SORCE Solar Spectral Irradiance Measurements

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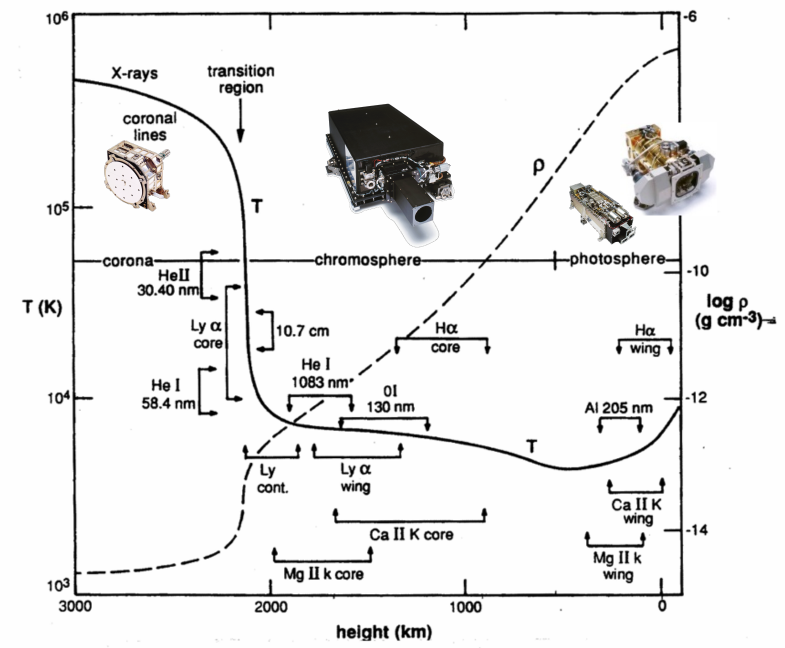
Outline

- Mission Overview
- SOLSTICE Methodology
- SIM Methodology
- Solar Variability Results
- Current Mission Status

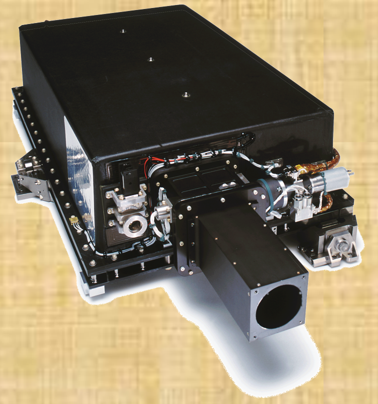
Solar Radiation and Climate Experiment

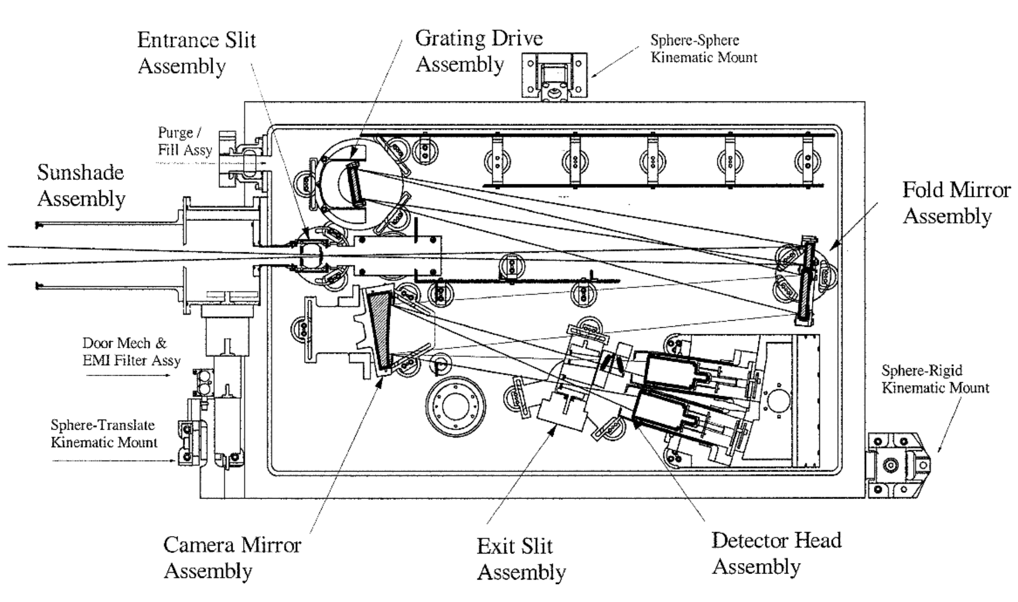
- Launched in 2003
- Produces daily (and 6-hour) averages of Solar Spectral Irradiance (SSI)
  - XPS – EUV
  - SOLSTICE – FUV and MUV (115-300 nm)
  - SIM – MUV to Infra-red (240-2400 nm)
- Data available from
  - LISIRD http://lasp.Colorado.edu/lisird
  - SORCE Web page http://lasp.Colorado.edu/sorce/data
  - NASA DAAC https://disc.gsfc.nasa.gov/SORCE



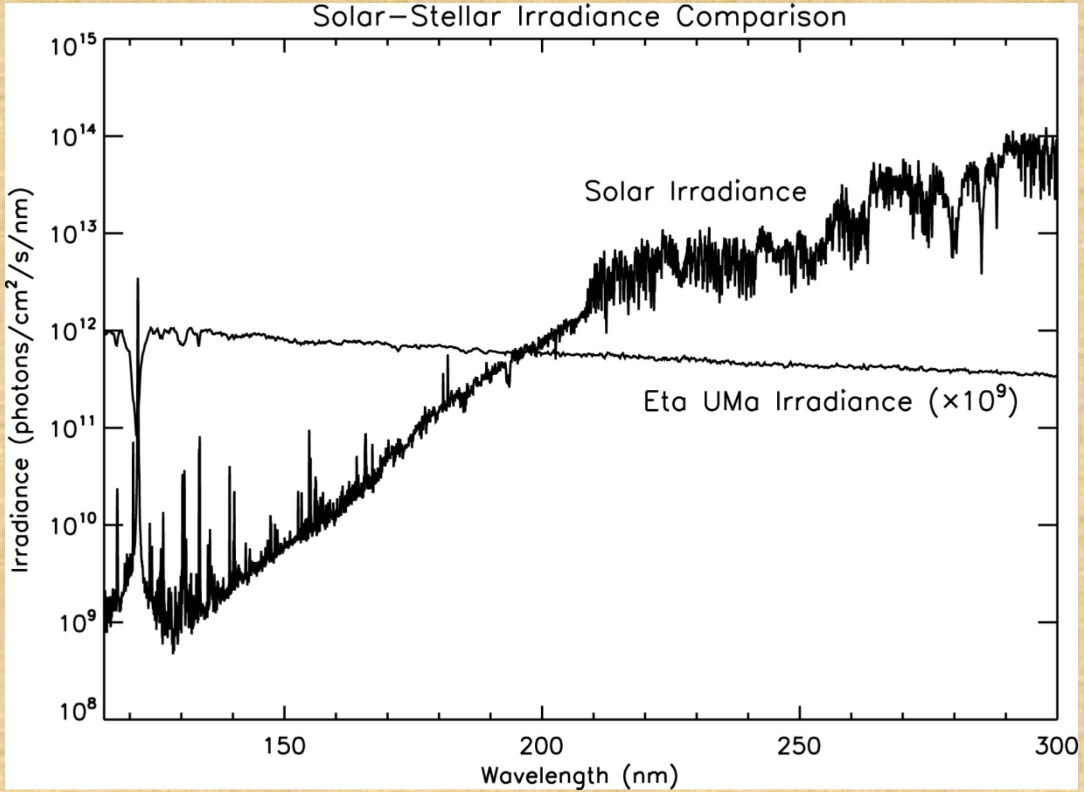
SOLSTICE II

- SOLar-STellar Irradiance Comparison Experiment.
  - Scanning Grating Monochrometer
    - Far Ultraviolet (FUV) 115-180 nm ($\Delta\lambda$=0.1 nm)
    - Middle Ultraviolet (MUV) 180-320 nm ($\Delta\lambda$=0.1 nm)
  - Observes both Sun and stars with same optics and detector, changing only the apertures and integration time.





Solar-Stellar Comparison



The solar spectrum varies by 5 orders of magnitude from 115 to 300 nm, and the stellar irradiances are 8 orders of magnitude smaller!

Measurement Equation

$$E_{AU}(\lambda) = \frac{C(\lambda,\tau,D_C,Sl,St)}{R_C(\lambda,T,\Omega)FOV(\lambda,\Omega,\theta,\phi)A_{Entrance}\Delta\lambda_{BP}T_{Filter}(\lambda)DEG(t,\lambda,\Omega,\theta,\phi)f_{AU}}$$

$$C(\lambda,\tau,Dc,Sl,St) = \frac{S(\lambda)N(\tau) - Dc - Sl(\lambda) - St}{\Delta t}$$

Measurement Eqn. Terms (1)

- E_{AU}=Irradiance at 1AU
- C=Corrected Count Rate
- R_c=Centerpoint Responsivity
- FOV = correction for pointing
- $A_{entrance}$=Area of Entrance Aperture
- Delta lambda = spectral bandpass
- T_{filter} = Transmission of filter
- DEG = long term degradation correction

$$E_{AU}(\lambda) = \frac{C(\lambda,\tau,D_C,Sl,St)}{R_C(\lambda,T,\Omega)FOV(\lambda,\Omega,\theta,\phi)A_{Entrance}\Delta\lambda_{BP}T_{Filter}(\lambda)DEG(t,\lambda,\Omega,\theta,\phi)f_{AU}}$$

Measurement Eqn. Terms (2)

- S = detector signal
- N = nonlinearity correction
- Dc = dark current
- Sl = Scattered light
- St = Stray light
- Delta t = integration time

$$C(\lambda, \tau, Dc, Sl, St) = \frac{S(\lambda)N(\tau) - Dc - Sl(\lambda) - St}{\Delta t}$$

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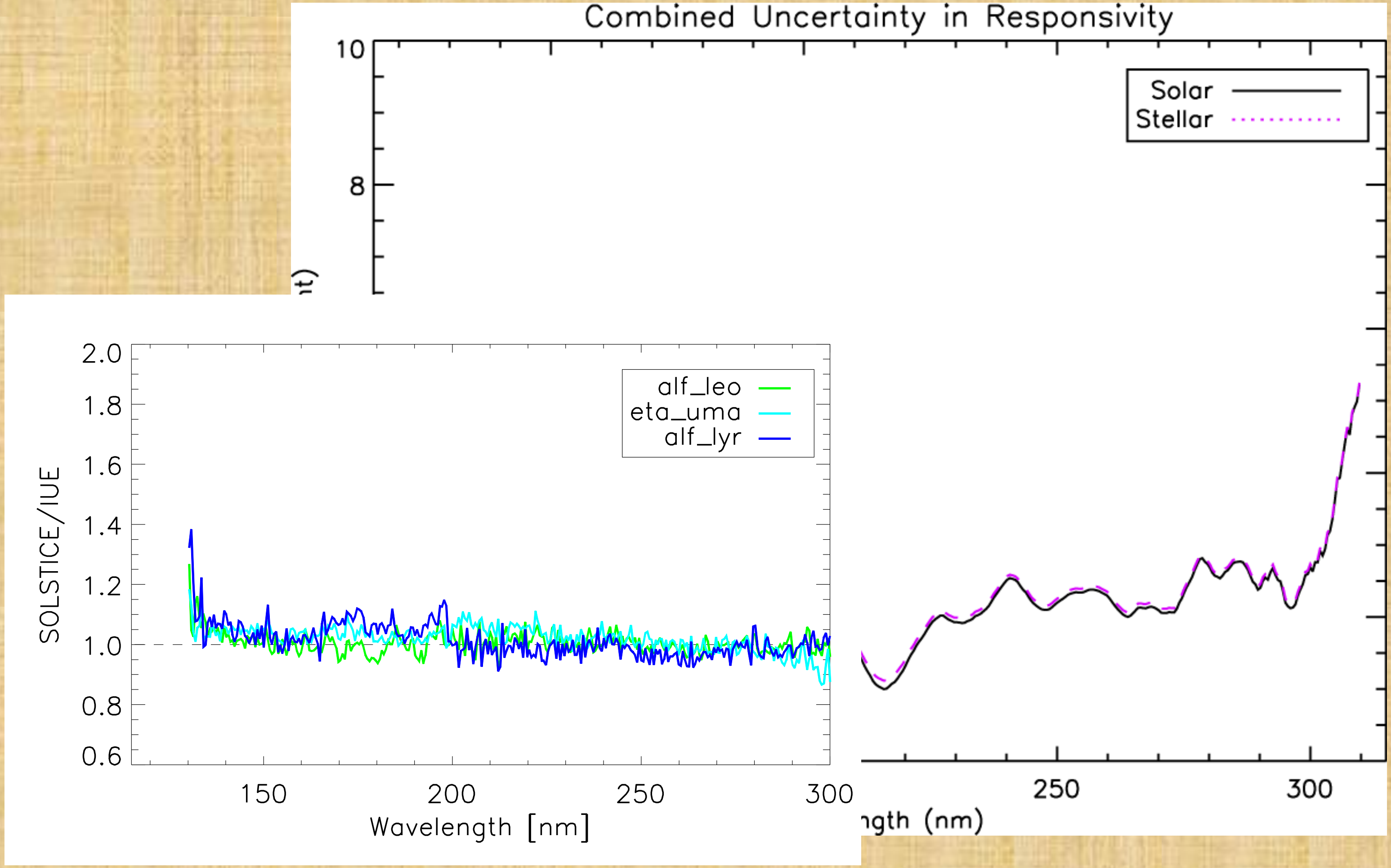
Measurement Eqn. Terms (3)

