Soft X-ray Irradiance Measured by the Solar Aspect Monitor on the Extreme Ultraviolet Variability Experiment

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Abstract

The Solar Aspect Monitor (SAM) is a pinhole camera on the SDO Extreme-ultraviolet Variability Experiment (EVE). SAM projects the solar disk onto the CCD through a metallic filter designed to allow only solar photons shortward of 7 nm to pass. Contamination from energetic particles and out-of-band irradiance is, however, present. We present a technique for producing the 0.1 to 7 nm broadband irradiance from the SAM images. The results agree with the zeroth-order product from the EUV SpectroPhotometer (ESP). Prior information is established through broadband and active region detection to assist photon event detection (PED) algorithm. A forward simulation of SAM images is developed to facilitate resolving the photon pileup issue and PED is performed on 360 simulated images.

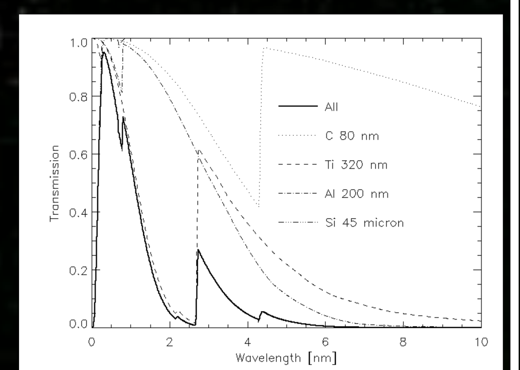
SAM – From SXR Images to Spectrum

Solar Aspect Monitor (SAM) is a pinhole camera (Fig. 1):

- High cadence (10 sec): a few photons per image
- Al/C/Ti Filter (Fig. 2): for SXR flux between 0.01-7 nm
- Camera: spatial information of individual events

Fig. 3 shows the rearrangement of the raw image:

- Projection of solar disk (light): 320 x 240 pixels
- A non-sunlit (dark) area close by: 480 x 160 pixels
- 4 virtual pixels are placed in front of each row



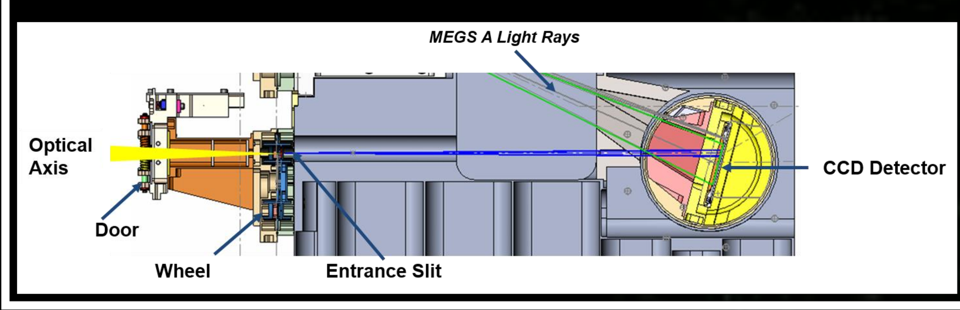


Fig 2

Fig 1

Fig 3

First Step – Broadband Irradiance

DN histograms of ***illuminated*** (IA) and ***unilluminated*** (UA) areas (Fig. 4):

- Very lose at low- & high-DN ends. Particles are everywhere!
- Difference = where solar signal reside, not varying much at 10s–100s DN.
- Light curve rises above dark curve during flares even at high DN values (Fig. 4b).

Sub-bands:

- High correlation between bands 1–8 and GOES, bands 10–15 with F10.7 (Fig. 5).
- A flaring component of the solar irradiance may be characterized by shorter-wavelength bands or a quiet component by longer-wavelength bands.

