XUV Photometer System (XPS)

Tom Woods

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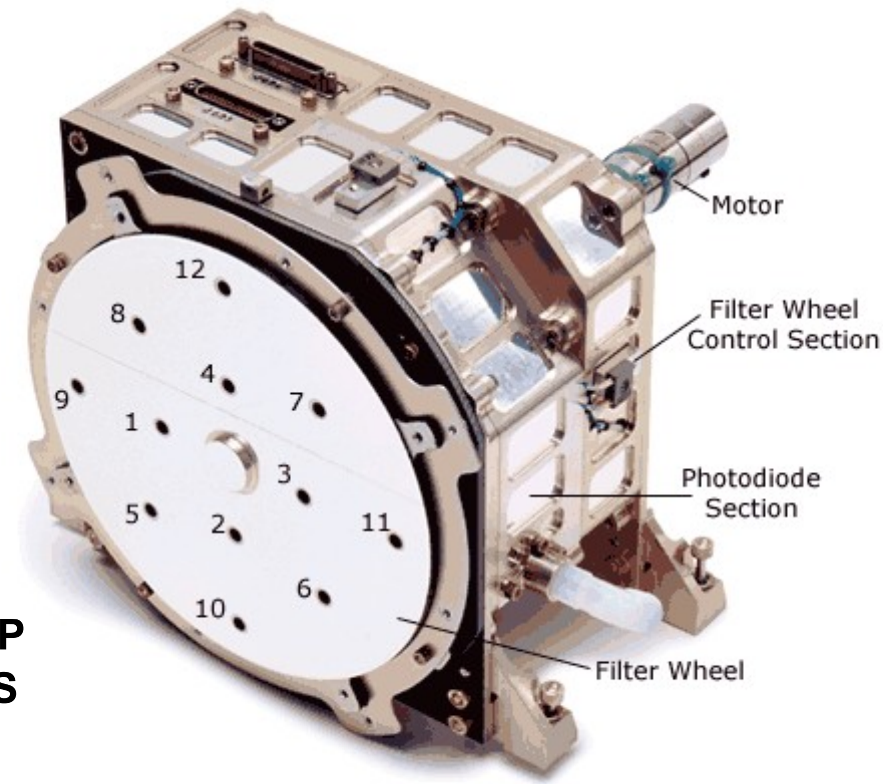
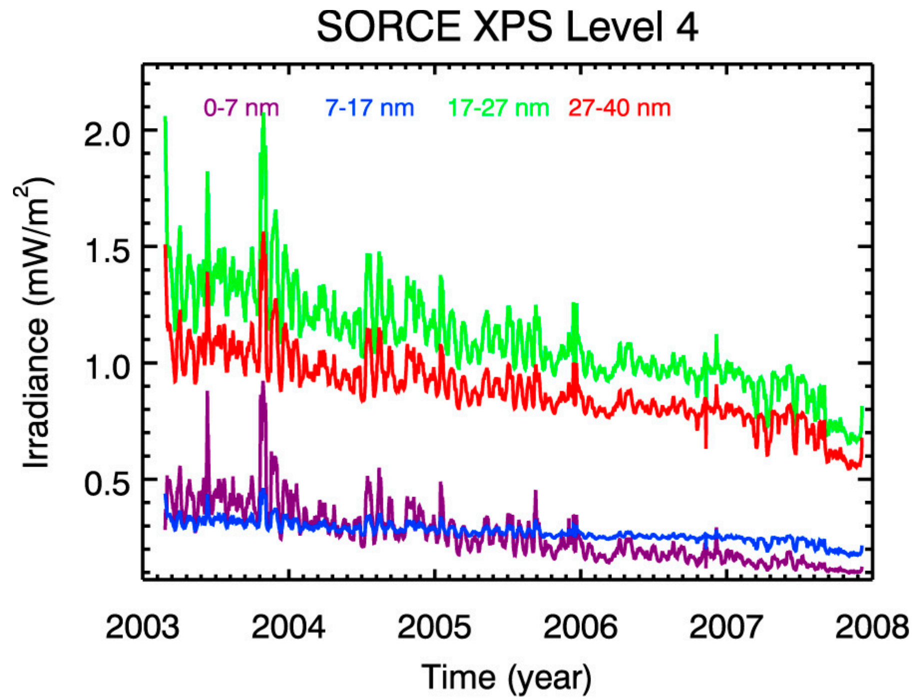


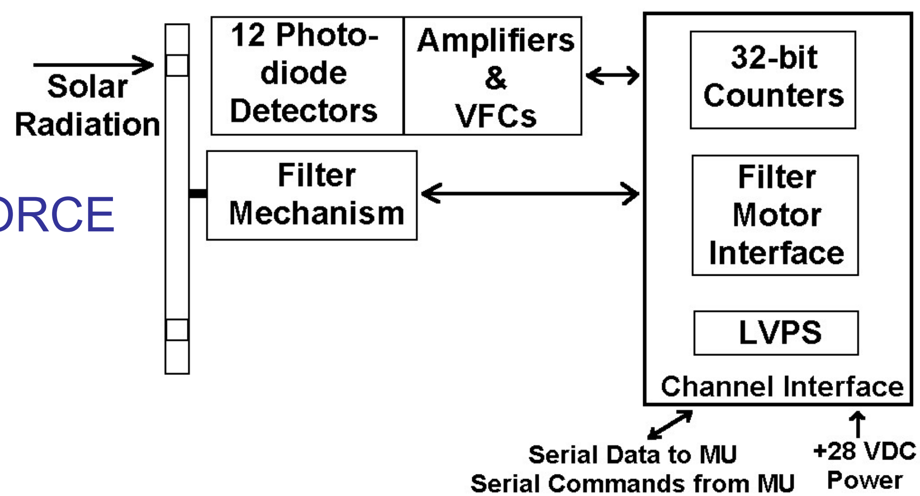
XPS Instrument Overview

Overview of XUV Photometer System (XPS)

- Instrument Type: Filter Photometers
- Wavelength Range: 0.1-40 nm
- Wavelength Resolution: 1-10 nm
- Optics: Thin film filters
  - deposited directly on Si diodes
- Detectors: 12 Si photodiodes
  - 8 XUV, Ly-α, 3 bare
- Absolute Accuracy: 20%
- Long-term Accuracy: 1%/yr
- Field of View: 4° cone
- Mass: 3 kg
- Orbit Average Power: 9 W
- Orbit Average Data Rate: 0.3 kbits/s
- Redundancy: 3 redundant XUV diodes
- Flights: rocket, SNOE, TIMED SEE, SORCE



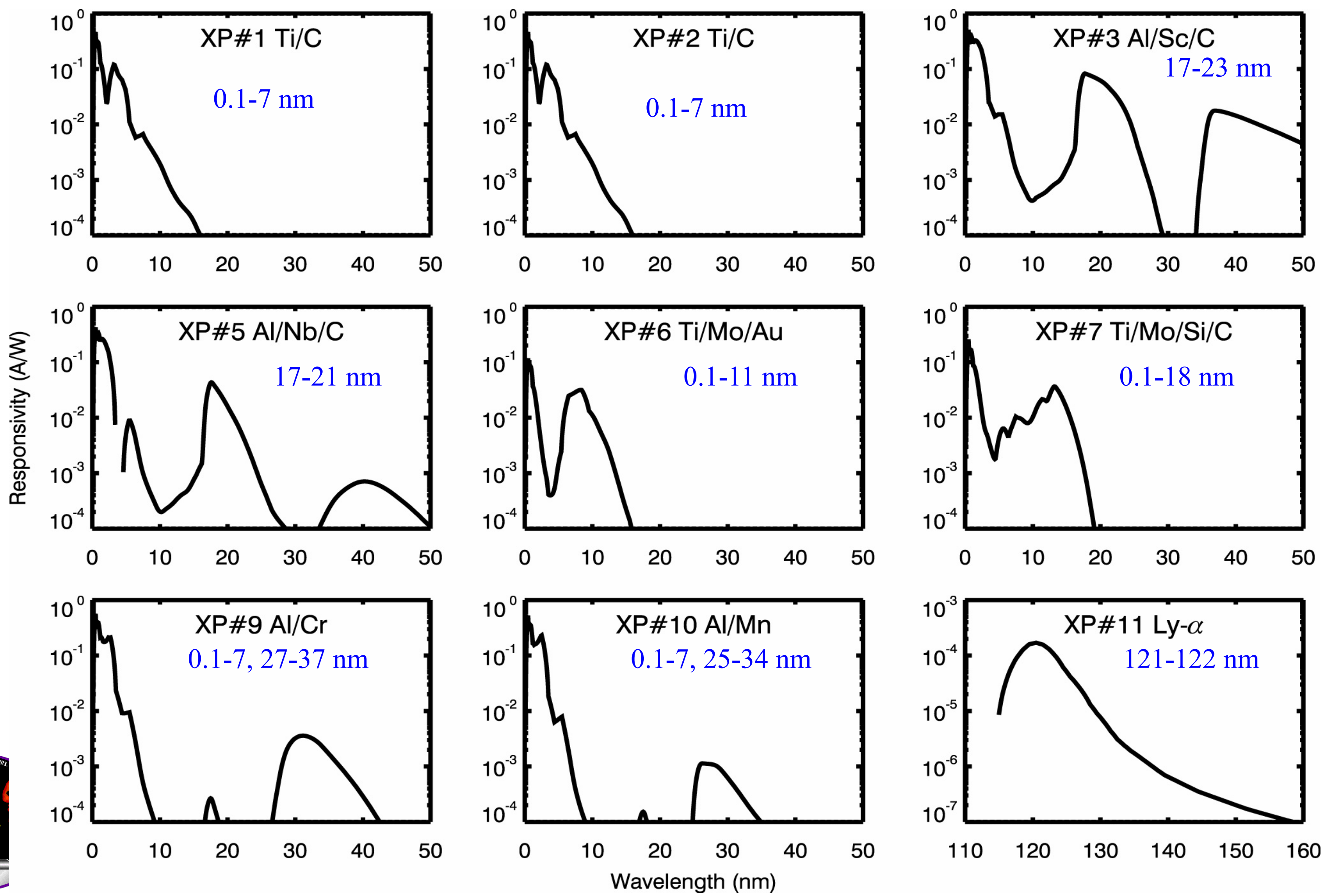
New Technology
Stable XUV Si Photodiodes
Low-noise Electrometers
Highly Linear VTFs with 32-bits