- Lambda = wavelength
- Omega = angular size of target
- Theta, phi = pitch and yaw angles of target
- T = temperature
- t = time (t=0 at start of mission)
- Tau = electronics dead time
- f_{AU} = correction to 1 AU

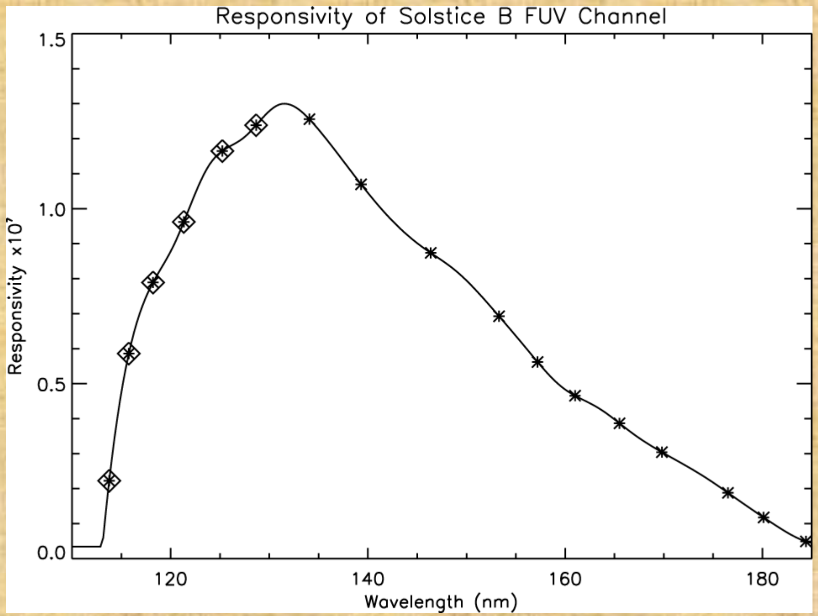
SORCE
Solar Radiation and Climate Experiment

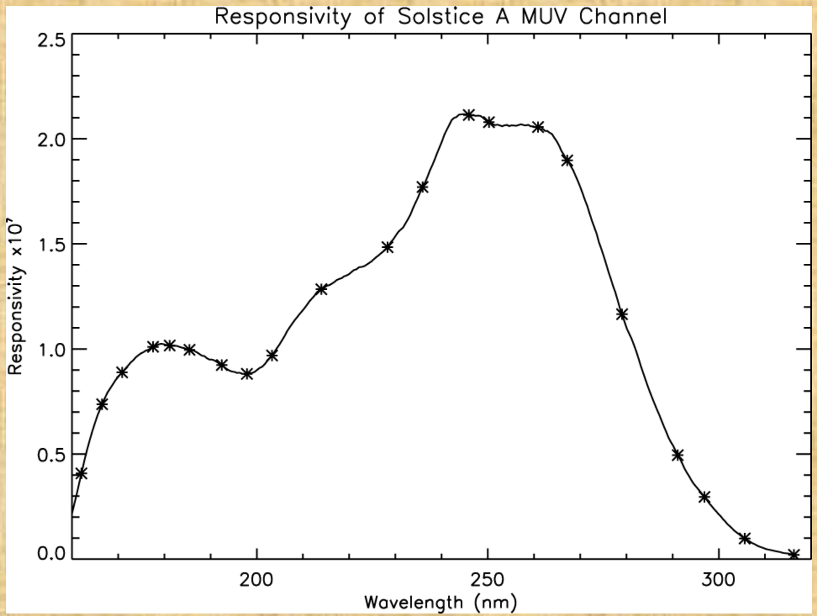
Responsivity Uncertainty Summary



The uncertainty in the responsivity is 2-3% at most wavelengths. McClintock, Snow, & Woods (2005) and Snow et al. (2013)

How can we maintain the preflight accuracy during the mission?



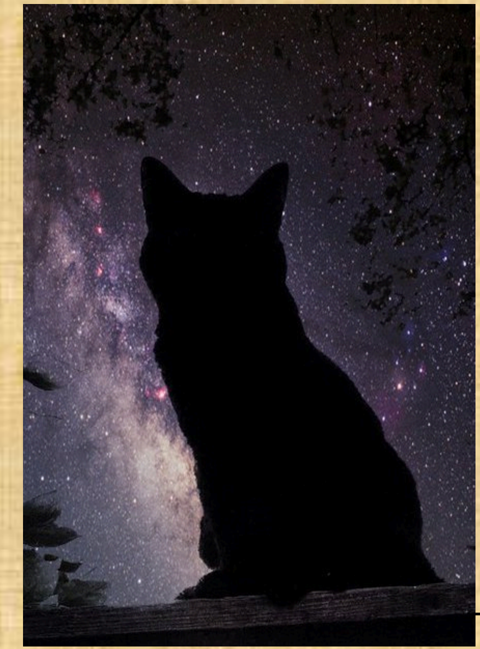


FUV channel is used below 180 nm.
Asterisks indicate wavelengths used for stellar observations.

Stellar Targets

SOLSTICE Program Stars:
Main Sequence B and A
Bright
Stable
Isolated FOV
Distributed on Celestial Sphere

These 18 stars are the same ones that UARS SOLSTICE observed.



Star Name	RA (2000)	Dec (2000)	V Magnitude	Spec Type
ε Per	3 h 57.8 m	40° 0'	2.90	B0.5 III
α CMa	6 45.1	-16 43	-1.46	A1 V
κ Vel	9 22.1	-55 1	2.50	B2 IV-V
α Leo	10 8.4	11 58	1.35	B7 V
δ Cen	12 8.4	-50 43	2.60	B2 IVne
α Cru	12 26.6	-63 7	1.35	B0.5 IV + B1 V
α Vir	13 25.1	-11 10	0.97	B1 IV + B2 V
η UMa	13 47.5	49 15	1.86	B3 V
ζ Cen	13 55.5	-47 17	2.55	B2.5 IV
β Cen	14 3.8	-60 22	0.61	B1 III
γ Lup	15 35.1	-41 10	2.78	B2 IV
δ Sco	16 0.3	-22 37	2.32	B0.5 IV
τ Sco	16 35.9	-28 13	2.82	B0 V
α Lyr	18 36.9	38 47	0.03	A0 Va
σ Sgr	18 55.3	-26 18	2.02	B2.5 V
α Pav	20 25.6	-56 44	1.94	B2.5 V
α Gru	22 8.2	-46 58	1.74	B7 IV
α PsA	22 57.7	-29 37	1.16	A3 V

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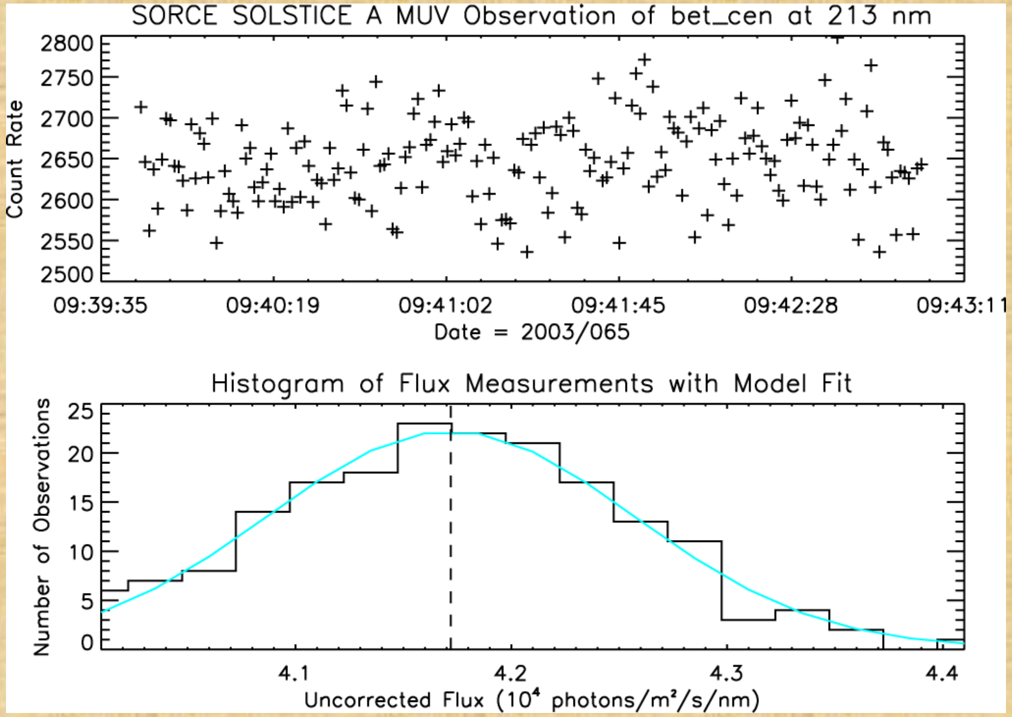
Single Stellar Observation