One-component v.s. ***two-component*** methods:

$$I_r = I_{s,1-comp} + s_{p,1-comp} \qquad I_r = I_{s,2-comp} + s_{p,2-comp} = I_q + I_a + s_{p,2-comp}$$

$$I_{BB} = I_{s,1-comp} + A \cdot I_{NB1-6} \qquad I_{BB} = I_q + B \cdot I_{NB_{6-8}} + A \cdot I_{NB_{1-6}}$$

Alternating coefficients A & B in the equations above to find maximum correlation between the quieter solar components ($I_{s,1-comp}$ for 1-component or I_q for 2-component case) with F10.7 suggests estimates of particle contribution that will be removed.

It is found that 1-component (2-component) irradiance estimate is better at low/medium (high) solar activities. A ***hybrid method*** is developed to switch between estimates based on solar activity level. Usually the 1-component estimate is reported but 2-component value is switched to once the standard deviation of the active component, I_a, of the day is above 5 x 10^{-4}, indicating possible flares.

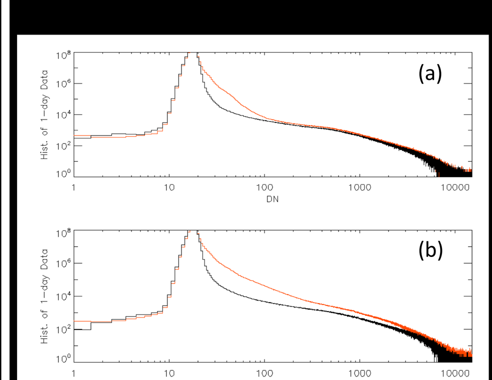
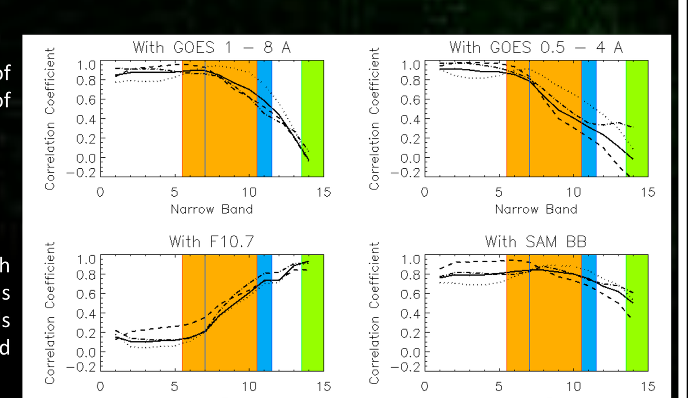


Fig 4. 1-day DN histograms of IA (red) and UA (black) images of a quiet(a) and a flaring (b) days.

Fig 5. NB correlation with other measurements as indicators to determine bands for estimation of quiet-Sun and particle components.



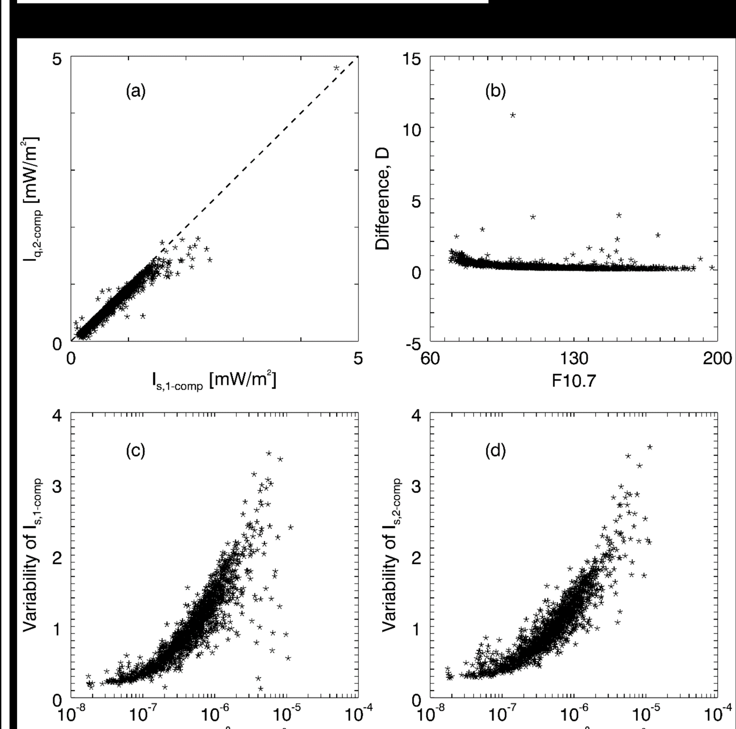


Fig 6. Comparison of 1-component and 2-component methods.

