences which are probably caused by insufficient knowledge about the response in the range between 240 and 300nm. In addition, it is difficult to compare heads 1 and 2 (MSM diamond detectors) to head 3 (Silicon detector), since the diamond detectors have an additional second peak around 200nm while the Silicon detector collects its 70% non-nominal input almost evenly between 200 and 1100nm. Therefore, it is hard to make a statement like "LYRA observes x% more irradiance as compared to SORCE" before more knowledge is gained about LYRA's spectral response. Until then, the SORCE value for 06 Jan 2010 for the nominal interval 120-123nm (including the H I Lyman-alpha line) must be assumed, i.e., 0.006320W/m^2, with the caveat that the LYRA value probably underestimates the pure Lyman-alpha variability, since 70% of the output originates from longer-wavelength contributions of unknown composition.

The other three cases appear to be less complicated.

In the case of the Herzberg channel, LYRA observes - on average - 18.0% more than SORCE seeing 0.5914 W/m^2 in the range 190-222nm on 06 Jan 2010.

In the case of the Aluminium channel, LYRA observes - on average - 13.3% more than TIMED seeing 0.002008W/m^2 in the range 17-80nm, plus SXR below 5nm, on 06 Jan 2010.

In the case of the Zirconium channel, LYRA observes – on average – 9.2% more than TIMED seeing 0.0007187W/m^2 in the range 6-20nm plus SXR below 2nm on 06 Jan 2010.

Thus, for an arbitrary day following First Light, the dark current has to be estimated and subtracted, the degradation has to be estimated and added, and the resulting value has to be converted into the corresponding irradiance:

ch*-1	ch*-2	ch*-3	ch*-4	
(120-123nm)	(190-222nm)	(17-80&0-5nm)	(6-20&0-2nm)	
0.006320 W/m^2	0.5914 W/m^2	0.002008 W/m^2	0.0007187 W/m^2	
? (0.0%)	+18.0%	+13.3%	+9.2%	=>
0.006320 W/m^2	0.6979 W/m^2	0.002275 W/m^2	0.0007848 W/m^2	corresponding to:
492 kHz	703.5 kHz	16.6 kHz	37.5 kHz	

Again, a caveat is necessary: Until more knowledge is gained, this conversion is done with a simple linear factor. This assumes that the relationship between observed count rates and irradiance is linear, at least in an environment as observed during solar-minimum quiet Sun on First Light Day. Thus, especially flare values are most probably over-estimated since the LYRA short-wavelength channels are relatively more responsive to SXR input.

Minor corrections, like flat-field (off-pointing) effects, distance from the Sun, or slow MSM-detector development after switch on, are still to be done; effects like large-angle spacecraft rotations, ASIC reloads, or other instrument artifacts, are still to be either corrected or flagged; the level-2 quality factors still have to be defined. So there will definitely be calibration-version updates in the future.