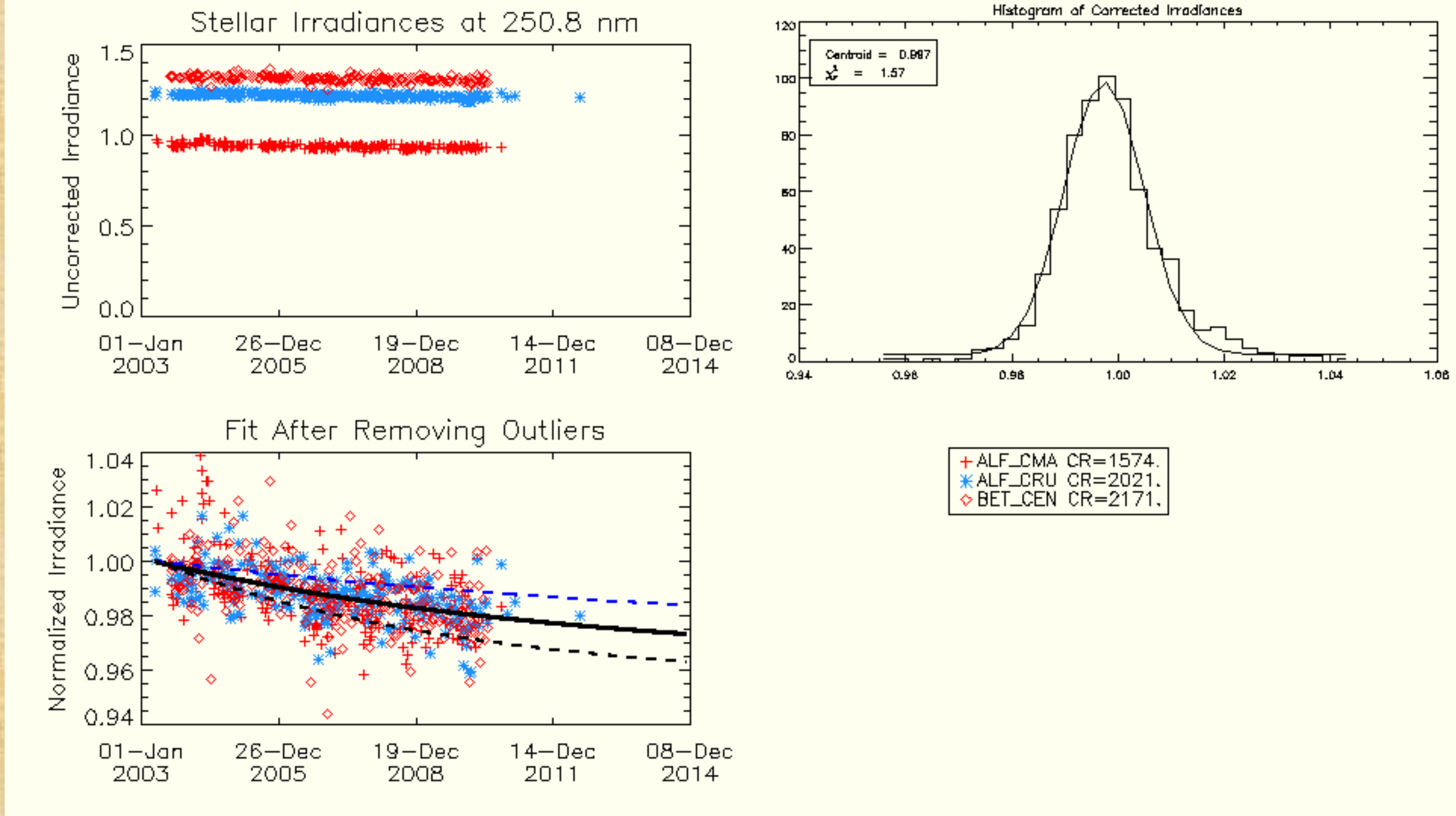
A standard SOLSTICE observation of a star consists of a series of 1 second integrations at a fixed wavelength. The total dwell time is a tailored to the count rate for each star at each wavelength.

The integrations are fit to a normal distribution whose peak is the irradiance for that observation.

The uncertainty for each observation is about 1%.

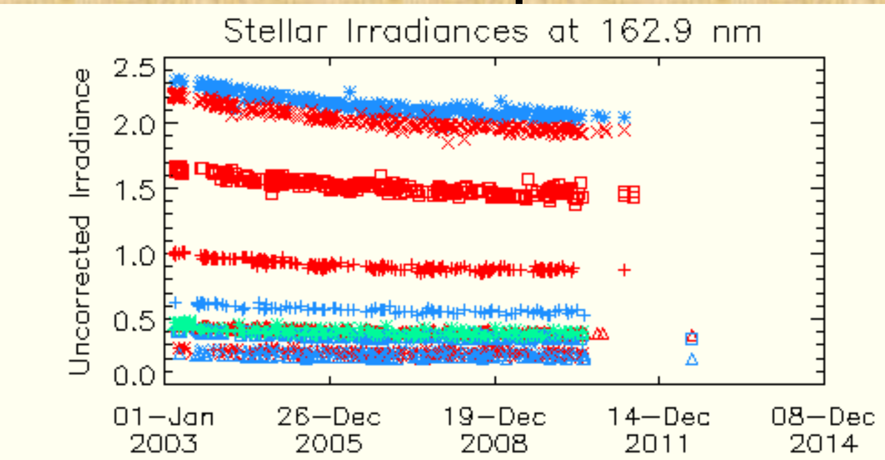
Snow, McClintock, Rottman, and Woods, 2005, Solar Phys.

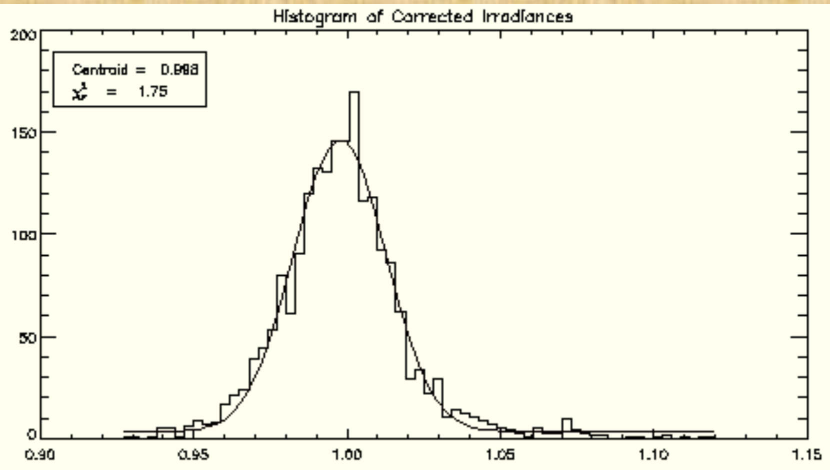
MUV Stars Example

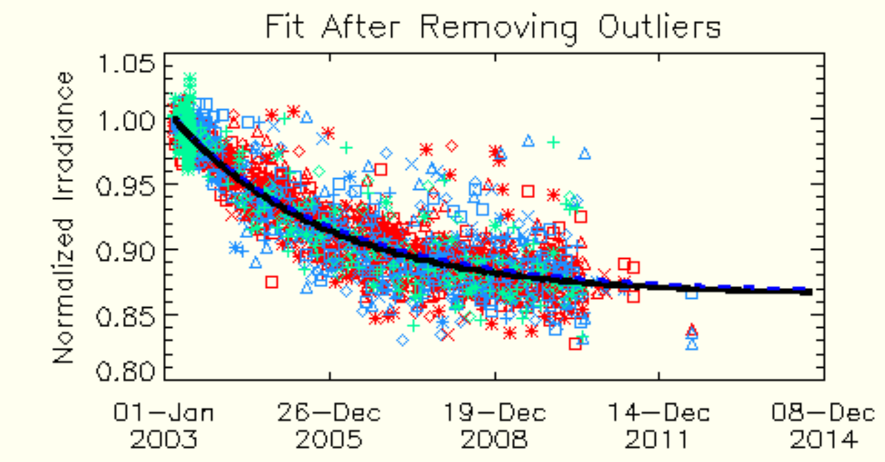


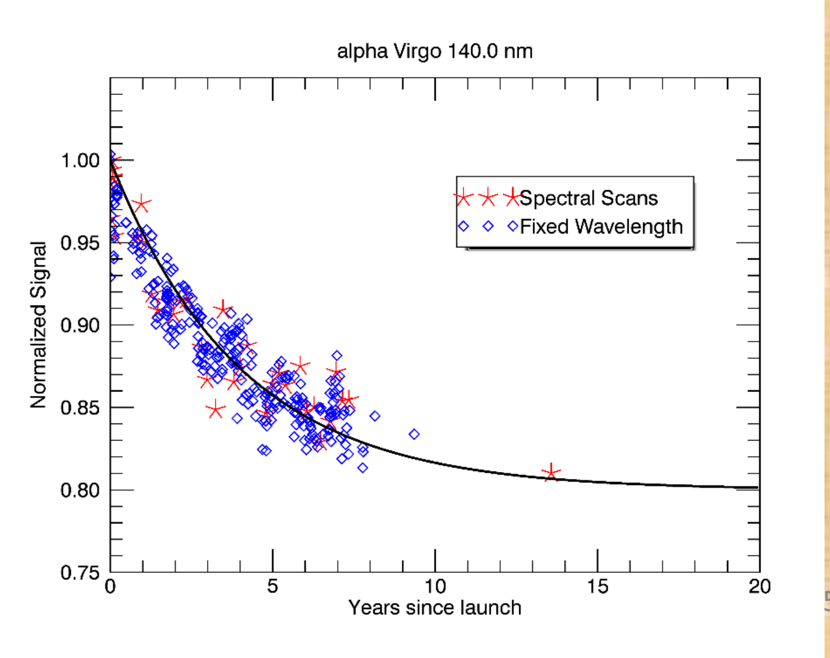
Extrapolation of stellar degradation begins July 2011 due to degradation of spacecraft battery capacity.

FUV Stars Example







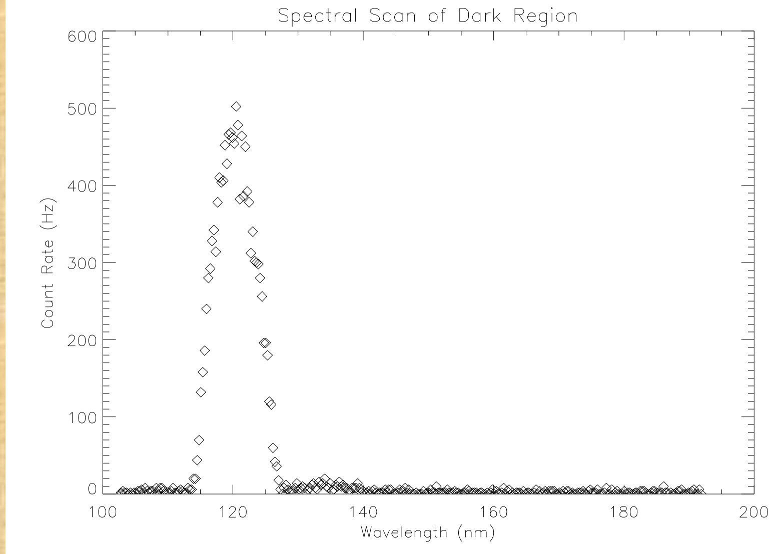


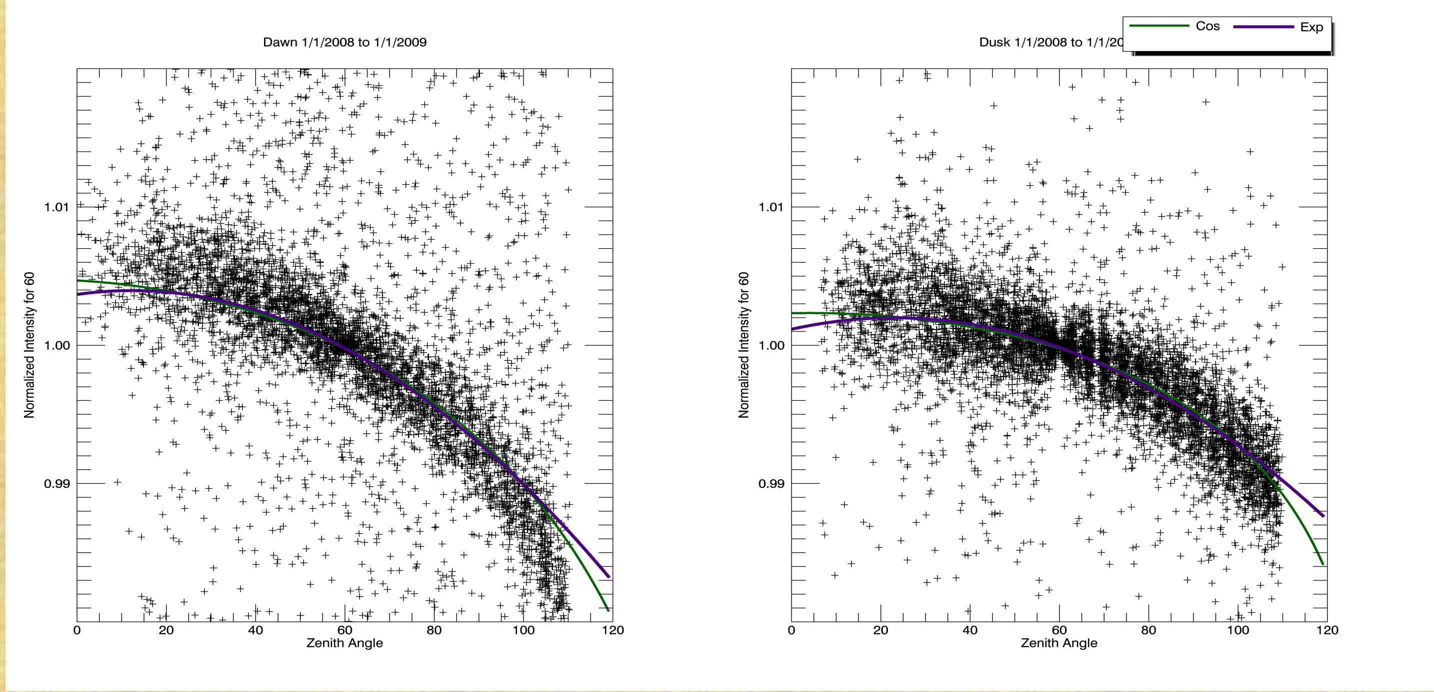
Geocoronal contamination

- SORCE is in low earth orbit, well within the extended hydrogen atmosphere
- Special observing technique is required to remove variable geocorona