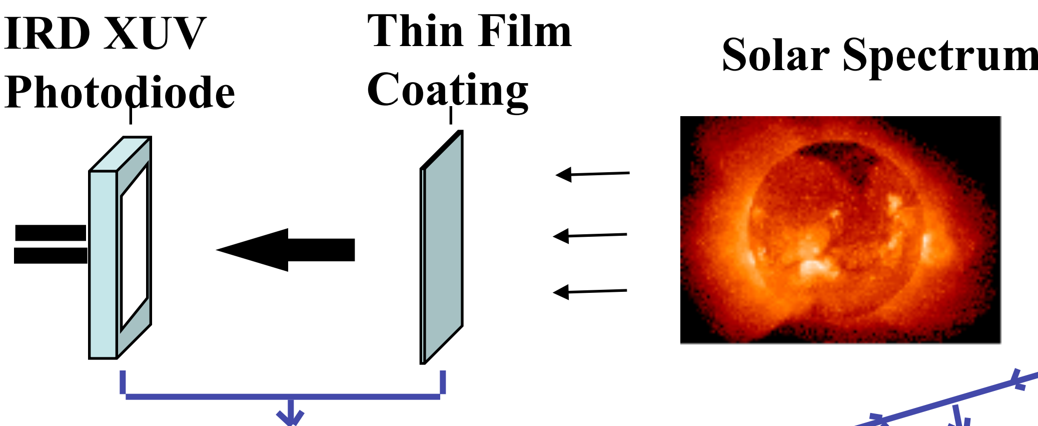
SORCE

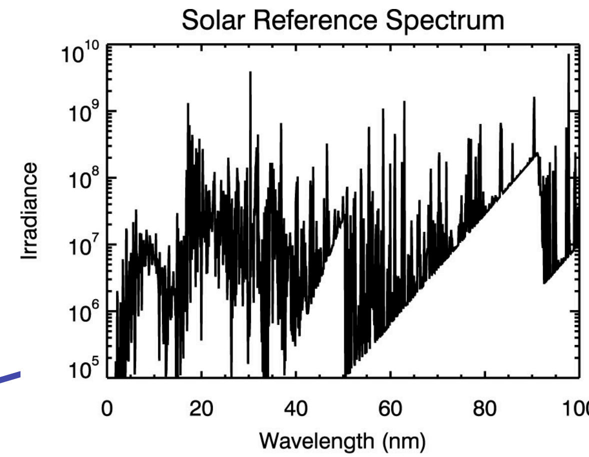
XPS Wavelength Coverage / Resolution

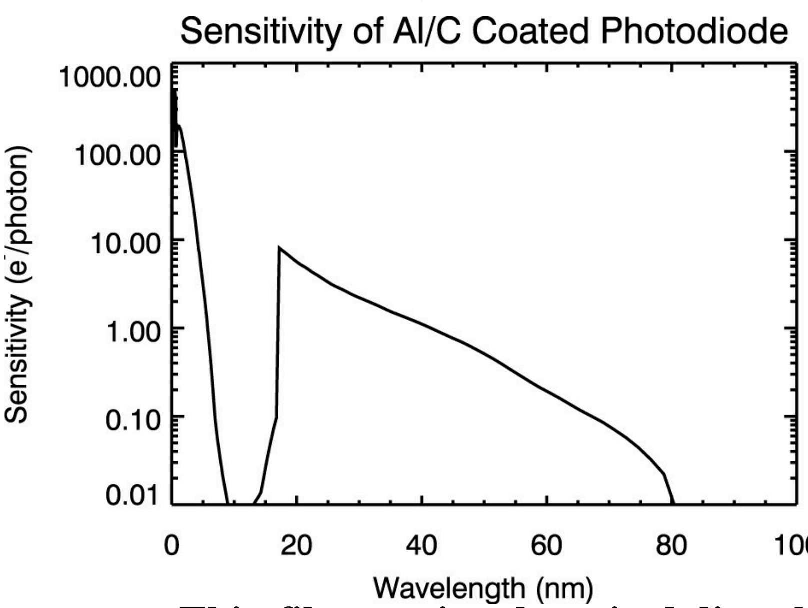
- Designed / selected filter coatings for specific broad bands
  - 0.1-7 nm, 7-17 nm, 17-24 nm, 24-34 nm, 121.5 nm
- TIMED SEE XPS and SORCE XPS are essentially the same
  - 12 photometers: 8 XUV, 1 Lyman-α, 3 bare (visible) diodes

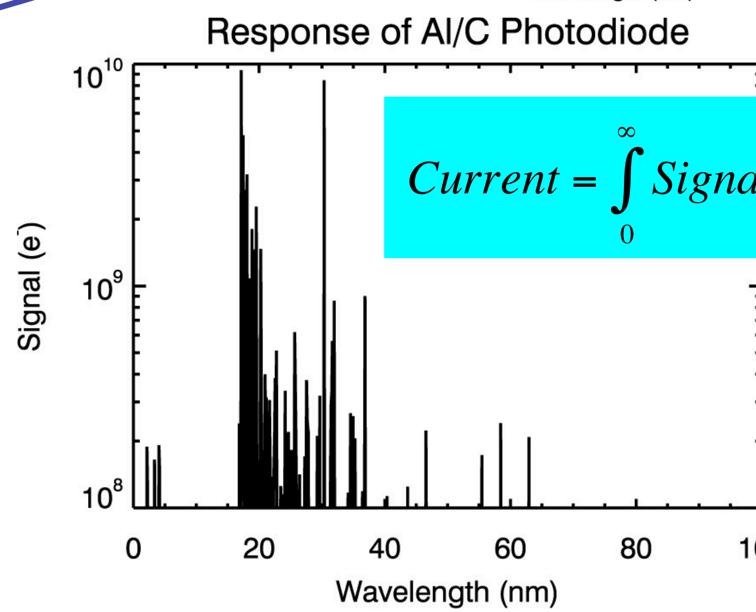


XPS Measurement Approach - Filter Photometer







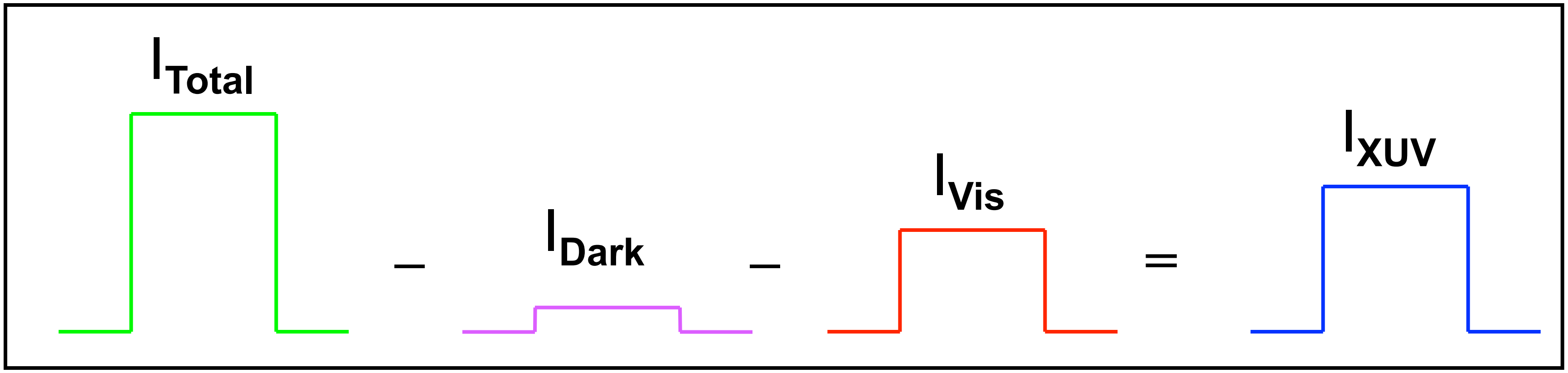


$$Current = \int_0^\infty Signal \bullet d\lambda$$

Thin film coating deposited directly on photodiode produces detector with a defined x-ray bandpass.

X-ray bandpass convolved with solar spectrum defines range of solar sensitivity.

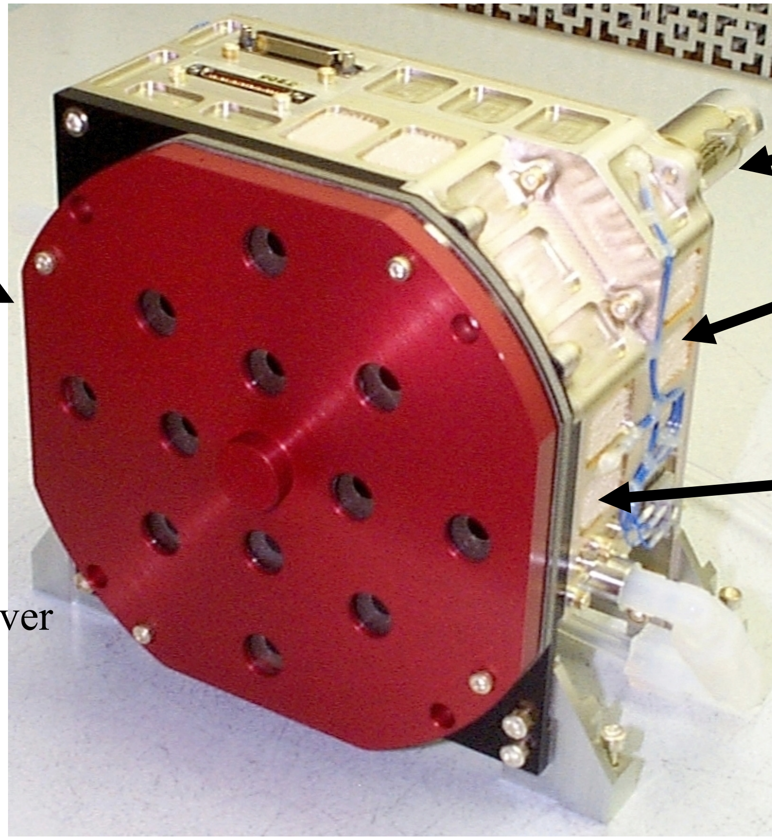
XUV Photometer Signal Contributions



- I_{Total} : integrated signal across all wavelengths that pass through the coating
- I_{Dark} : dark signal related mostly to DC offset of charge amplifiers and also to thermal noise of the Si photodiodes
- I_{Vis} : signal from long wavelength red-leaks and minor pinholes in thin-film metal coatings
  - To measure I_{Vis} a fused silica window is placed in front of the photometer, absorbing XUV wavelengths. $I_{VisMeasured}$ results.
  - $I_{VisMeasured}$ requires a window transmission correction to get I_{Vis}