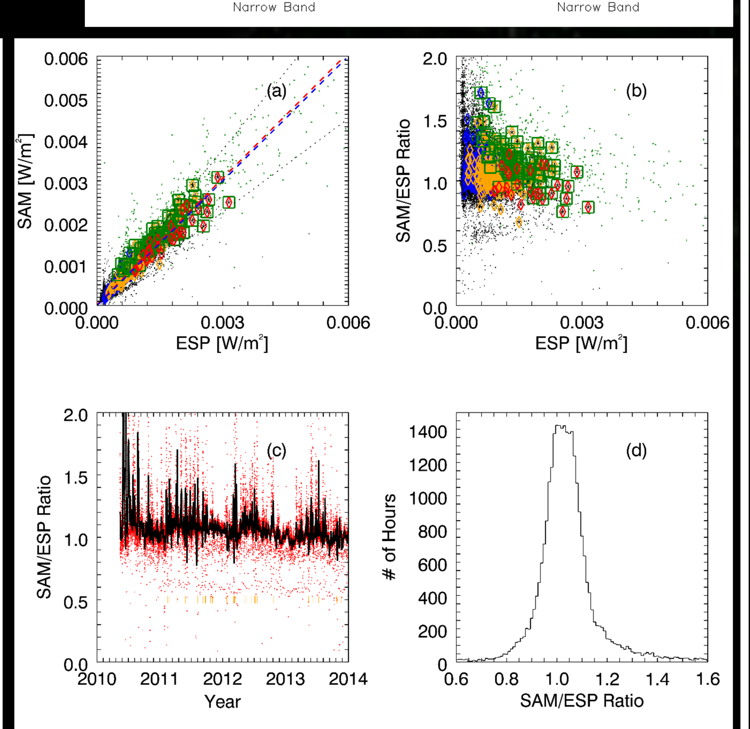


Fig 7. Comparison of 1-component and 2-component methods.

Second Step – Active Region Detection

We have seen: Hard X-ray photons → a circular feature at an active region during flare

We now study it: The Apertural Progression Procedure for Light Estimate (APPLE) studies the evolution of active regions. Locations of two most active regions are fed to the photon detection process so a circular mask allows the detected events to be registered properly.

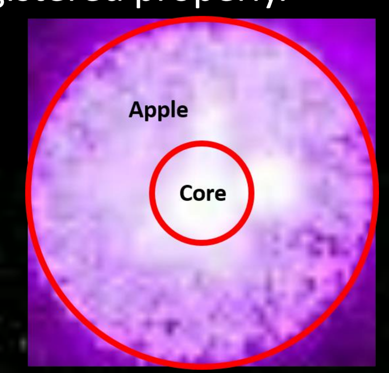


Fig 8. Larger aperture seen during a flare. Core (inside the inner circle) and apple (between two circles) are defined to track light evolution for the flaring cases.