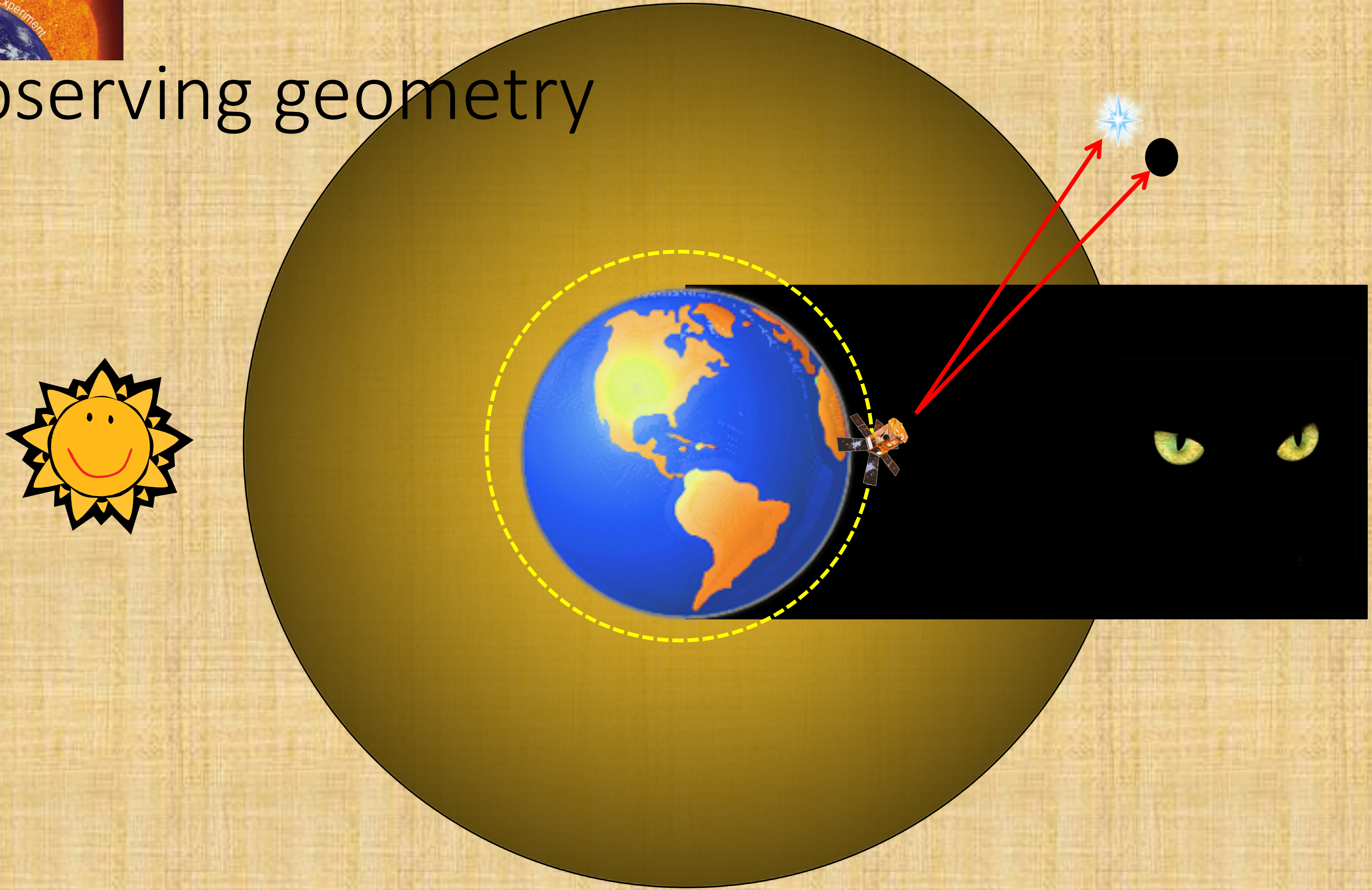
Geocoronal spectrum

- Although the geocoronal emission is intrinsically narrow, in stellar mode SOLSTICE is an objective grating spectrograph with a large FOV.
- Width matches measured stellar FOV determined from stellar alignment scan.