$$I_{Vis} = I_{VisMeasured} / T_{Vis\ Fused\ Silica\ Window}$$

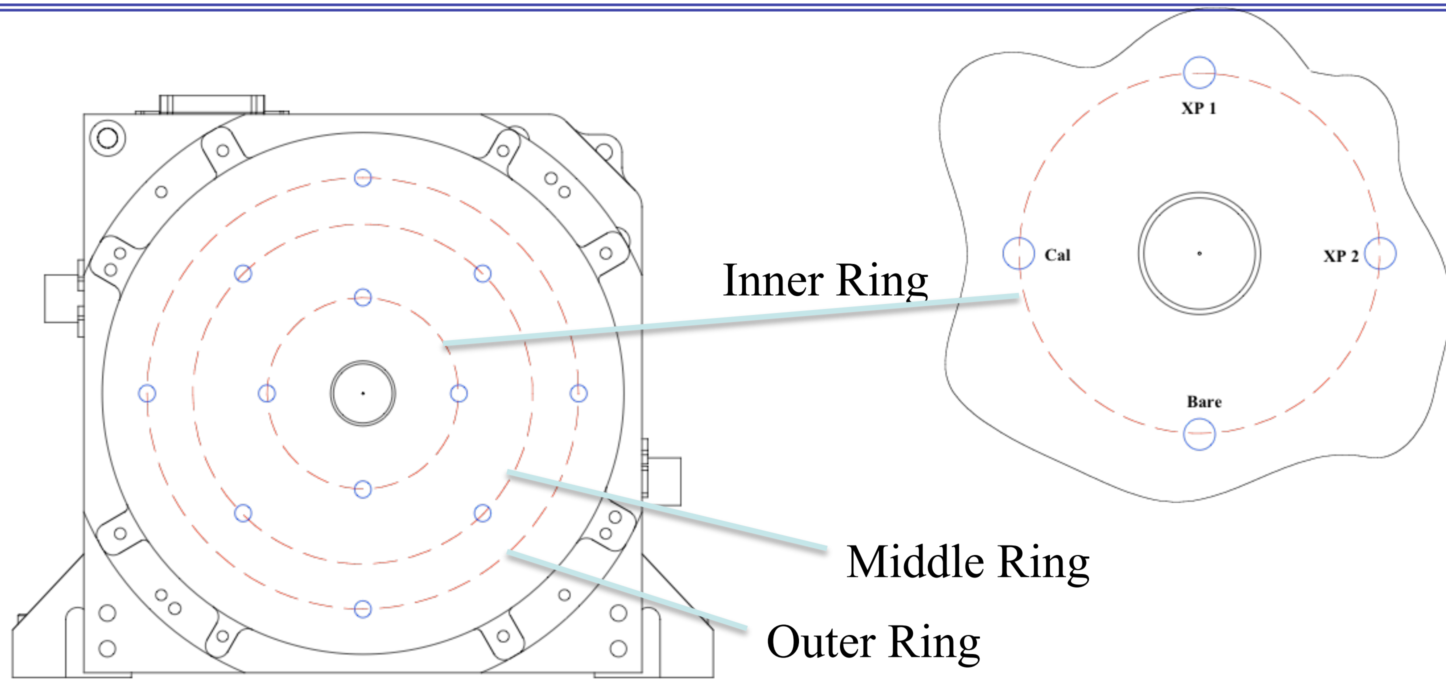
XPS Has One Mechanism



A filter wheel mechanism is used to measure separately the XUV, dark, and visible signals for the XPS photometers.

- Filter Wheel has 8 positions
- Each diode has 5 dark, 1 open (XUV), and 2 windows (visible)

Aperture Layout



- 3 concentric rings of photometers, 4 photometers per ring, total of 12
- Each ring consists of a set of photometers with:
  - 2 primary XUV photodiodes
  - 1 bare photodiode
  - 1 redundant (calibration) XUV photodiode

TIMED Solar Euv Experiment SORCE

XPS Filter Wheel Positions / Operations

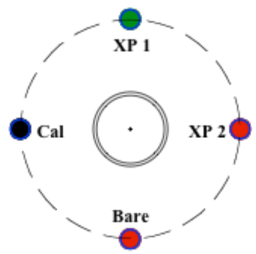
- Filter wheel has 8 positions
- Each photometer has 5 dark, 1 light, 2 FS windows

XP No.	Filter Coating	Filter Wheel Position							
		0	1	2	3	4	5	6	7
1	Ti/C	FS-1	Dark	Dark	Dark	FS-2	Dark	**Clear**	Dark
2	Ti/C	Dark	Dark	FS-2	Dark	**Clear**	Dark	**FS-1**	Dark
3	Al/Sc/C	FS-2	Dark	**Clear**	Dark	FS-1	Dark	**Dark**	Dark
4	None	**Clear**	Dark	FS-1	Dark	Dark	Dark	**FS-2**	Dark
5	Al/Nb/C	FS-2	Dark	**Clear**	Dark	FS-1	Dark	**Dark**	Dark
6	Ti/Mo/ Au	**Clear**	Dark	FS-1	Dark	Dark	Dark	**FS-2**	Dark
7	Ti/Mo/Si/ C	FS-1	Dark	Dark	Dark	FS-2	Dark	**Clear**	Dark
8	None	Dark	Dark	FS-2	Dark	**Clear**	Dark	**FS-1**	Dark
9	Al/Cr	**Clear**	Dark	FS-1	Dark	Dark	Dark	**FS-2**	Dark
10	Al/Mn	FS-1	Dark	Dark	Dark	FS-2	Dark	**Clear**	Dark
11	Ly-α	Dark	Dark	FS-2	Dark	**Clear**	Dark	**FS-1**	Dark
12	None	FS-2	Dark	**Clear**	Dark	FS-1	Dark	**Dark**	Dark

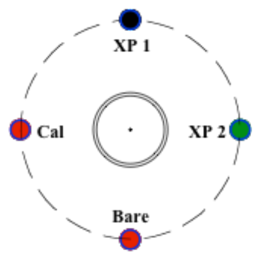
FS = Fused Silica window (2 per ring)

Post-Anomaly is Position 6

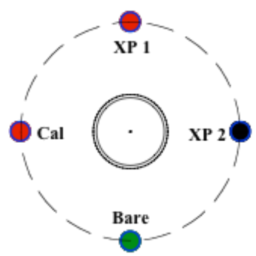
Filter Wheel Operation



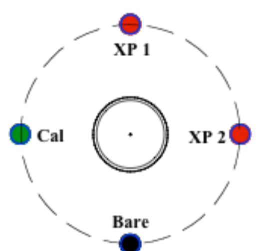
Position 1



Position 3



Position 5

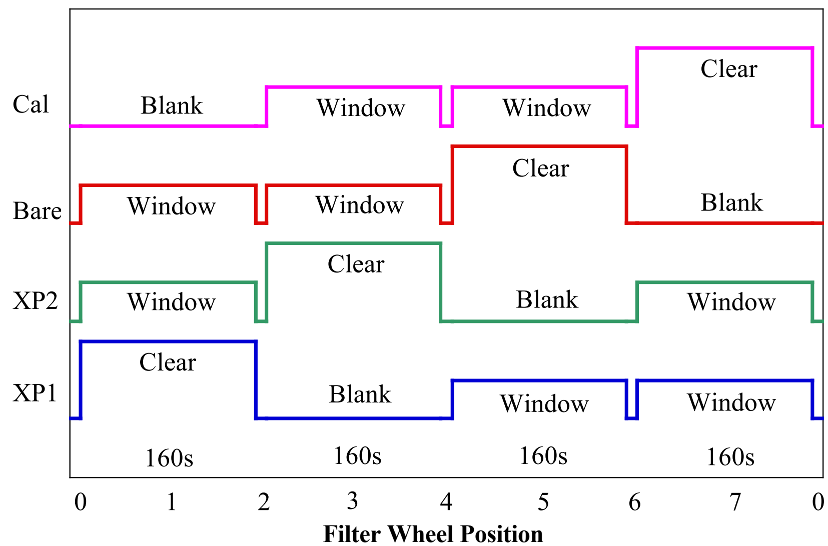


Position 7

On the rotating Filter Wheel, each ring has

- – 1 Clear aperture
- – 2 Fused silica windows
- – 1 Blank (additional 4 positions also blank)

These cycle past each of the photometer apertures during one revolution of filter wheel



TIMED SEE: Filter wheel rotated each orbit
SORCE: Filter wheel rotated around every 5 minutes

XPS Flights and Current Status

- 12 rocket flights since 1992
  - prototype TIMED SEE XPS used since 1997
- SNOE version of XPS: 1998-2000
- TIMED SEE XPS: Jan. 2002 – present
  - XPS filter wheel anomaly in July 2002
    - Stuck in position 6 – operations have continued on in this position
    - Suspect issue is due to vespel part in mechanism detent system
- SORCE XPS: Mar. 2003 – present
  - XPS filter wheel anomaly in Dec. 2005
    - Stuck in position 0 but started to work 2 days later - continues to work OK
    - New XPS operations approach started in 2006 with 1-minute cadence in position 6 and monthly calibrations that use the filter wheel

XPS Data Products

- Level 0b/1: raw data

First # is for TIMED SEE, Second # is SORCE

- Level 1/2: irradiance data
  – simple algorithm: Irradiance = XUV_Signal * Factor
  – but complicated to understand for broad bands..
- Level 2/3: daily average of Level 1 irradiances
- Level 4: spectral model that matches Level 1
  – next slide
- Level 3: insertion of XPS Level 4 data into 1-nm bins for composite spectra on TIMED SEE and SORCE

TIMED Solar EUV Experiment

SORCE

XPS Level 1/2 Simple Irradiance Algorithm

- Irradiance = Signal * Factor
  - "Signal" is first corrected for dark and visible contributions
  - "Factor" has many parameters

$$E_i = \frac{\left(I_{i,total} - I_{i,dark} - I_{i,visible}\right)}{f_{i,E\_total} \bullet < T_{i,xuv} > \bullet A_i \bullet f_{i,xuv\_fov}} \bullet k_E \bullet f_{Degrade}$$

- Visible Signal is based on in-flight measurements
  - Transmission is measured by the "visible" diodes

$$I_{i,visible} = \frac{\left(I_{i,window} - I_{i,dark}\right)}{T_{window}} \bullet \frac{f_{i,clr\_fov}(\alpha_{xuv}, \beta_{xuv})}{f_{i,vis\_fov}(\alpha_{window}, \beta_{window})}$$

$$T_{window} = \frac{\left(I_{b,window} - I_{b,dark}\right)}{\left(I_{b,clear} - I_{b,dark}\right)} \bullet \frac{f_{b,clr\_fov}(\alpha_{clear}, \beta_{clear})}{f_{b,vis\_fov}(\alpha_{window}, \beta_{window})}$$

- "Reference Spectrum" is required
  - One factor is the ratio of the total signal to the signal over a limited band. Band width is adjusted so this factor is close to 1.
  - Another factor is average transmission value over the band.
  - "Reference Spectrum" is average of solar cycle Min and Max (NRLSSI)