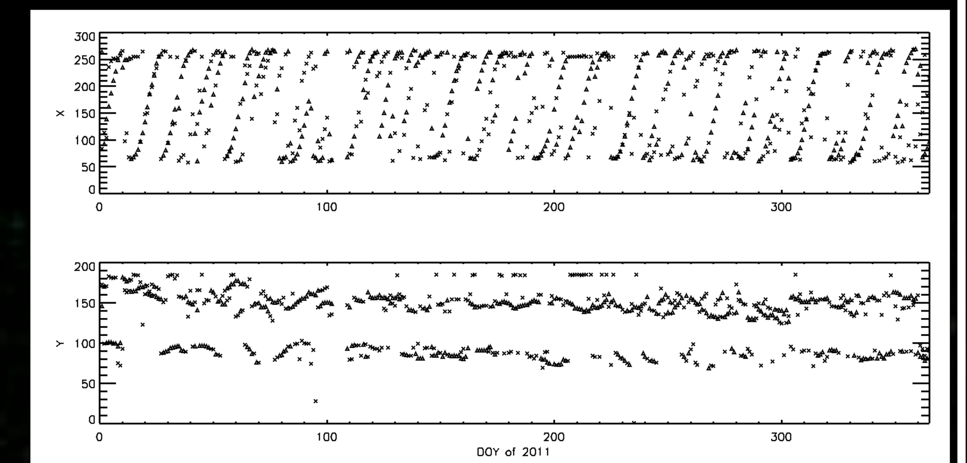


Fig 9. Progression of aligned AR locations in X & Y coordinates on the images as the Sun rotates. Color indicates the most populated 1st and 2nd peaks.

What APPLE does:

- Pair-wise minimum
- Median of 5 pairs of images
- Identify the most active pixels

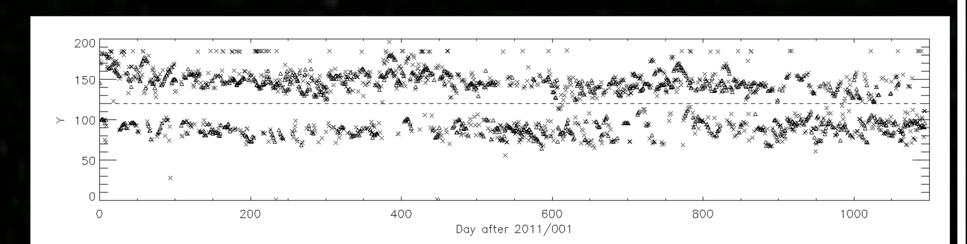


Fig 10. The Butterfly effect is visible. The Sun's equator is at around 120 (dish).

Locations of identified ARs can move around on the solar disk in one day so they need to aligned. To align the AR locations:

- Obtain histogram of AR locations in X & Y
- Detect the 1st and 2nd most populated X & Y

Fig. 9 shows the progression of two AR locations (different color) after the alignment for first 100 days of 2014. As the Sun rotates, X coordinate varies. As the Earth orbits around the Sun, Y coordinates fluctuates (Fig 10). Fig. 11 shows the integrated DN inside the two most active areas.

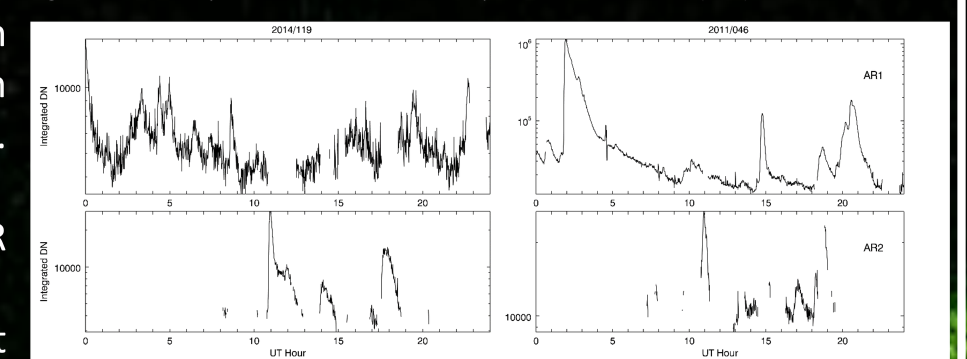


Fig 11. Integrated DN in the vicinity of the detected AR peaks after alignment is performed.