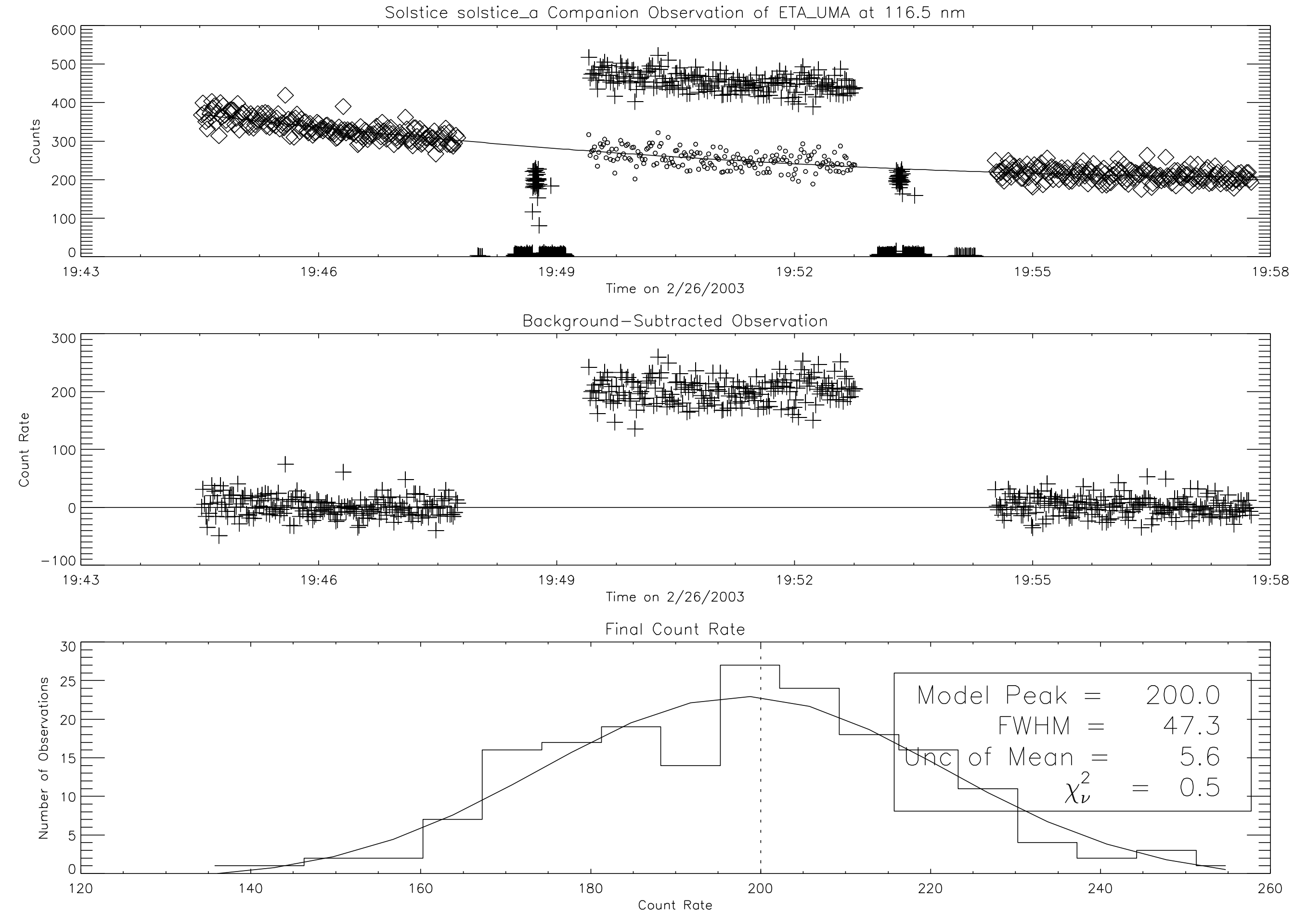




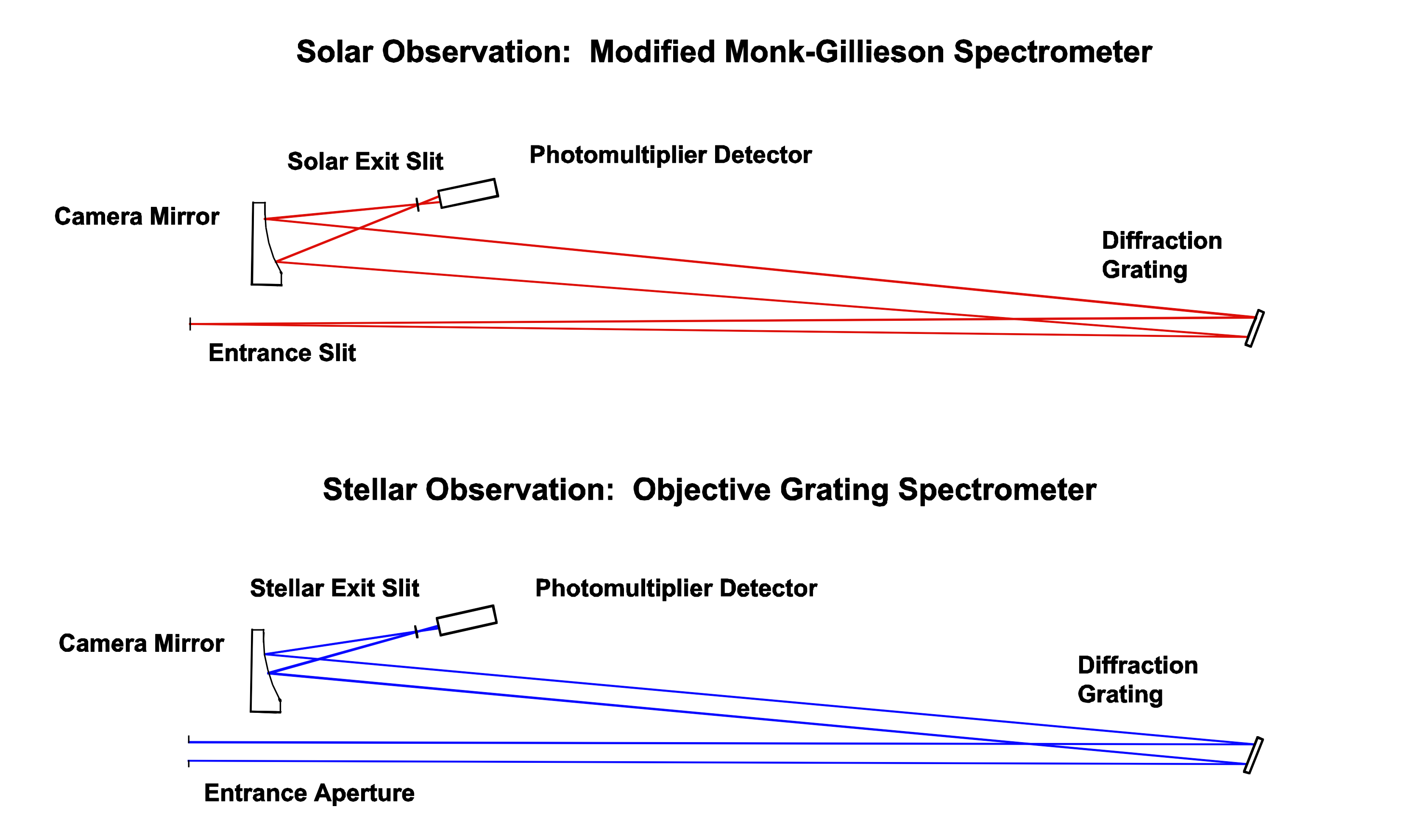
Observing geometry



Airglow correction observation

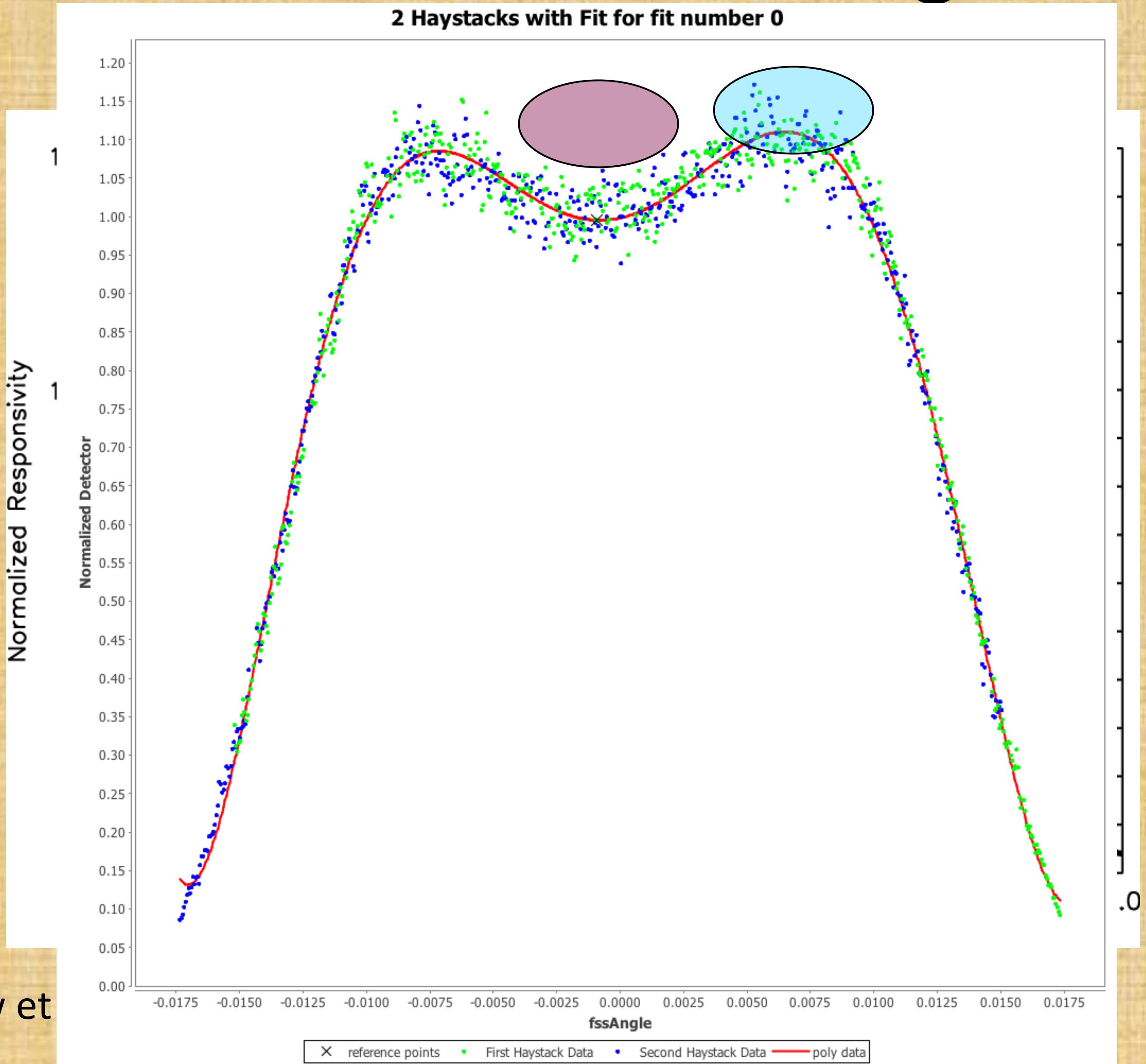


Solar/Stellar Illumination



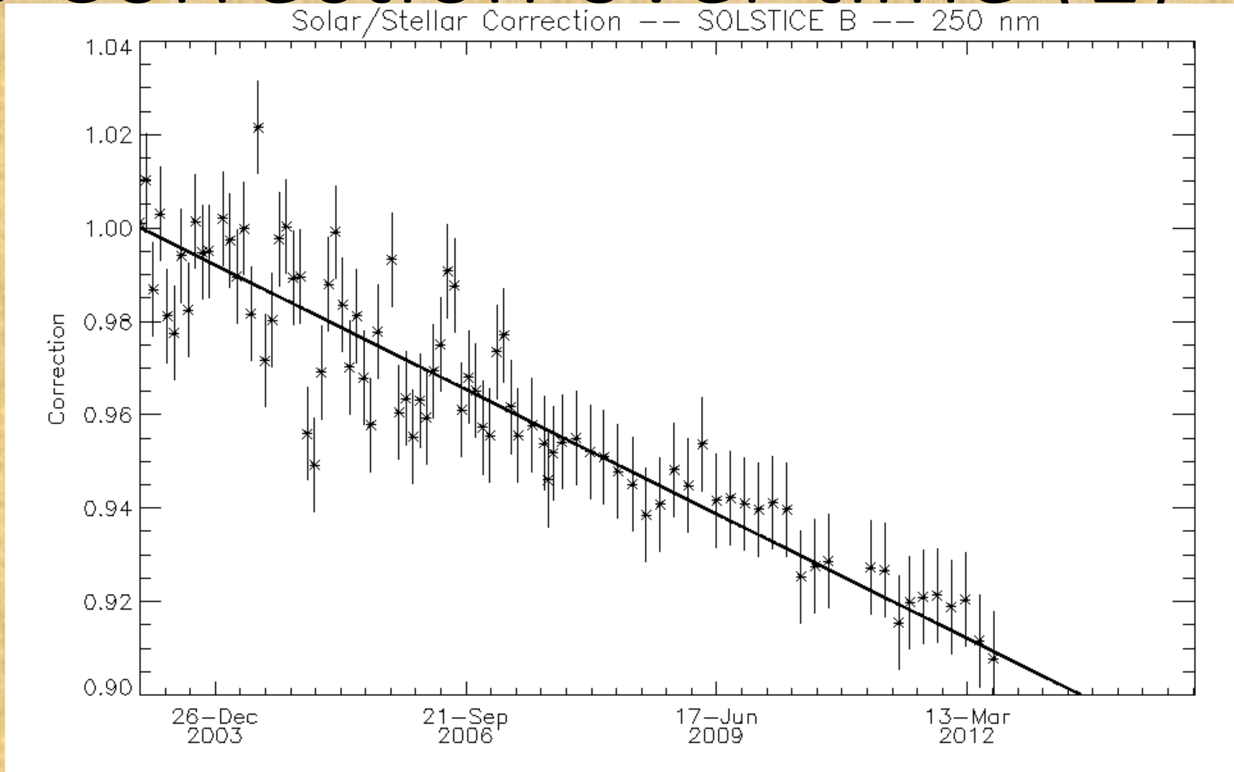
This diagram is for the UARS SOLSTICE layout. For SORCE, the mirror and grating are reversed.

Solar/Stellar Correction Tracking



Snow et

S/S Correction over time (1)



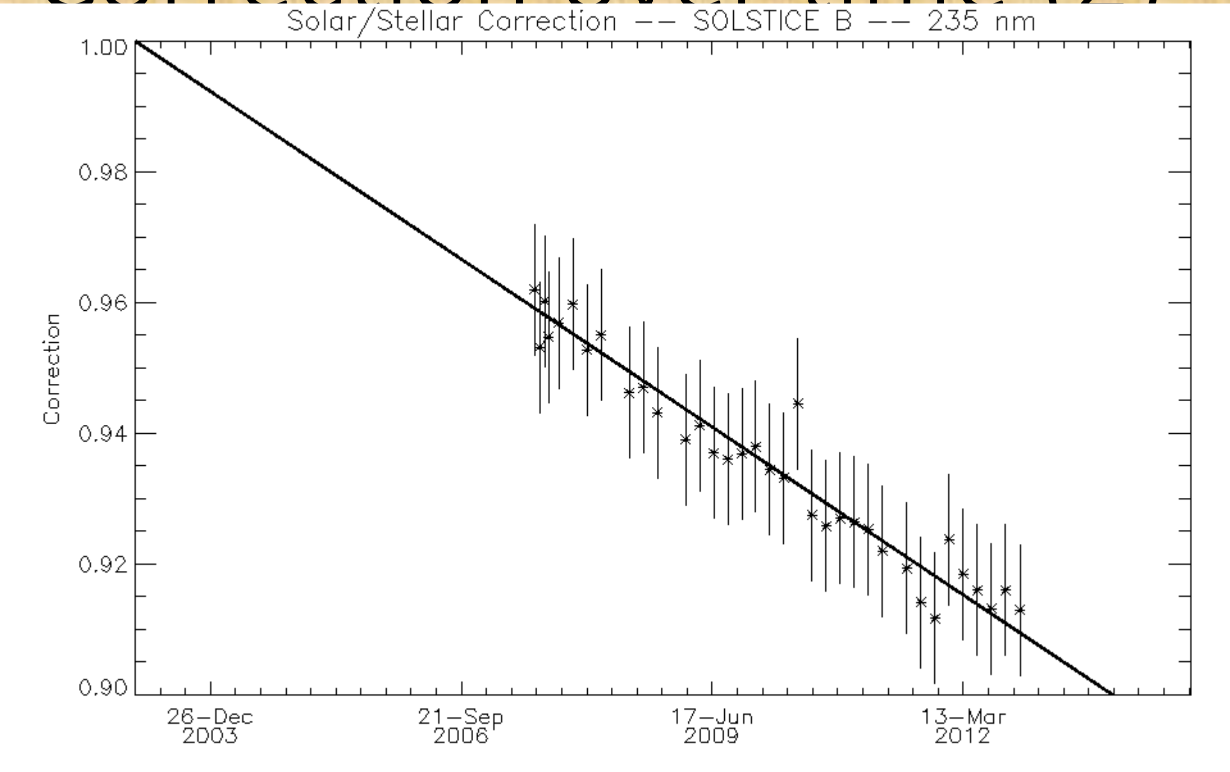
10% change over 10 years. Uncertainty from this correction is probably about 0.2%/year.

Four "primary" wavelengths have been measured on a monthly basis since the start of the mission
189, 218, 250, and 289 nm.

They were observed once per four weeks until mid 2007.

These observations have resumed in 2016 in modified form.