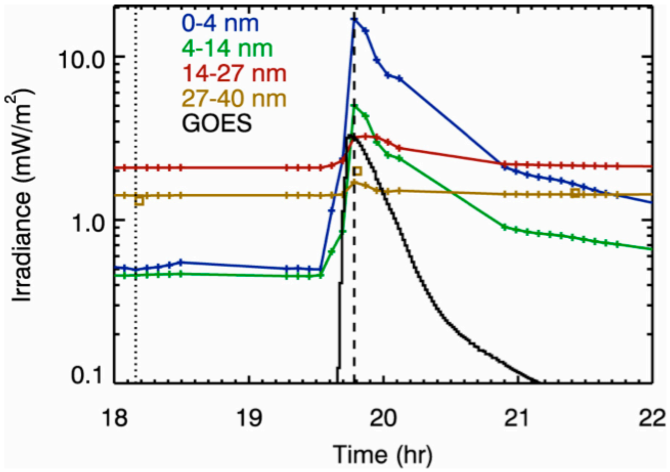
$$f_{i,E\_total} = \frac{\int_0^{\infty} T \bullet E \bullet d\lambda}{\int_{\lambda_1}^{\lambda_2} T \bullet E \bullet d\lambda}$$

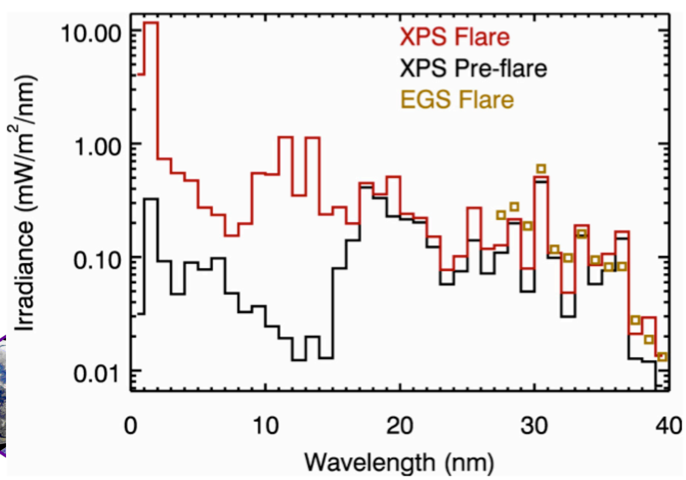
$$\langle T_{i,xuv} \rangle = \frac{\int_{\lambda_1}^{\lambda_2} T \bullet E \bullet d\lambda}{\int_{\lambda_1}^{\lambda_2} E \bullet d\lambda}$$

This works fine for non-flare data.

Motivation for Level 4 Spectral Model

- Improve the XUV irradiance during flare events
- Provide higher spectral resolution than the broad bands of the XPS





<u>Example flare time series and spectra.</u>

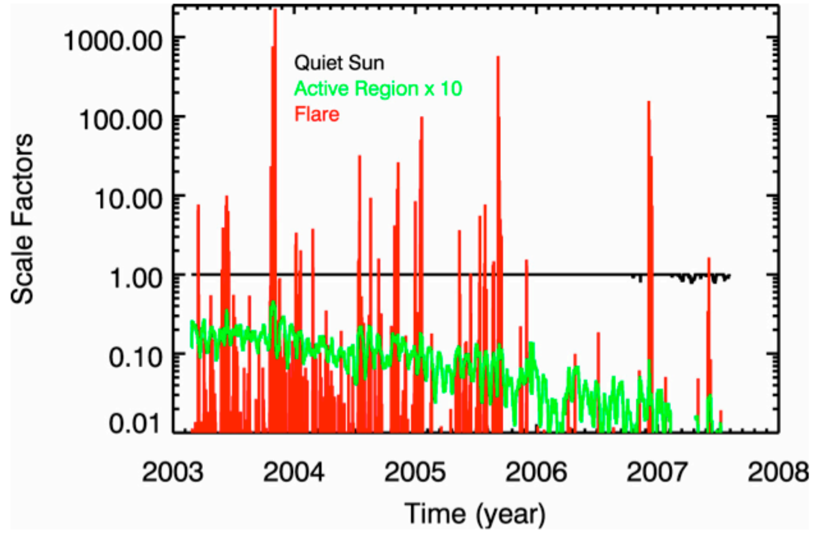
In the top panel, the time series of the large X28 flare on 4 November 2003 is shown for several bands from the new XPS Level 4 product, along with the GOES 0.1-0.8 nm X-ray measurement. As for this example, the 0-4 nm band is often the dominant emissions during a flare but is a minor contribution at other times.

In the bottom panel, the spectrum near the peak of the flare (dashed line in top panel) is compared to the pre-flare spectrum (dotted line in top panel). The majority of the irradiance increase is shorter than 15 nm. The XPS Level 4 model results are in reasonably good agreement with the SEE EGS spectral measurements at longer than 27 nm.

XPS Level 4 Spectral Model uses CHIANTI Spectra

- Two daily components fit to daily minimum value
  quiet Sun (QS) - $E_{Min}(\lambda)$
  active region (AR) - $E_{AR}(\lambda)$
- **Flare** component (above daily min.) - $E_{flare}(T,\lambda)$
  flare temperature from GOES X-ray data

Level 4 Results are Irradiance Spectra, Flare Temperature, and three Scale Factors (f_{Min}, f_{AR}, and f_{Flare})



Input: XPS Measurement - photometer current (I), responsivity (R)

$$I_{measure} = I_{day\_min} + I_{flare}$$

$$I_{day\_min} = f_{Min} \bullet \int_0^{\infty} R(\lambda) \bullet E_{Min}(\lambda) \bullet d\lambda + f_{AR} \bullet \int_0^{\infty} R(\lambda) \bullet E_{AR}(\lambda) \bullet d\lambda$$

CHIANTI Spectral Models
[Dere *et al.*, 1997; Landi *et al.*, 2006]

$$E_{L4}(\lambda) = f_{Min} \bullet E_{Min}(\lambda) + f_{AR} \bullet E_{AR}(\lambda) + f_{Flare} \bullet E_{Flare}(T,\lambda)$$

Output: XPS Level 4 Irradiance Spectra (0.1 nm resolution)
flare Temperature (T), 3 scale factors

TIMED Solar EUV Experiment
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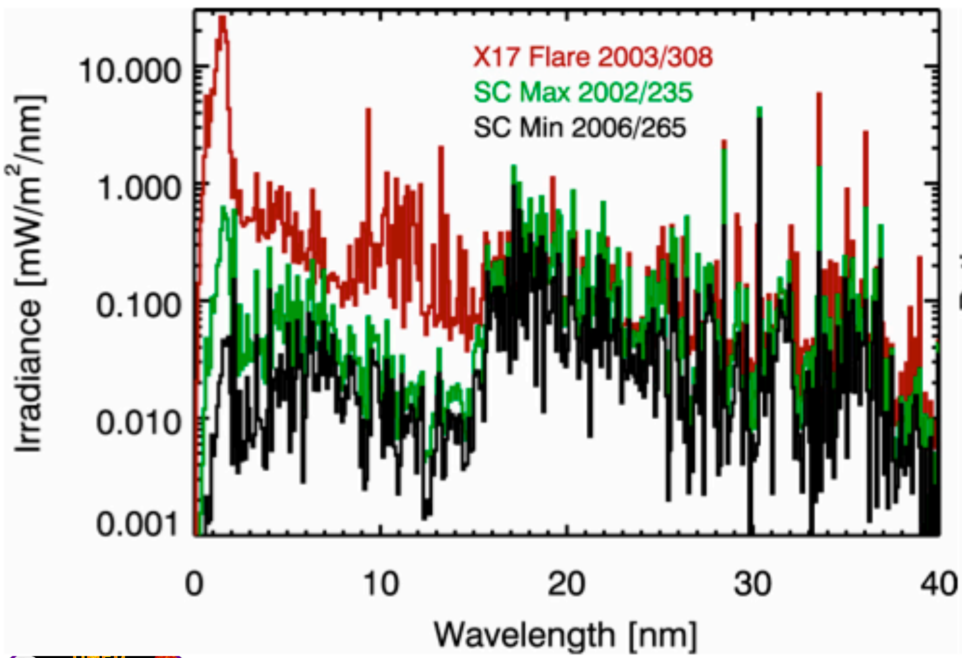
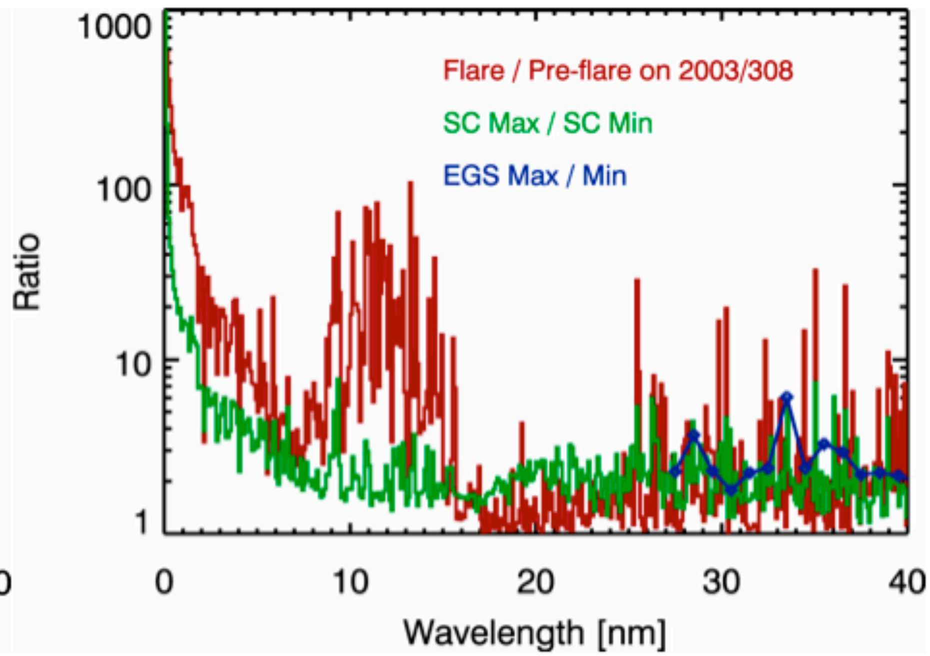
Example Solar Flare Variation

- Variations for the large flares are larger than solar cycle variations
- Flare variations dominate shortward of 15 nm
- Level 4 active region scale factor represents the fractional disk covered by active regions