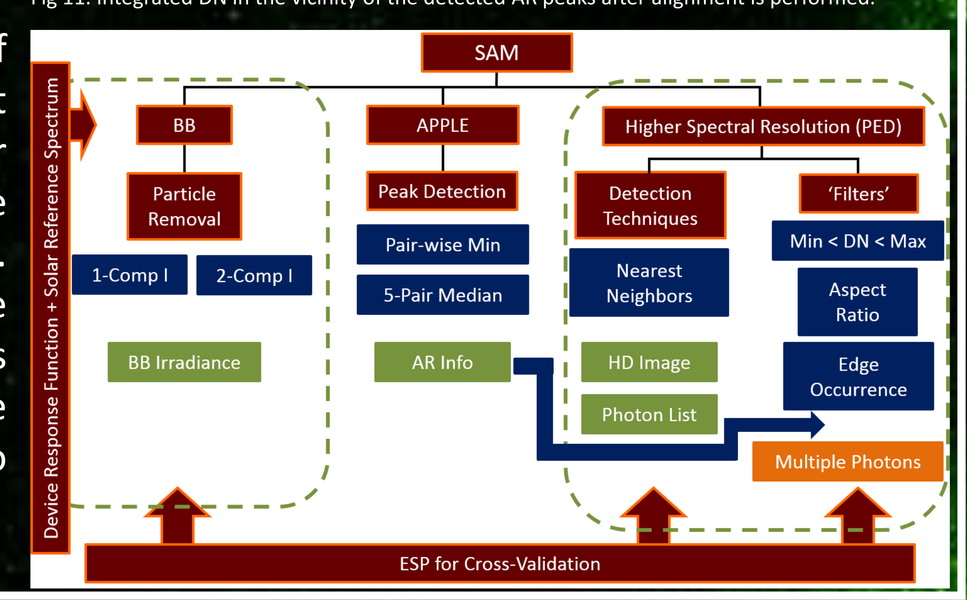


Fig 12. Algorithms facilitating interpretation of SAM data.

Third Step – Photon Event Detection

Event detection is based on ***nearest-neighbor search***. Criteria developed for screening detected events are based on observing behavior of photons and particle strikes on single SAM images. These software filters for particles include:

a) high-value maximum
b) aspect ratio far away from one
c) maximum at the edge of the event box
d) ratio of occupied pixels over vacant pixels

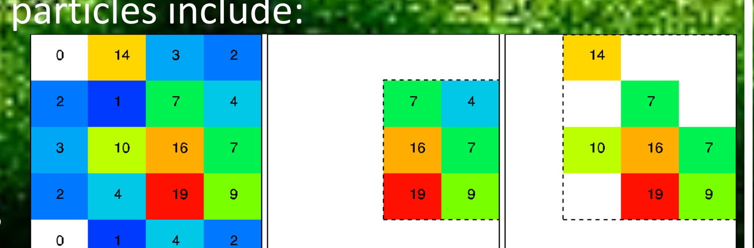


Fig 14. Event detection techniques performed on a made-up image (left) by monotonically decreasing edges (middle) and nearest neighbor (right).

Now, BB + APPLE + PED = Fruitful results!!!

PED procedures take in results from BB and APPLE for decision making:

- BB tells PED if likely a flaring day or not
- If a flaring condition is predicted, PED reads in APPLE AR information to apply circular masks around 2 ARs (core/apple for 1st AR, core only for 2nd AR)

Assumption made: the most populated AR = the AR likely to have hard X-ray penetration

Improvement from previous-version PED:

- Photons in the flaring vicinity previously discarded are now recognized.
- All screening filters (photons vs particles) may be applied.

Photons are registered with their *centroid location*, *total DN*, *size*, and *time*.

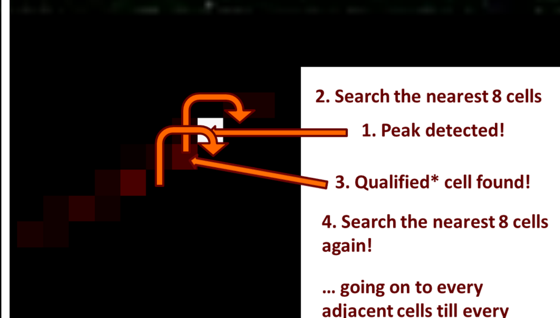


Fig 13. Nearest-neighbor search for event detection.