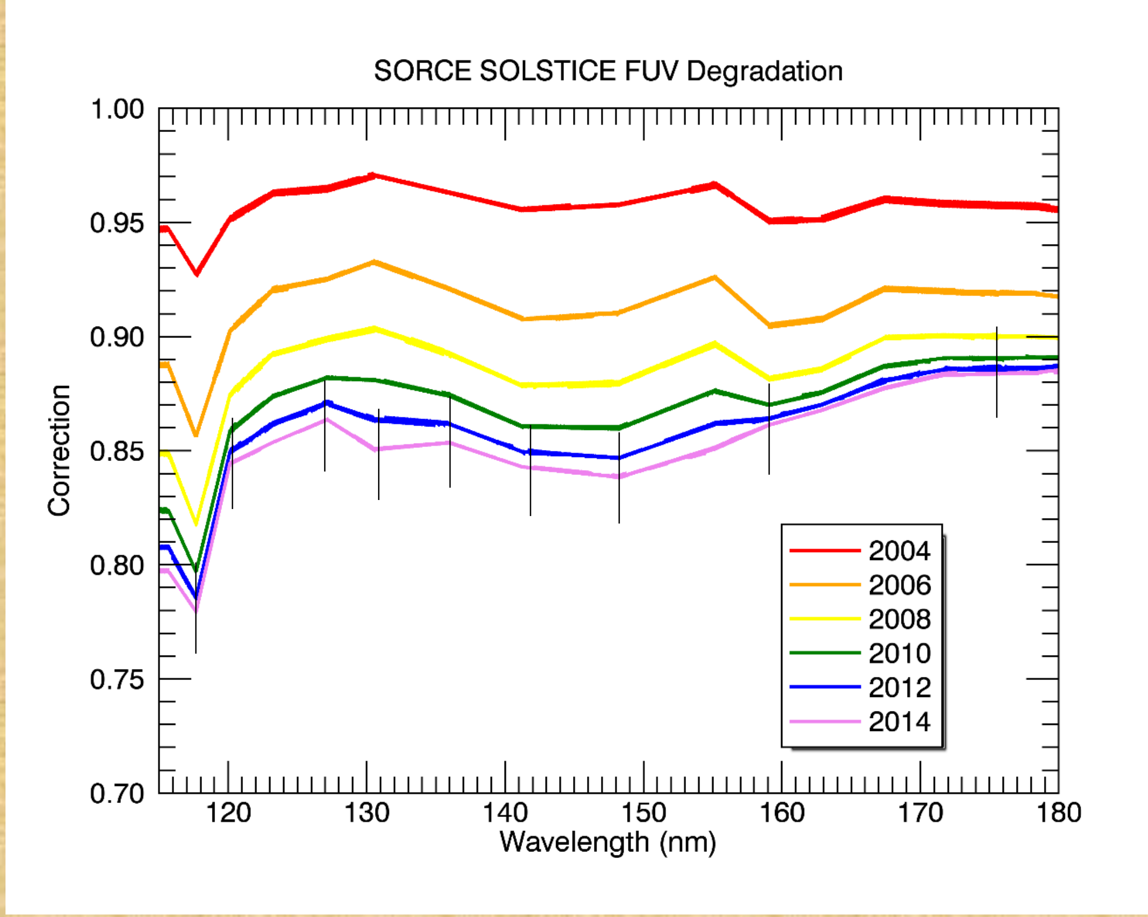
S/S Correction over time (2)

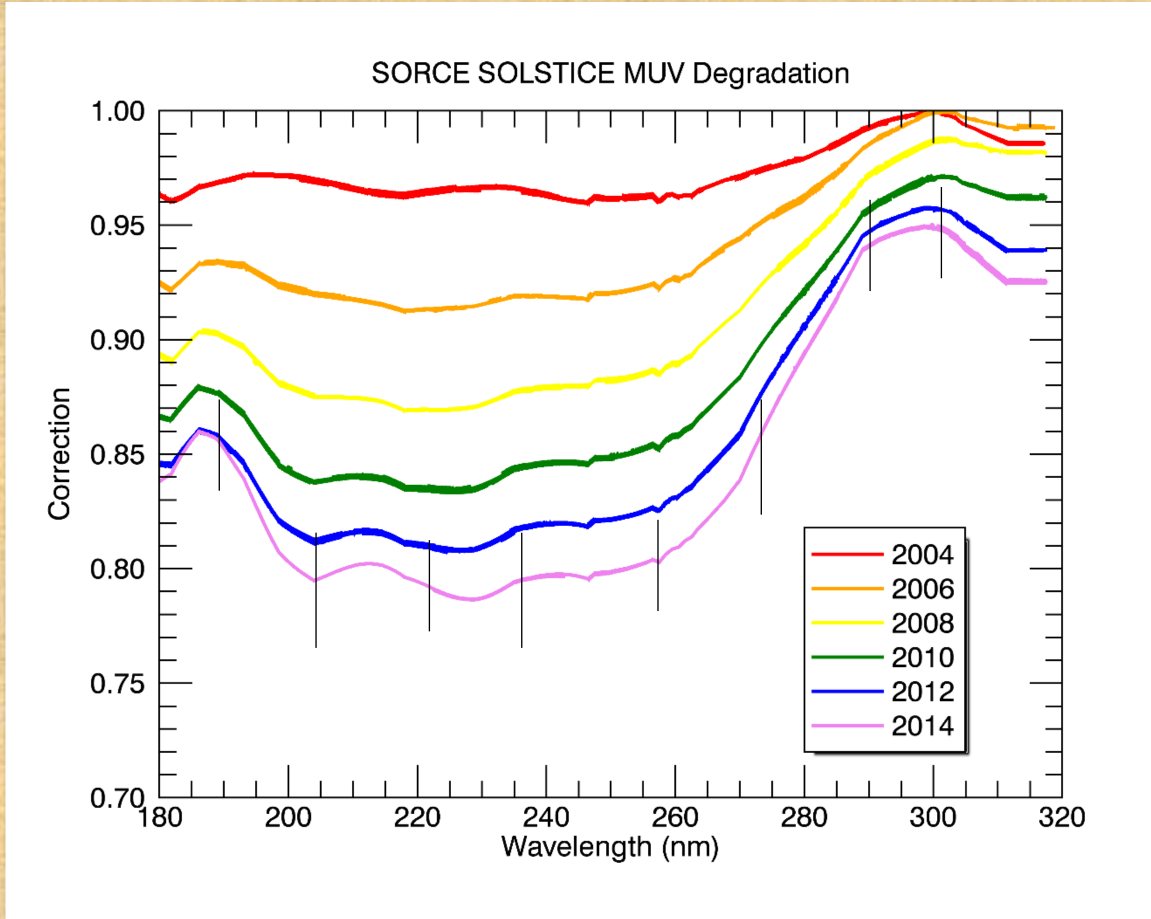


Four additional "secondary" wavelengths were added in mid 2007.
204, 235, 270, and 300 nm.
The fit for these wavelengths is extrapolated back to the beginning of the mission.

When the four additional wavelengths were added, the cadence for each wavelength (primary and secondary) became once every 8 weeks.

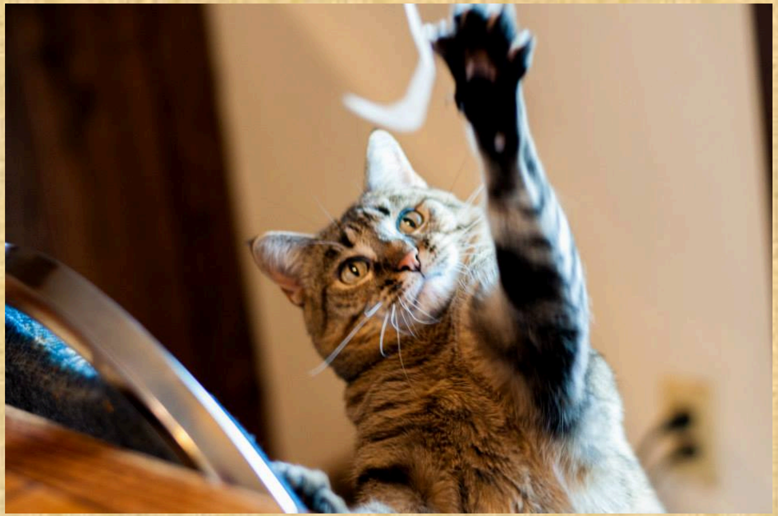
Degradation Correction Summary





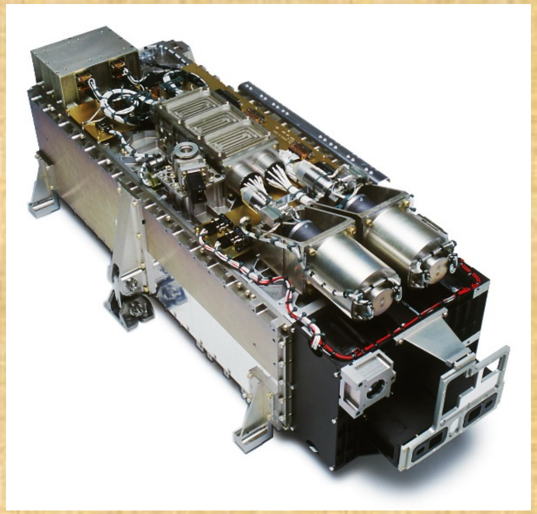
SOLSTICE Summary

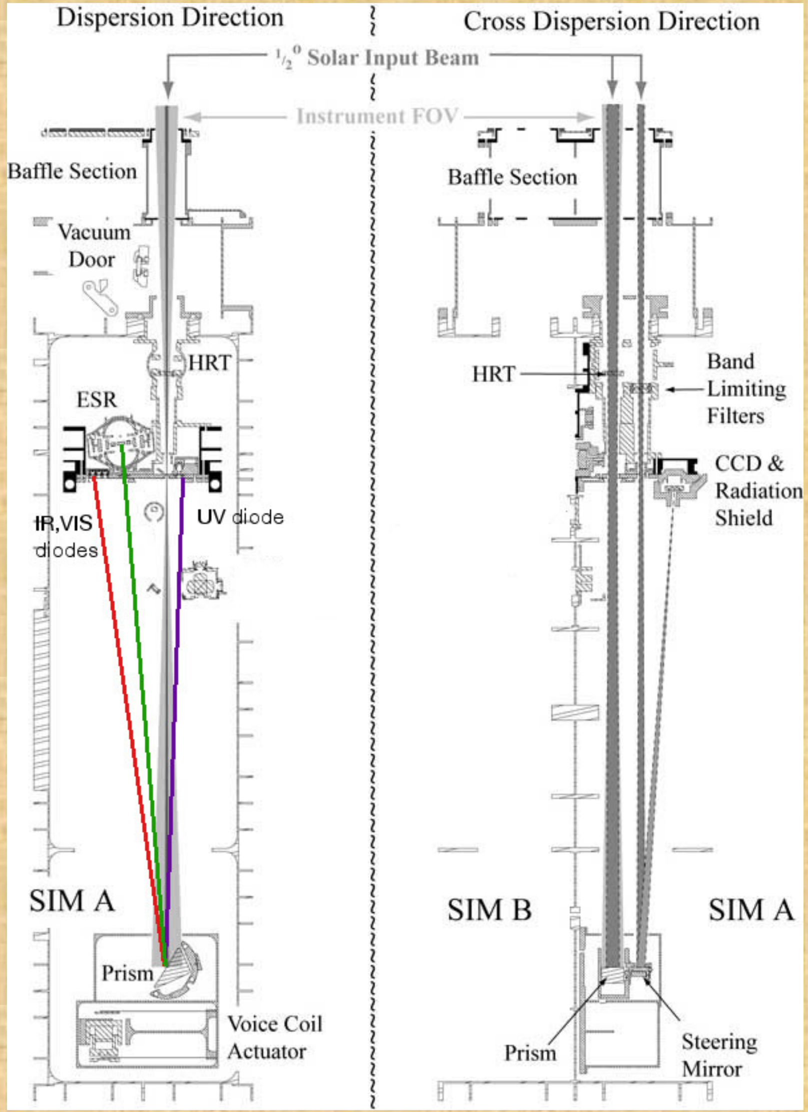
- Ultraviolet 115-320 nm
- Uncertainty in measured degradation trends about 0.3% per year
  - Stars
  - Solar/Stellar Field of View correction
- Analysis of calibration data ongoing….