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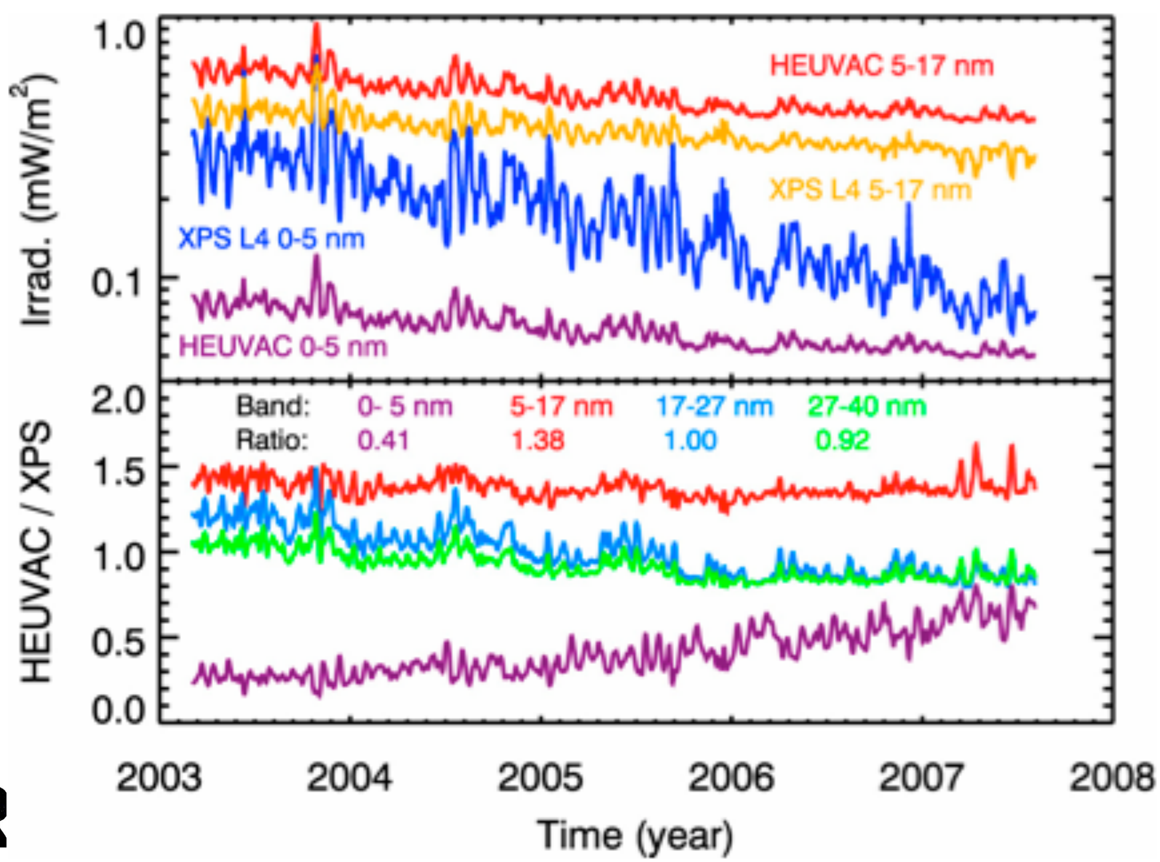
Comparison of XPS Level 4 to HEUVAC Model

- HEUVAC model is by Richards et al. [2006]
- The top panel shows the irradiances for the 0-5 nm and 5-17 nm bands as they differ the most.
- The bottom panels shows the ratio of HEUVAC to XPS Level 4 bands.



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Lessons Learned from XPS Instrument

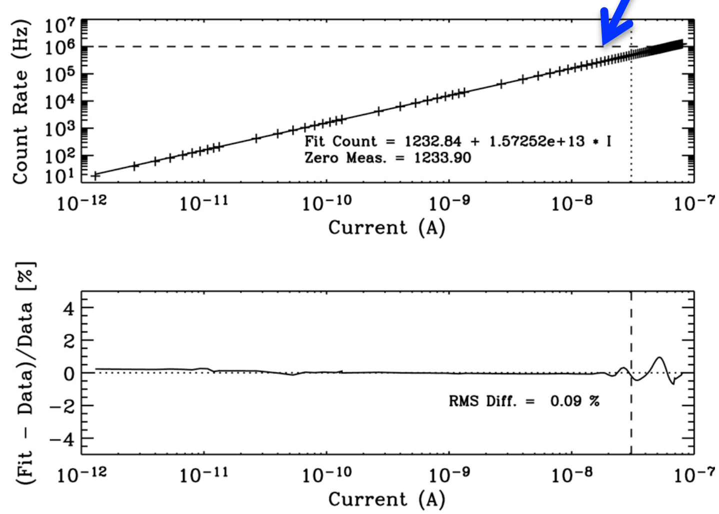
- Calibration (accuracy) Lesson
  - Use multiple calibration techniques / references to achieve best accuracy
- Spectral Resolution Lesson
  - Easier to interpret results with higher spectral resolution
    - i.e., data processing results can be dependent on spectral models when working with broad band photometers
- Filter Wheel Mechanism Lessons
  - Better to use direct drive, or at least few gears
  - Motor control should have forward/reverse direction and, if possible, redundant winding
  - Braycote (wet) lubrication better for gears (versus dry lub)

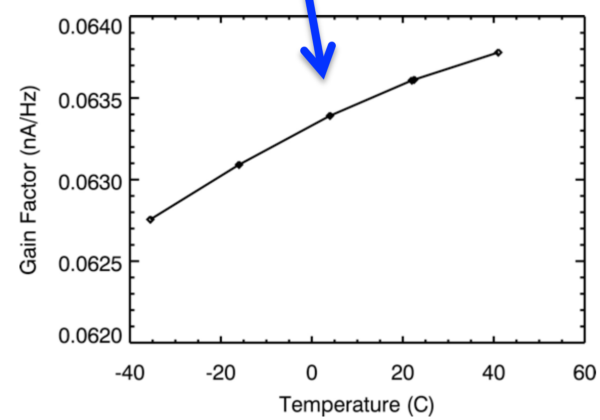
XPS Calibrations

XPS Calibration Overview

➢ Pre-flight Calibrations

- Selection of filter diodes without pinholes
- Responsivity calibrations (PTB BESSY, NIST SURF-III) with 5-15% accuracy
- Electronics gain calibration: linearity check and as function of temperature





➢ In-flight Calibrations

- Rocket underflight calibrations using prototype XPS (about once per year)
  - NIST SURF-III used for the rocket XPS calibrations
- Redundant channel calibrations (initially once a day, now once a month on SORCE)

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XPS Diode Calibration History

- TIMED XPS diodes calibrated at PTB BESSY in 1998 (Frank Scholze)
  - reference diode used with monochromator and synchrotron source
  - calibrations are between 1 and 25 nm
  - TIMED launched in Dec. 2001
- SORCE XPS diodes calibrated at NIST SURF-III in 2001 (Rob Vest)
  - reference diode used with monochromator and synchrotron source (BL-9)
  - calibrations are between 5 and 50 nm
  - SORCE launched in Jan. 2003
- Rocket XPS diodes calibrated at NIST SURF-III in 2003 (Tom Woods)
  - direct use of synchrotron source (BL-2) with multiple beam energies
  - calibrations are over all wavelengths, but results primarily over the 0-34 nm range
  - Annual underflight calibration rockets: Feb. 2002, Aug. 2003; next: Oct. 2004
- TIMED SEE Version 7+ data and SORCE XPS Version 5+ data are based on the 2003 rocket XPS calibration

Two Batches of Diodes Calibrated

Batch 1 (1998-TIMED)

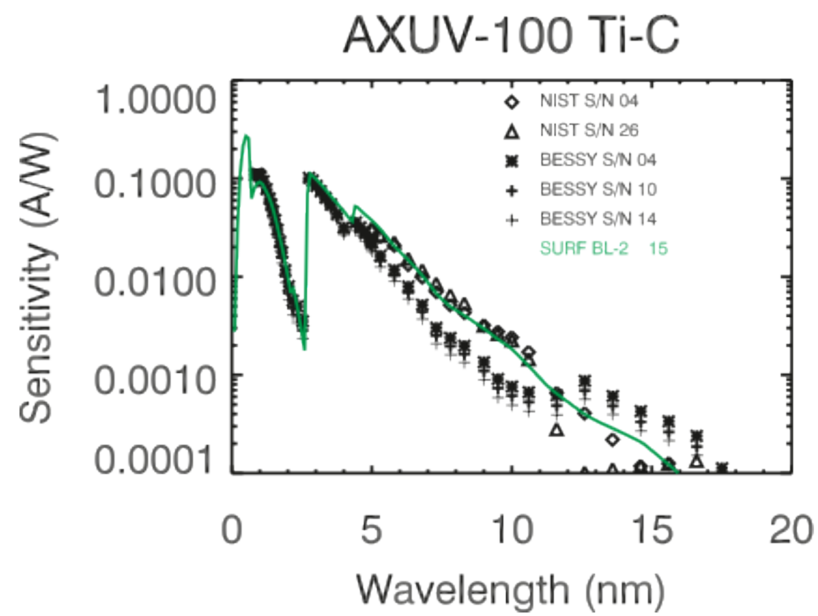
Filter Coating	Thickness (Å) Specification	Thickness (Å) from BL-2
Ti - C	5000 / 500	3875 / 500
Ti-Zr-Au	200/2000/1000	-
Ti-Pd	2000 / 1000	1628 / 791
Al-Sc-C	2000/1000/500	-
Al-Nb-C	2500/500/500	2089/392/473
Al-Cr	2000 / 1000	-
Al-Mn	2000 / 1000	-

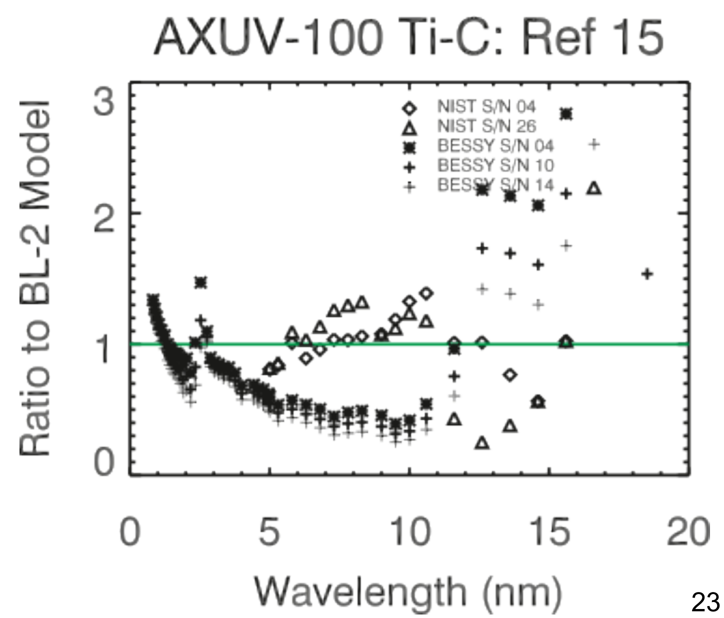
Batch 2 (2000-SORCE)

Filter Coating	Thickness (Å) Specification	Thickness (Å) from BL-2
Used Batch #1 Ti-C		
Ti-Mo-Au	400/2000/1000	452/1113/741
Ti-Mo-Si-C	400/2000/1000/500	341/1313/1035/461
Al-Sc-C	2700/500/500	1791/500/250
Used Batch #1 Al-Nb-C		
Al-Cr	2700 / 1000	1750 / 1114
Al-Mn	2700 / 1000	1750 / 1447