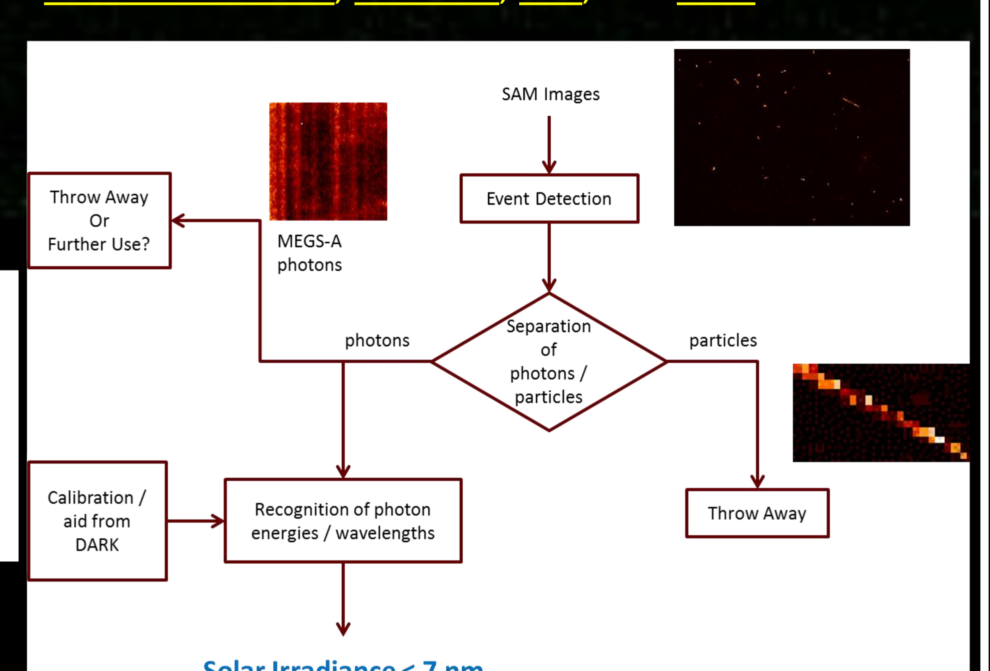


Fig 15. Block diagram of PED process.

PED During the Most Active Flares

PED is performed on days with different levels of flares in 2013/2014. The comparison of total DN of the detected events of the entire day with total GOES 1-8 Å flux for the listed flare dates shows a very good linear relationship (Fig. 16). With photon centroids recorded recreation of high-resolution solar SXR images is made possible. Fig. 17 is an example of recreating the SAM images into low-, medium-, and high-energy channels for one of the flaring days.

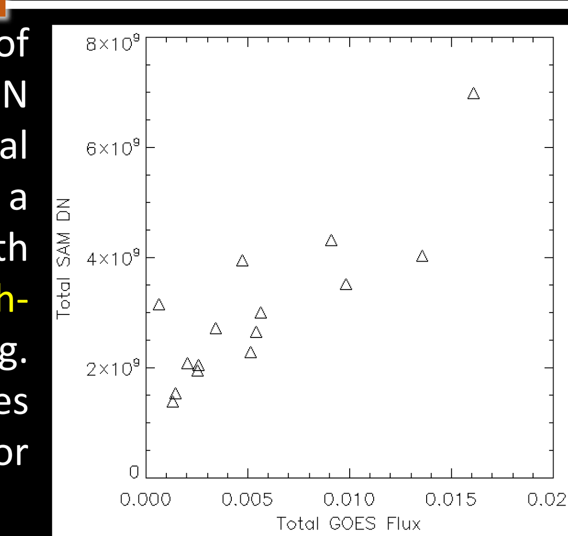


Fig 16. Total DN of PED photons on the selected flaring days has a linear relationship with total GOES 1-8 Å flux.