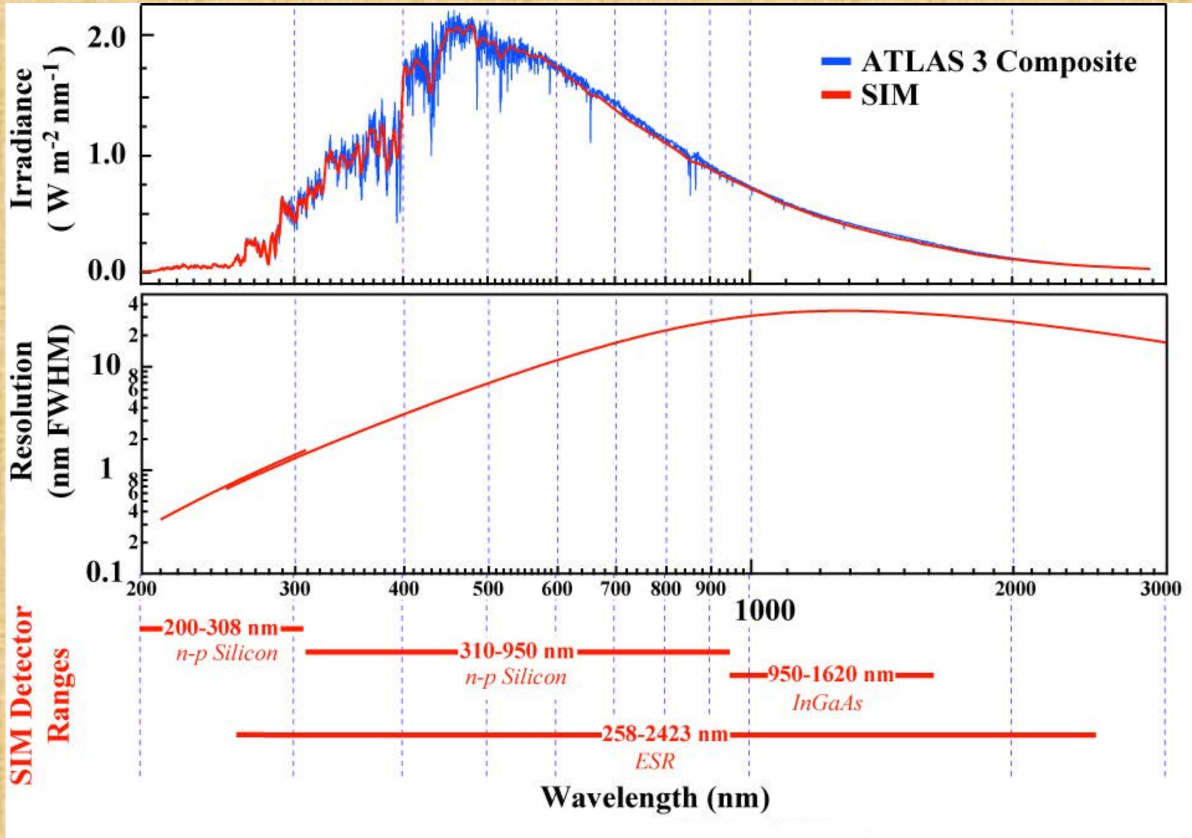
Spectral Irradiance Monitor (SIM)

- **Instrument type:** 2 x Féry Prism Spectrometer
- **Wavelength range:** 200-2400 nm
- **Wavelength resolution**: 0.24-34 nm
- **Detectors:** ESR, n-p silicon photodiodes, InGaAs
- **Relative accuracy:** ~0.5 – 0.02% (210-2400nm)
- **Long-term accuracy:** 0.3-0.02%/year (210-2400nm)
- **Single Optical Element**: prism!





SIM Spectrum



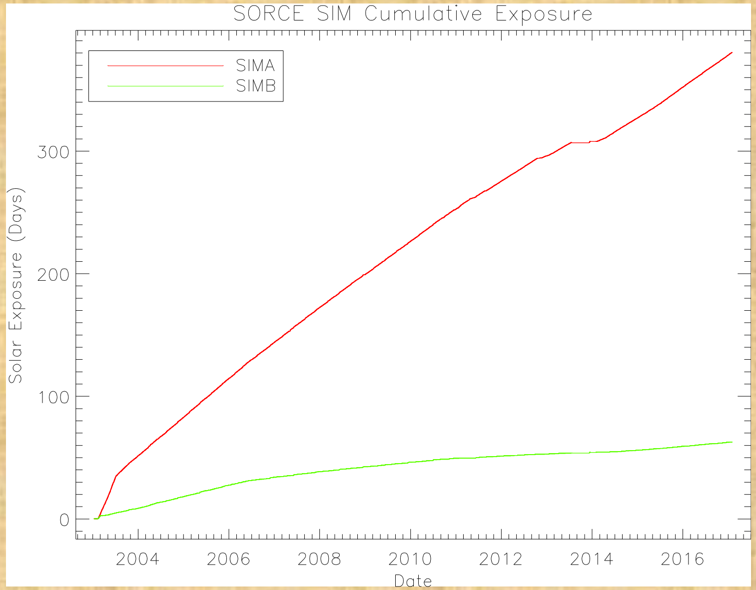
$$\int_{\lambda=201}^{\lambda=2423} E(\lambda)\,d\lambda \approx 1324.49\ \mathrm{Wm^{-2}}$$

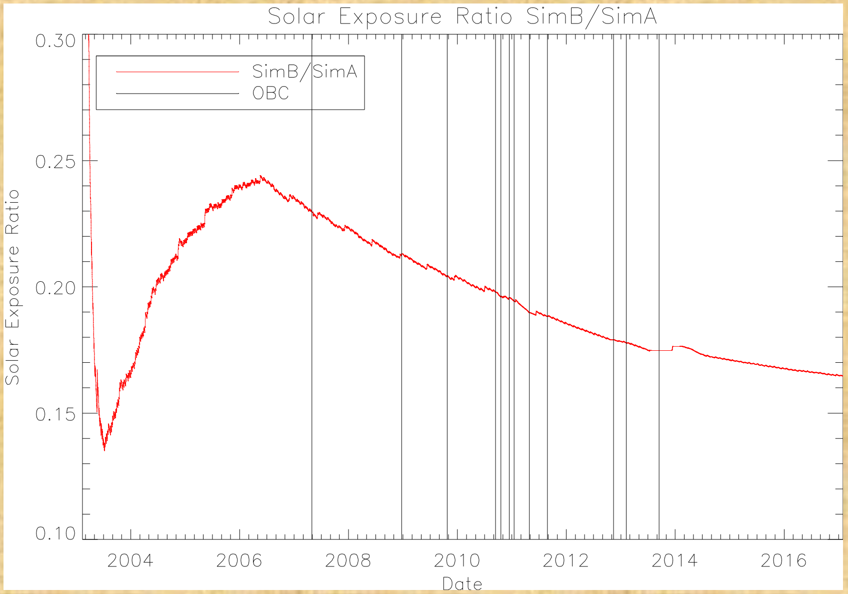
$$\approx 97.3\%\ \text{of TSI}$$

$$\Leftrightarrow\ 36.32\ \mathrm{Wm^{-2}}\ \text{missing from TSI}$$

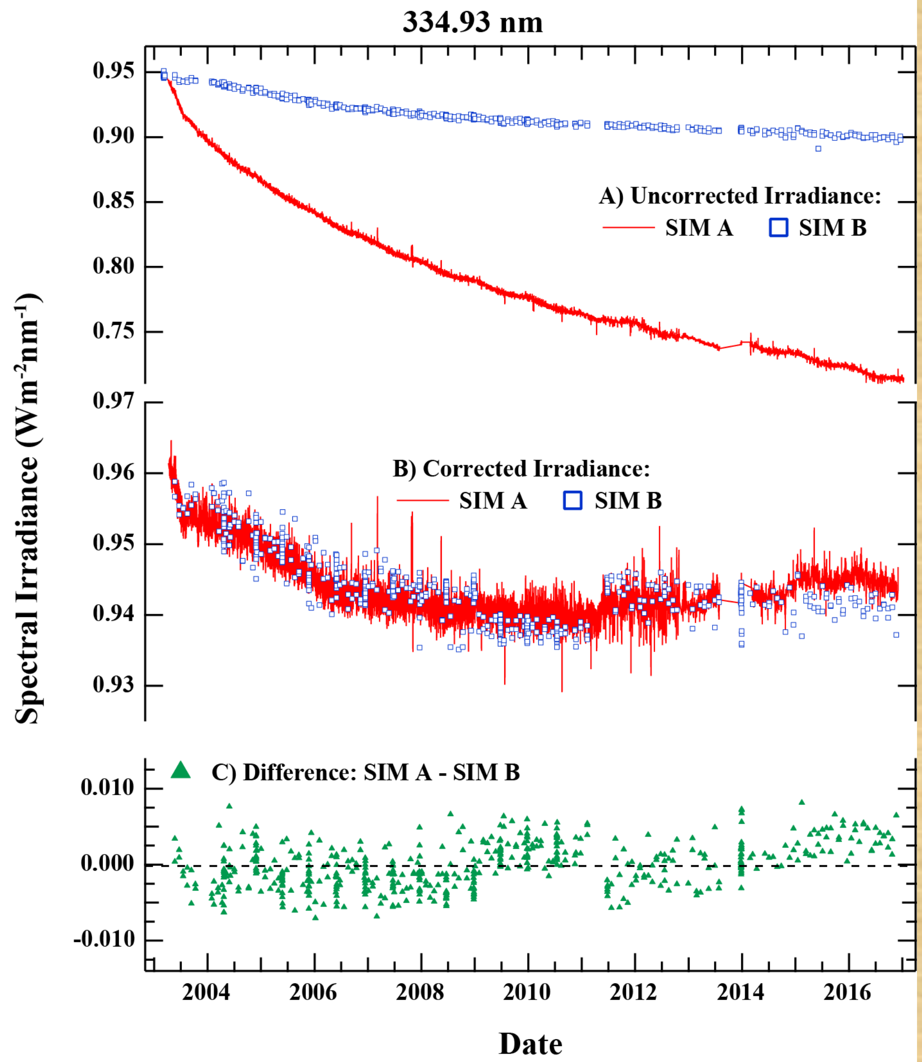
SIM Prism Degradation Model

- Based on comparing two identical spectrometers used at different rates of solar exposure
- Same physical, chemical and thermal environment
- Model validated when measurements of the sun at the same time with both spectrometers result in same calibrated irradiance
- Increased confidence by comparing integrated SSI with TIM TSI measurements
- On-Board-Computer events affected characteristics of degradation model



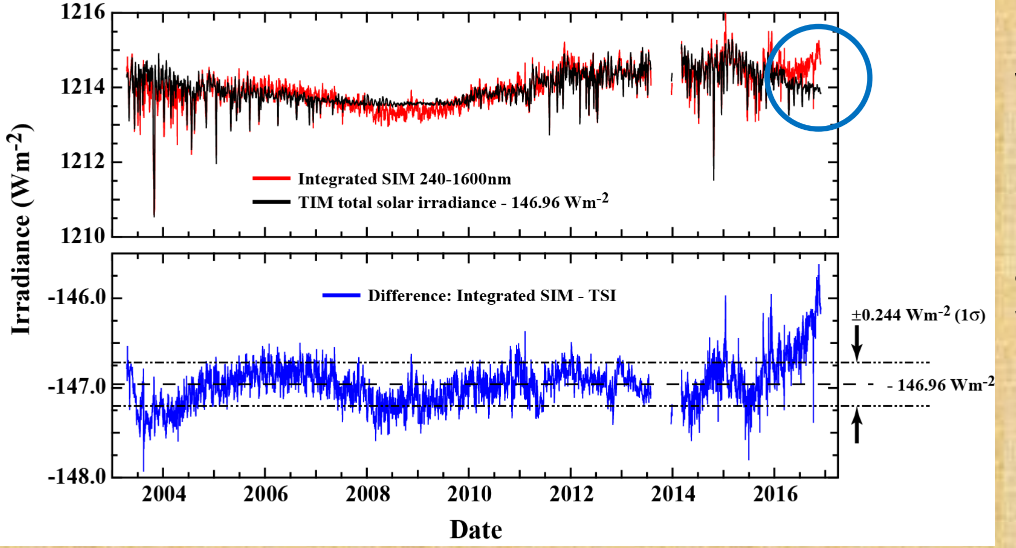


SIM Correction Example



Observations from the two channels (A and B) are both fit using a function that depends on exposure time rather than calendar time.