Ti-C Photodiode Calibration

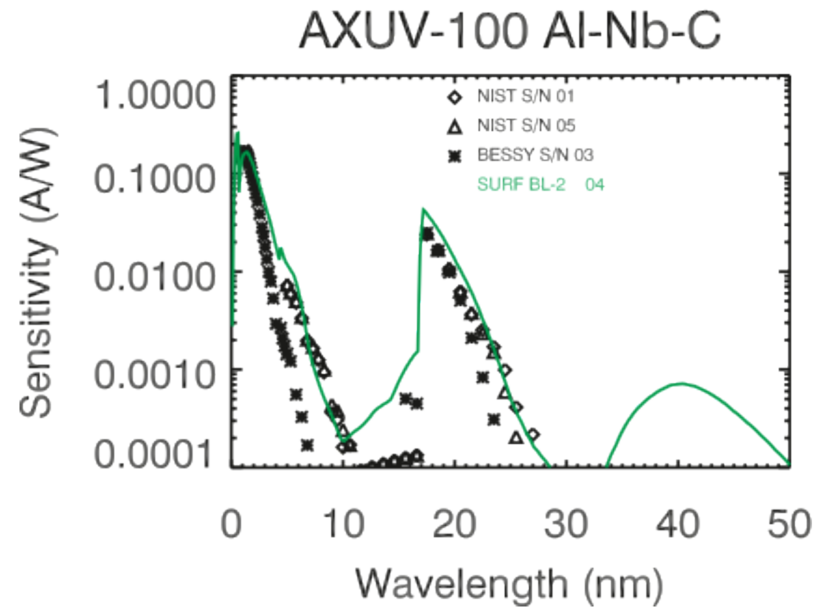
- All Ti-C diodes are from Batch 1 and are expected to be similar
- Factor of 2 differences at some wavelengths
  - BESSY has good agreement < 4 nm, lower 4-12 nm, higher >12 nm
  - SURF BL-9 and BL-2 results agree

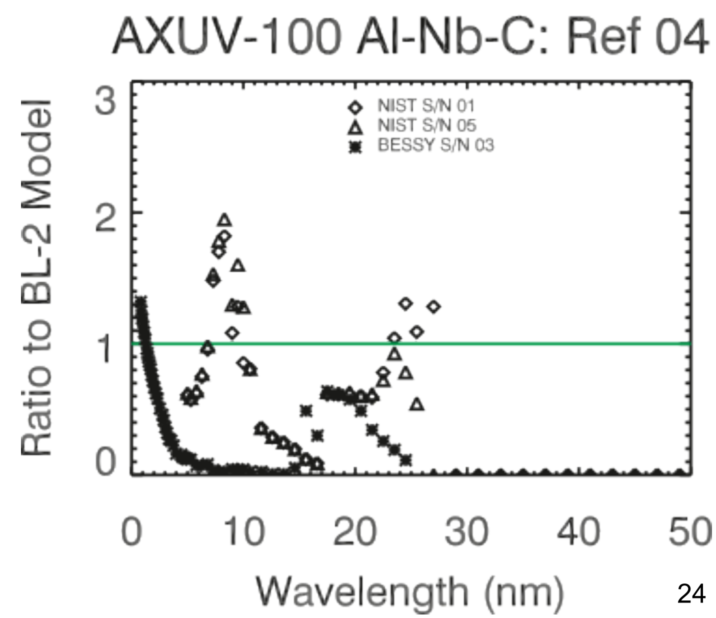




Al-Nb-C Photodiode Calibration

- All Al-Nb-C diodes are from Batch 1 and are expected to be similar
- Large differences at some wavelengths
  - BESSY has good agreement < 3 nm, lower 3-17 nm and >21 nm
  - SURF BL-9 and BL-2 results agree < 10 nm and > 23 nm
  - SURF BL-2 is higher 17-21 nm





TIMED Solar EUV Experiment

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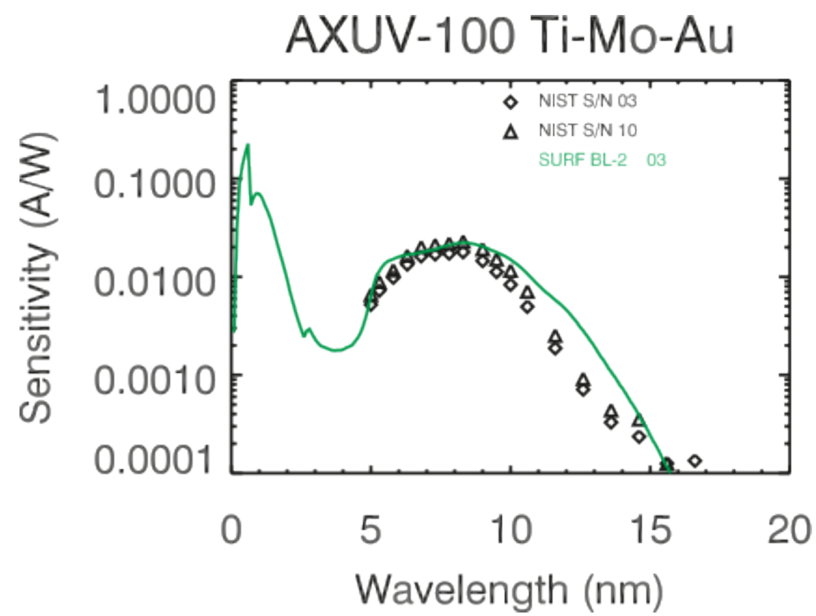
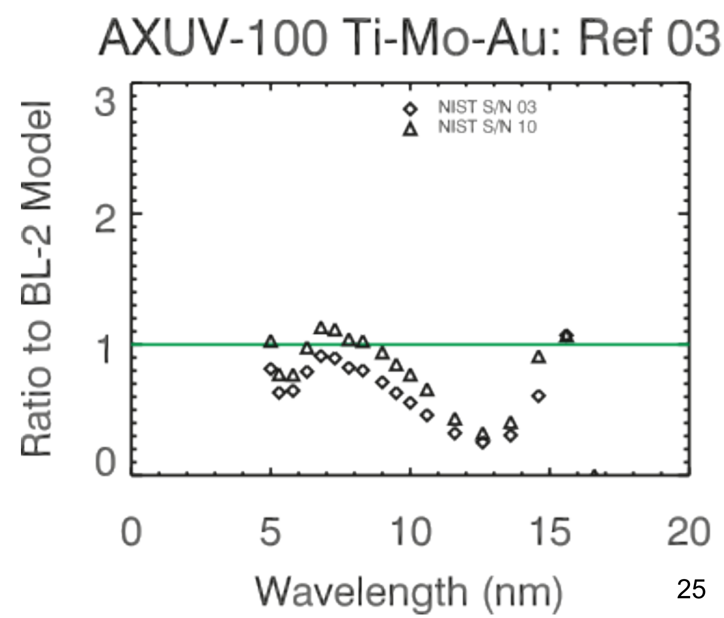
Ti-Mo-Au Photodiode Calibration

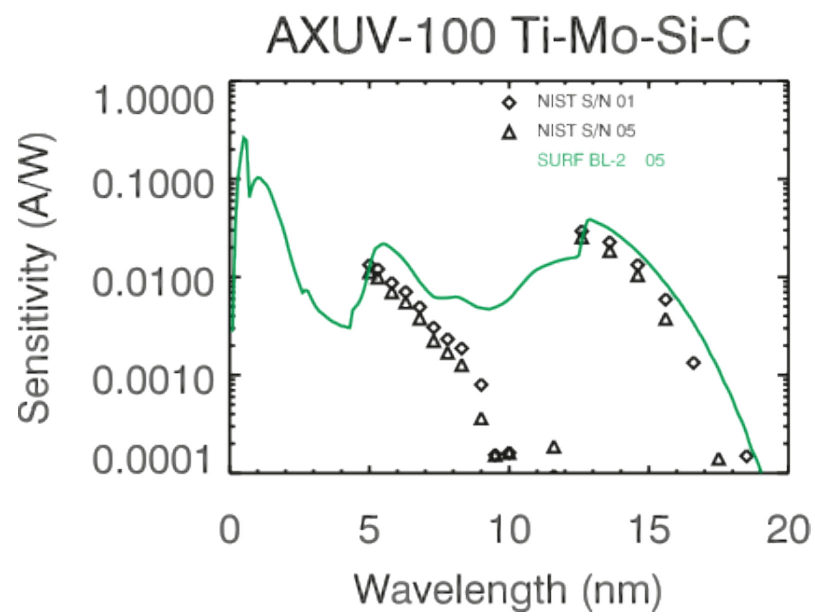
- Ti-Mo-Au diodes are from Batch 2 and are expected to be similar
- None of these diodes were calibrated at BESSY
- Good agreement between SURF BL-9 and BL-2 results
  - BL-2 result is higher 10-14 nm

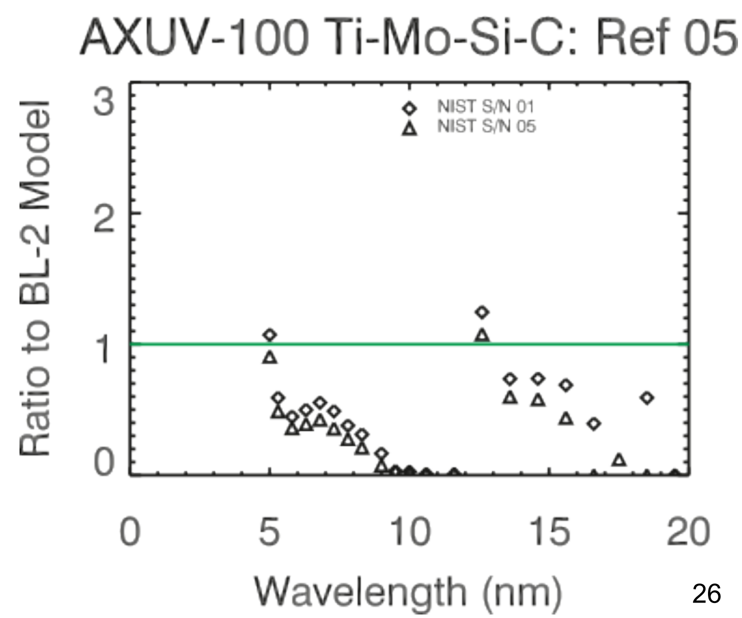




Ti-Mo-Si-C Photodiode Calibration

- Ti-Mo-Si-C diodes are from Batch 2 and are expected to be similar
- None of these diodes were calibrated at BESSY
- BL-2 results are higher than SURF BL-9 results