Date	DOY	Flare Class
03/05/2013	064	M1.2
05/12/2013	132	M1.9
05/13/2013	133	X2.9
05/14/2013	134	X3.2
05/15/2013	135	X1.3
05/16/2013	136	M1.3
11/05/2013	309	X3.4
01/07/2014	007	X1.3
01/30/2014	030	M6.7
02/25/2014	056	X5.0
03/28/2014	087	M2.6
03/29/2014	088	X1.0
04/02/2014	092	M6.5
04/16/2014	106	M1.0
04/25/2014	115	X1.4

(*Flare class shown by 1-m data)

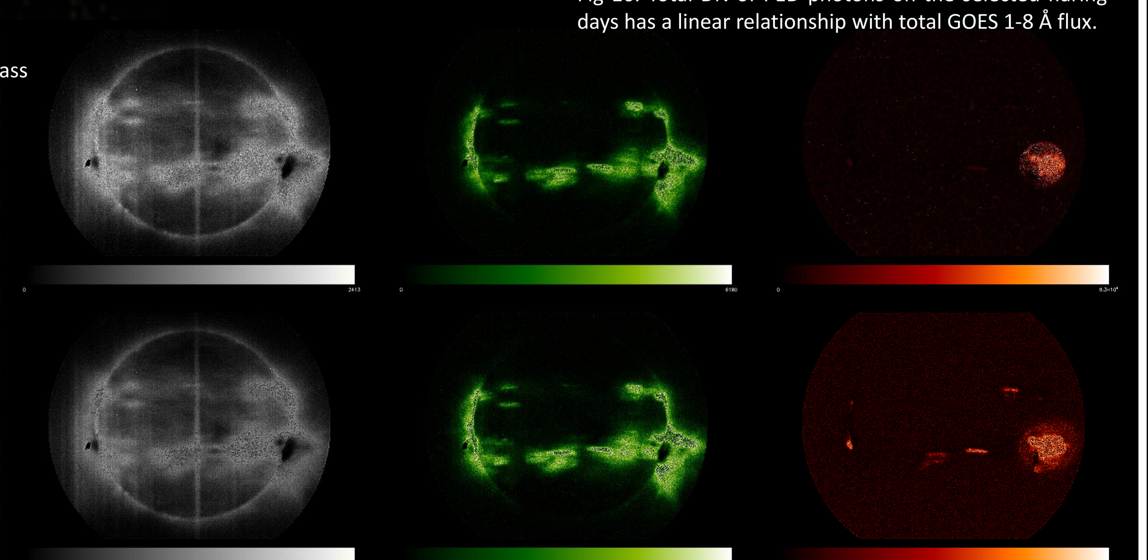


Fig 17. From left to right are the daily stacked images of detected low-, medium-, and high-energy photons. A map of photon population (bottom) is produced so one may use to recreate the solar images (top).

Forward Simulation & Spectrum

Photon pileups are observed on SAM images. The key to resolve soft X-ray spectrum lies in accurately binning the detected photons. In a forward model, photons are generated with a scaled DEM spectrum (black line in Fig18), assigned various impact sizes, and randomly populates onto simulated images. Every image is exposed to the artificial photon flux for 10 seconds and PED is performed. The PED results are able to reproduce most spectral features. The probability of high-DN population increases with the number of simulated images. Solar model constrains reproduction of photons that can results in > 300DN. Real observation (green) contains contamination from out-of-band photons below ~50DN.

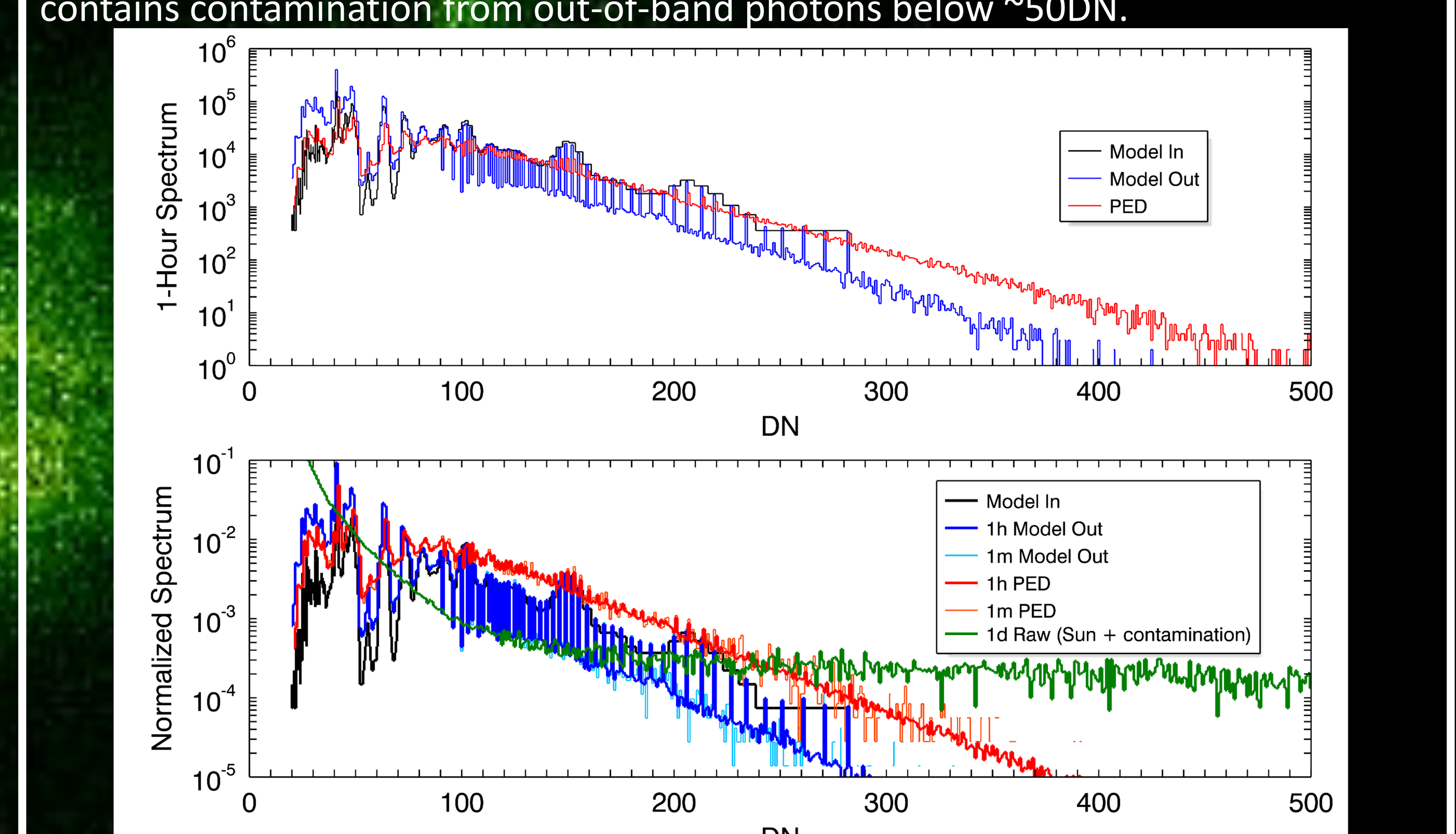


Fig 18. DN spectra on SAM from the simulation and real observations. The modeled DN spectrum is based on a DEM solar spectrum (black). Pre-analysis DN histograms (blue/light blue) bias toward the smaller DN values below 100DN. PED-analyzed spectra (red/orange) preserve most of the spectral features. The 1-day data contains high contamination from the out-of-band photons which bias the spectral shape (green).

Summary & Future Work

Five years of SAM broadband irradiance is validated against ESP. The ratio of SAM to ESP has a mean of 1.07 and a standard deviation of 0.30. The validation sets a firm ground for the next steps of retrieving individual photon events. The APPLE procedure provides AR locations to PED for proper photon registration. The combination of BB, APPLE, and PED is demonstrated on the 2013/2014 flares at various levels. The integrated irradiance shows a linear relationship with GOES. A forward model is developed to address the photon pileup issue. PED-analyzed spectra preserve the original spectral features but tend to smear line edges. Simulation gets closer to the real observations as the number of images involved increases.

References

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