Summary of Comparisons

Generalization of Differences

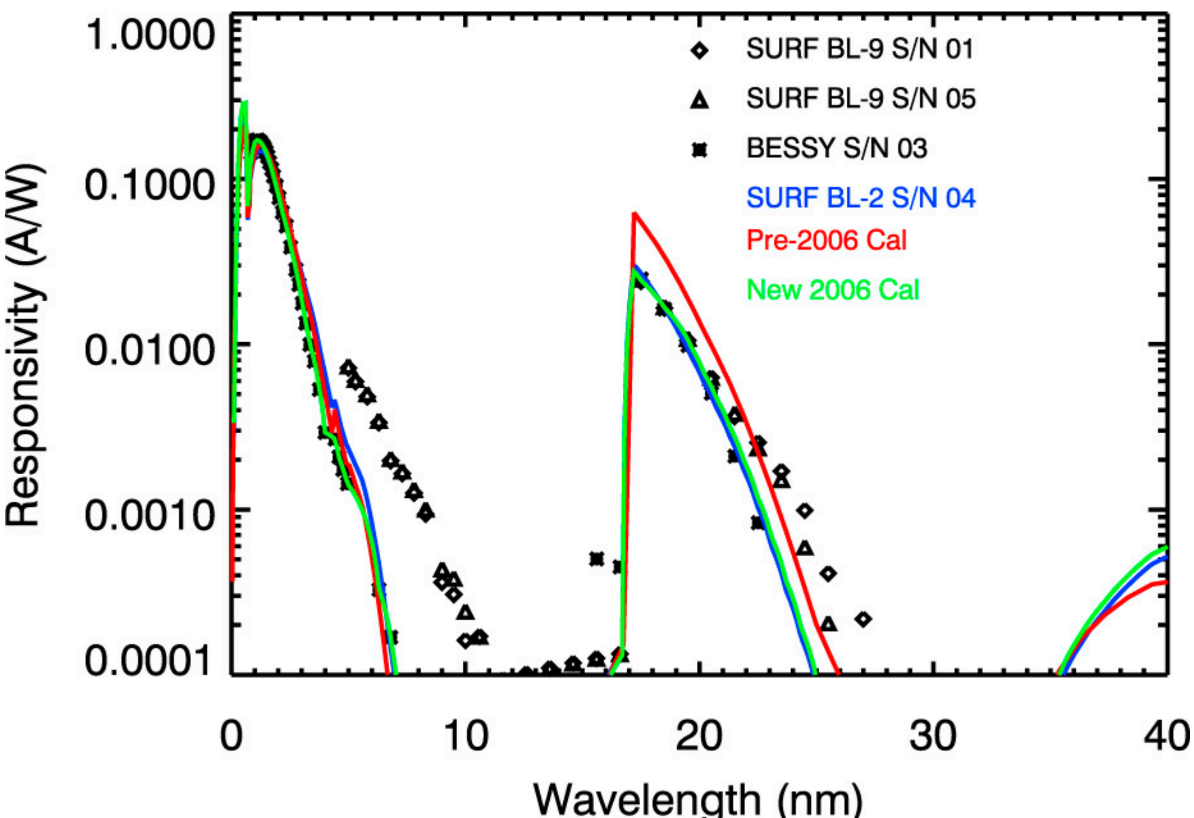
- BESSY is lower in the 3-10 nm range: exceptions are the Ti-Pd and Ti-Zr-Au diodes
- SURF BL-2 method is higher in the 17-35 nm range

Possible Causes for Differences

- Photodiode sensitivity could change with time, e.g. filter oxidation
  - Rocket XPS calibrated on SURF BL-2 in May 2003 and Jan. 2004 showed no degradation
  - Photodiodes stable now, but could have changed early in life
- SURF BL-2 method has larger errors at longer wavelengths (>17 nm) because sensitivity is much lower than peak sensitivity at short wavelength
- Filter transmission model (Henke material constants) could have wavelength dependent errors and would affect SURF BL-2 results
- BESSY and SURF BL-9 monochromator corrections for scattered light and higher orders are possibly more problematic where the sensitivity is low (orders of magnitude weaker than peak sensitivity)

Average is Used for XPS Data Processing

- XPS has three different pre-flight calibrations
  - NIST SURF BL-9 (monochromator + reference detector)
  - PTB BESSY (monochromator + reference detector)
  - NIST SURF BL-2 (direct synchrotron source: primary std)



- Updated XPS calibration in 2006 by merging best of these results
  - Previously used single calibration set in data processing
- Example shown for XP#5 (Al/Nb/C)

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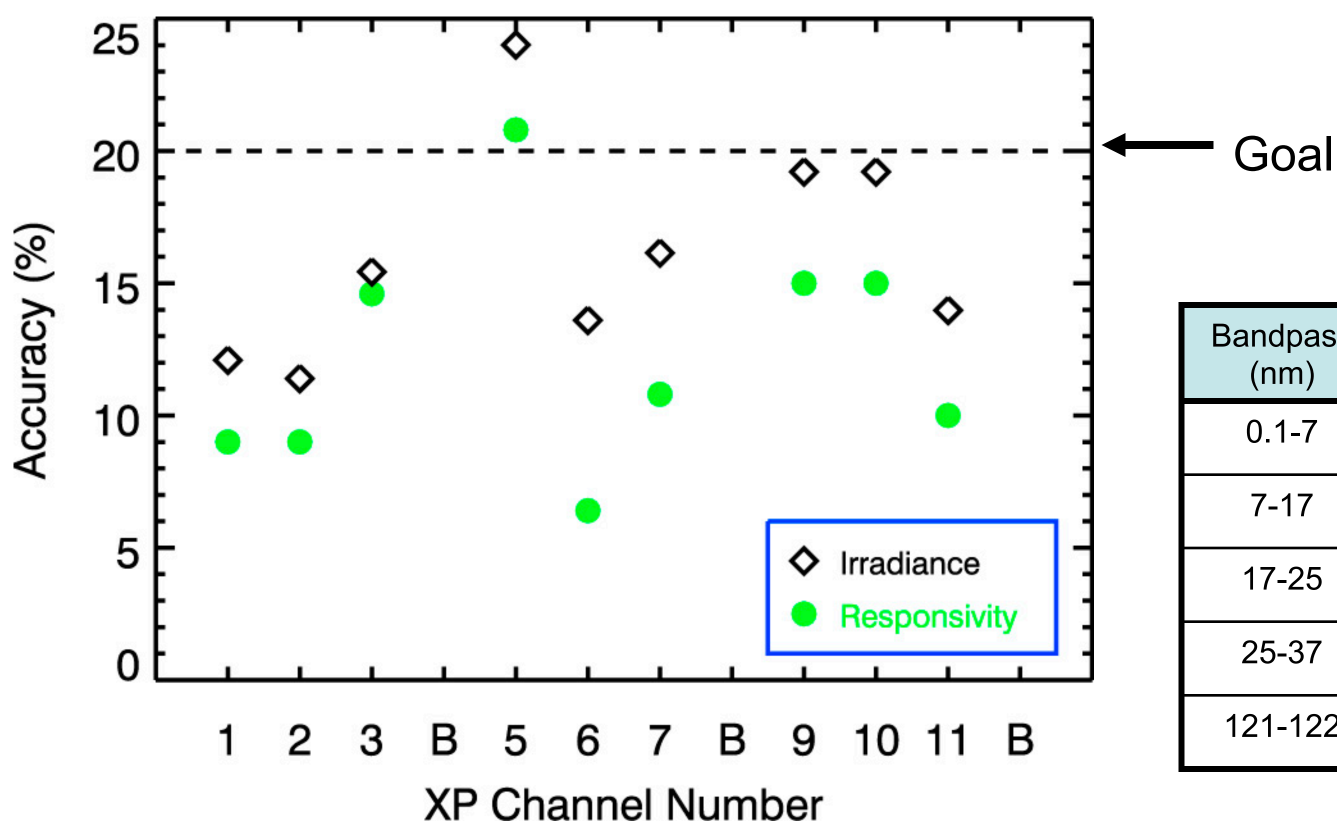
Irradiance Accuracy is about 15%

- Reponsivity accuracy is primary contribution to irradiance accuracy
- XP#1, #2, and #7 are used in XPS Level 4 processing
- XP#5 and #10 have higher than expected visible light signals and are not included in the public XPS data products



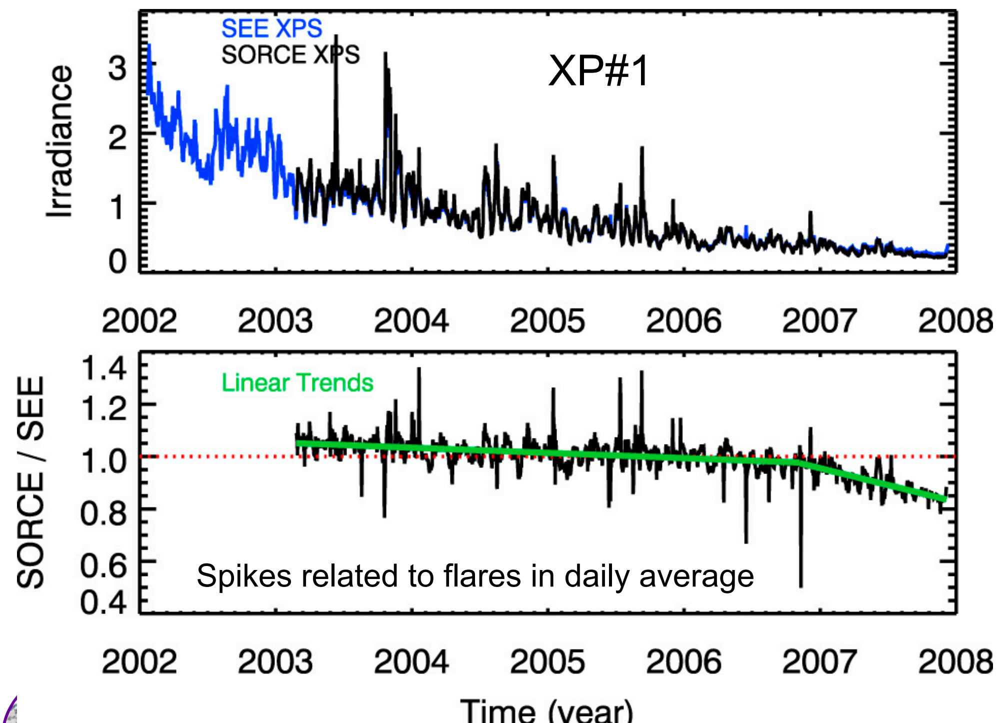
Bandpass (nm)	XP Channel
0.1-7	1, 2
7-17	6, 7
17-25	3, 5
25-37	9, 10
121-122	11

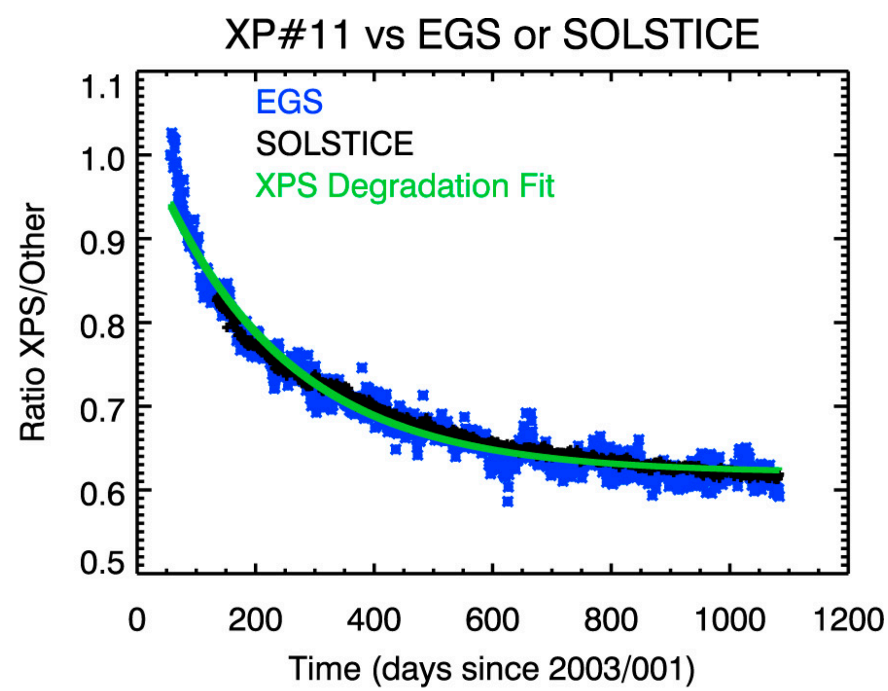
SORCE XPS Degradation Results

- Degradation tracked in-flight by using weekly on-board redundant channel calibrations, overlapping measurements by TIMED SEE and SORCE SOLSTICE, and annual calibration rocket flights
- Degradation Results (note goal is 10%/year for σ_{LT}):

Small for XUV channels before 2007
Moderate after 2007 (higher exposure rate)
σ_{LT} = 1.1%/5 yr = 0.2%/yr

Moderate for Ly-α filter (XP#11)
Exponential decay down to 0.62
σ_{LT} = 4.5%/3 yr = 1.5%/yr

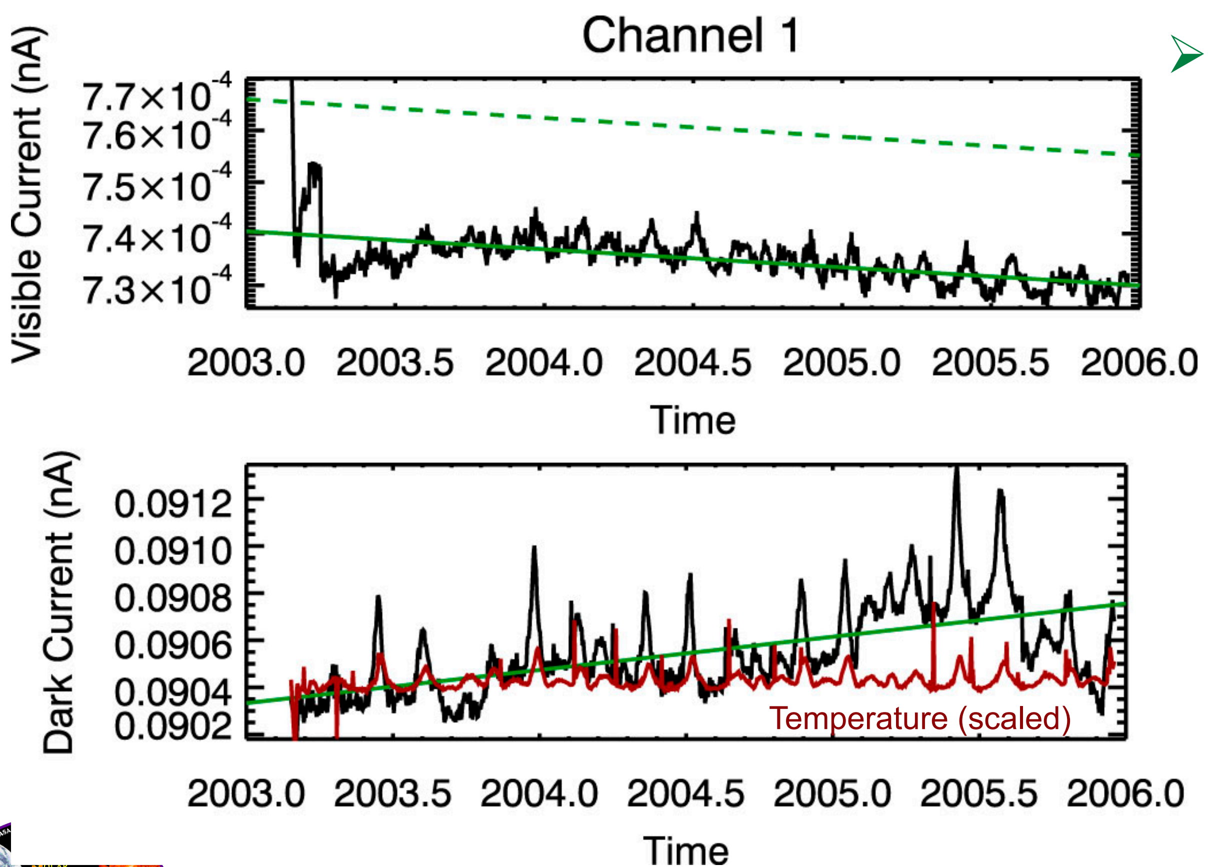




Due to its low duty cycle (3%), TIMED SEE XP#1 has had no degradation.

Additional In-flight Calibrations (trending)

- Visible Light Trend: Small time and temperature dependency
- Dark (background) Trend: Small time and temperature dependency



- Example shown for XP#1 (Ti/C)

Visible Light Current

- Time trend of 0.1%/year
- Temp. trend very small

Dark Current

- Time trend of 0.2%/year
- Temp. trend of 0.1%/°C

SORCE

Summary of XPS Calibrations

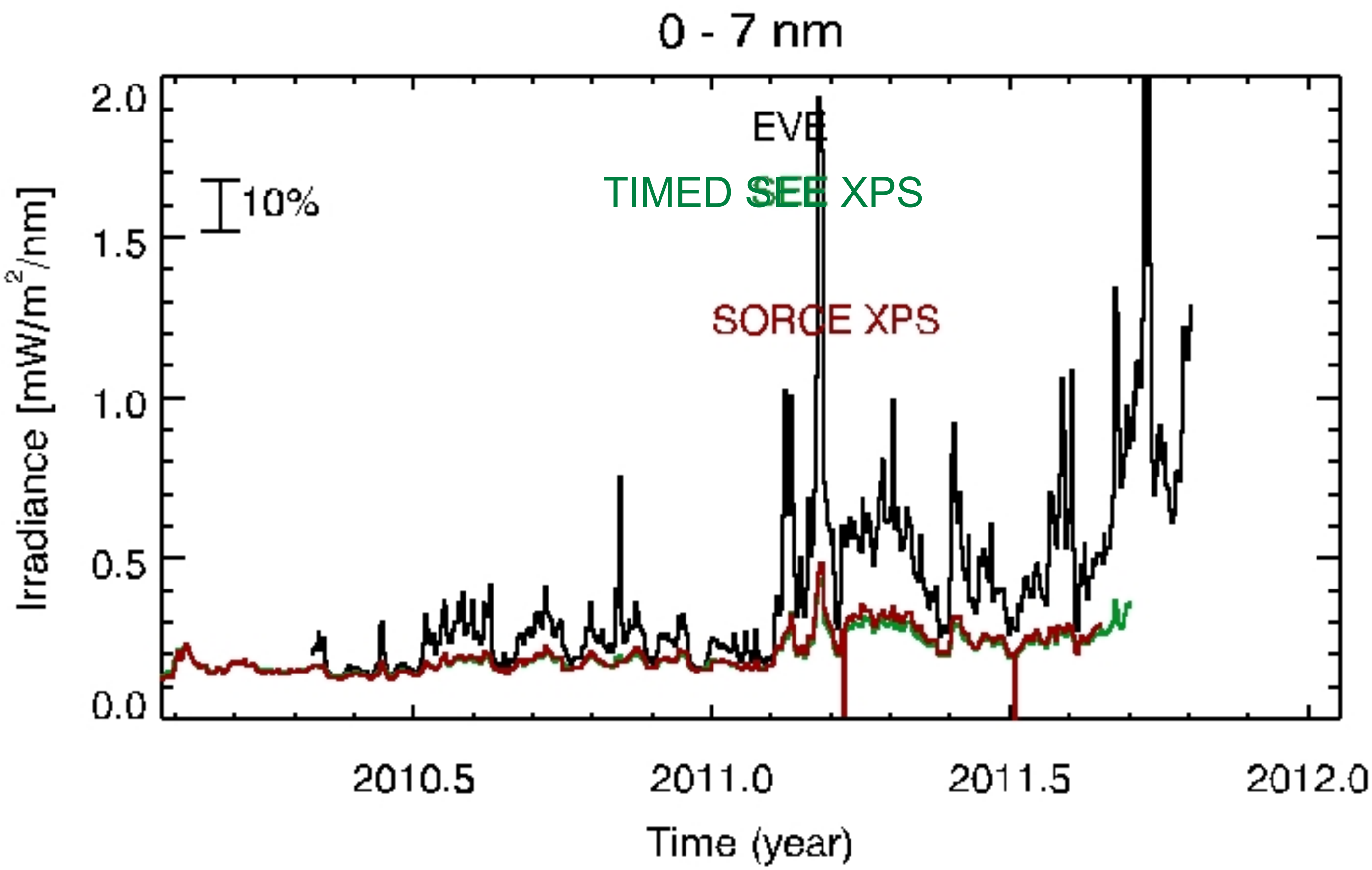
- The differences between BESSY, SURF BL-9, and SURF BL-2 are still not fully understood

- The XP#1 (0.1-7 nm) channels on both TIMED SEE and SORCE are the primary references for XPS
  - Best agreement for different BESSY and SURF calibrations
  - Has shown no degradation over 10 years for TIMED SEE XP#1
  - Has only single band and so is not very sensitive to spectral changes (such as flares)
  - Is used for scaling CHIANTI spectra for Level 4 product
  - Scales very well with the GOES XRS (X-ray) and thus is useful as proxy for the solar X-ray

XPS Comparisons to SDO EVE

XPS compared to SDO EVE ESP Quad

- XPS and ESP Quad agree for lower levels of solar rotation but not for the peaks - this might mean a difference in effective bandpass ???
- TIMED SEE XPS (3% duty cycle) and SORCE XPS (70% duty cycle) agree, so XPS – ESP difference is not expected to be a difference if including flares



XPS compared to SDO EVE MEGS

- XPS Level 4 spectral model has reasonable good agreement with the EVE MEGS spectra when XPS Level 4 is integrated over broad bands