Wavelength scale needs to be adjusted to take account of spacecraft events (shown on previous slide).



Validation: Integrated SIM spectrum shows good agreement with TSI

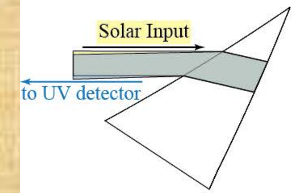
Correction factor for geometry at UV wavelengths

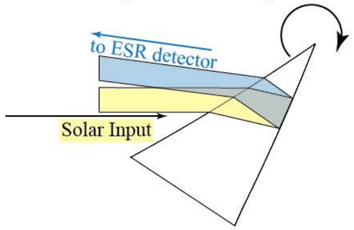
- Simplest degradation model: ***1 / exp(-Kappa(λ)*C(t))***
  - Separating the wavelength and the time dependencies (*Kappa(λ), C(t)*)
- Amount of prism degradation at a specific wavelength also depend on the geometry (ray path): beam enters and exits prism at different location of the "degradation spot"
- Calibration of TSIS prism confirms that degradation is a surface effect.

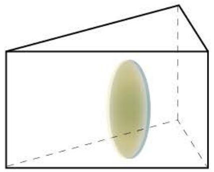
$$pd(\lambda,t) = (1-a_{detector})\bullet exp(-\kappa\, t_{expos}\bullet f') + a_{detector}\bullet exp\left(\frac{-\kappa\, t_{expos}\bullet f'}{2}\right)$$

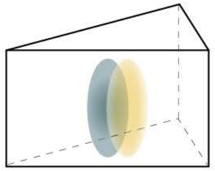
The ray path (*trends within the same spectrometer*):

$a_{detector}$ = Fraction of light not attenuated twice (both wavelength and detector posiition dependent)









The Outgoing beam overlaps with degradation spot: (UV detector position)

$a_{detector} \longrightarrow 0$

$pd(\lambda,t) \longrightarrow exp(-\kappa\, t_{expos}\, f')$

The Outgoing beam has smaller overlap with degradation spot: (ESR detector position)

$a_{detector} \longrightarrow 1$

$pd(\lambda,t) \longrightarrow exp\left(\frac{-\kappa\, t_{expos}\bullet f'}{2}\right)$

Degradation spot opacity (*trends between spectrometers*)

i.e. Lambert's law

$\tau = \kappa\, t_{expos}\, f'$

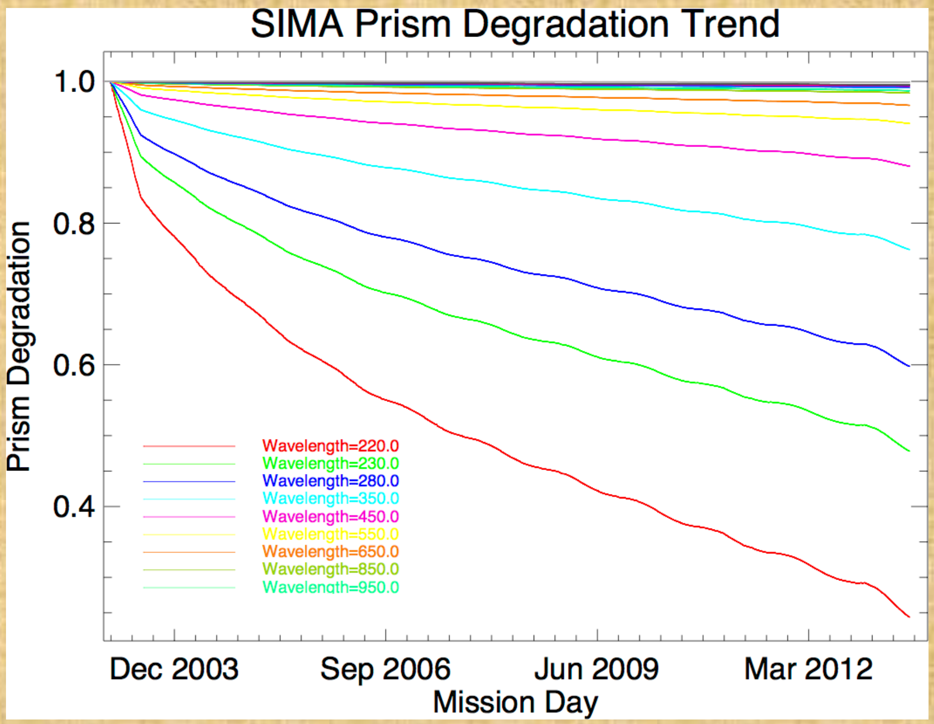
κ = *absorption coefficient*

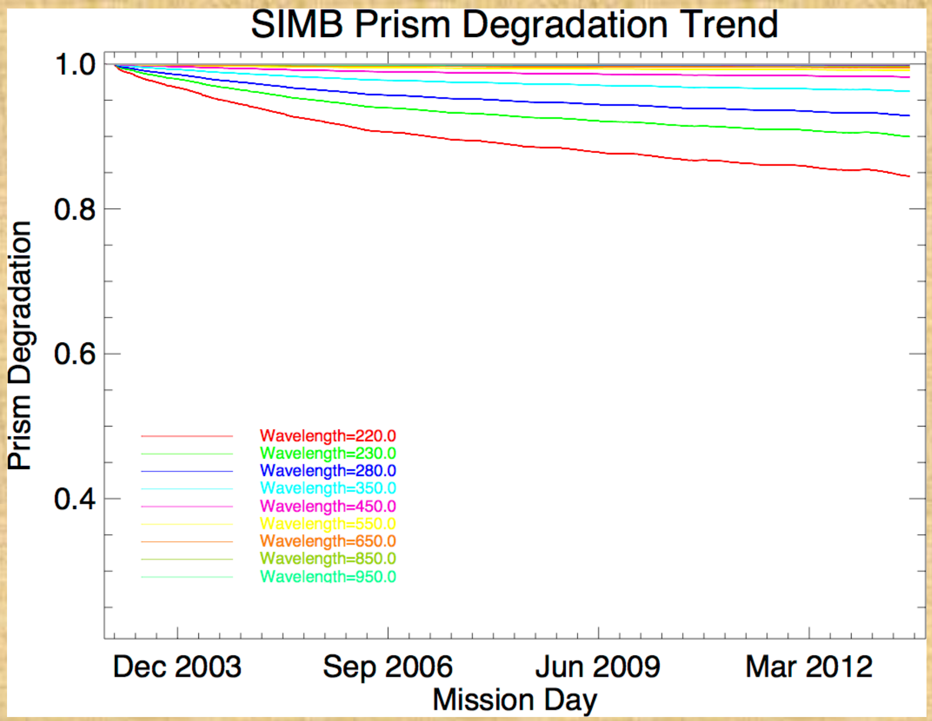
$t_{expos}\, f'$ = effective column thickness of absorbing layer

- κ is strongly wavelength dependent
- Degradation is a surface effect and is not darkening in the bulk of the glass.
- The degradation spot is not uniformly opaque.

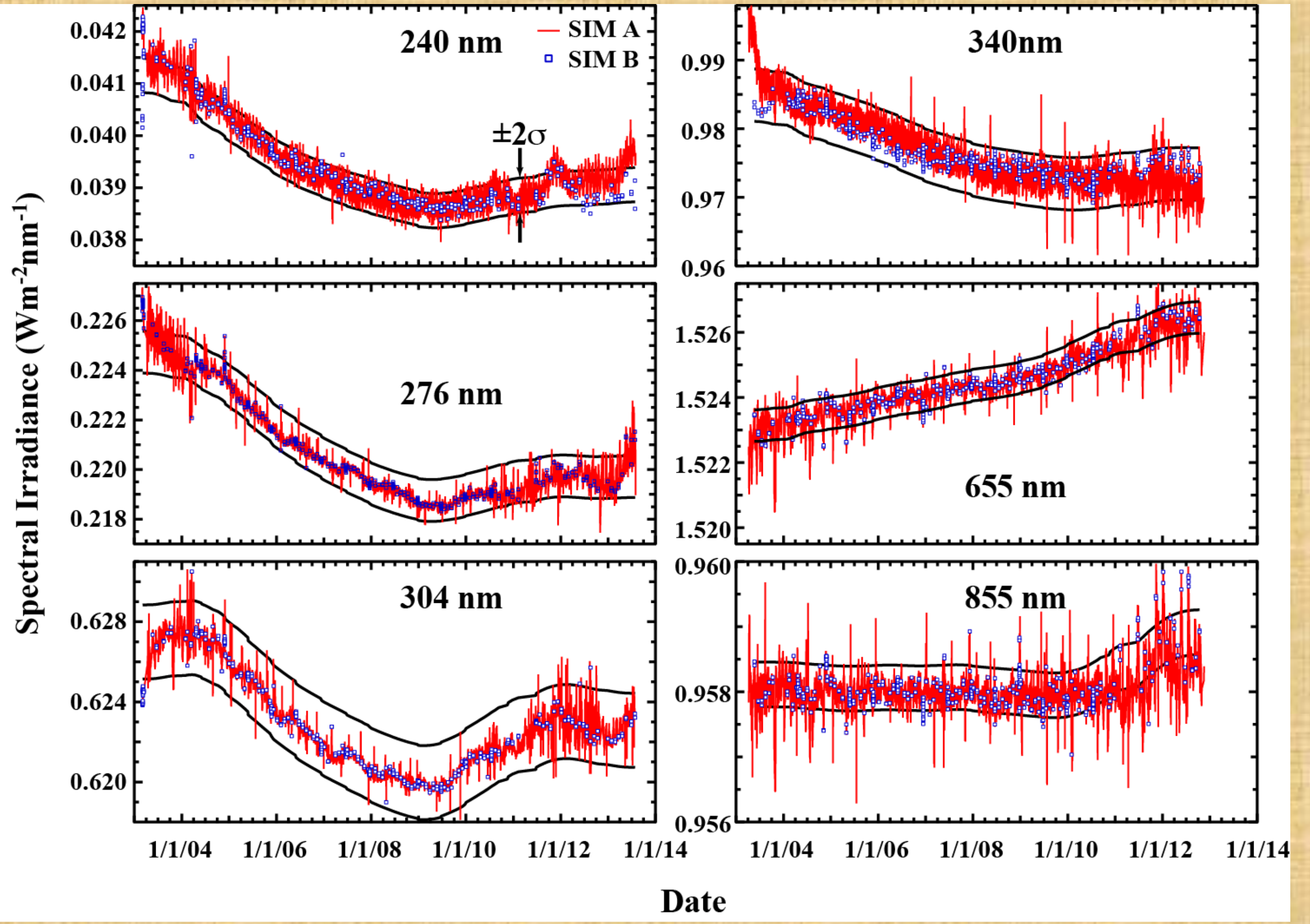
Resulting degradation over SORCE mission

Measured prism degradation over time for SimA and SimB





SIM estimated uncertainties



The technique using the full mission does not produce a time-dependent uncertainty, only a global error envelope.

±2σ error bands estimated from point-to-point difference between SIM A & B channels

SIM Summary

- Degradation correction derived from comparing daily channel to reference channel.
- Spacecraft events have greatly complicated analysis in rise of cycle 24, introducing small wavelength shifts. Recent data is more consistent.
- SIM instrument team is still confident in published out of phase trends at some wavelengths.

Comparison of Results

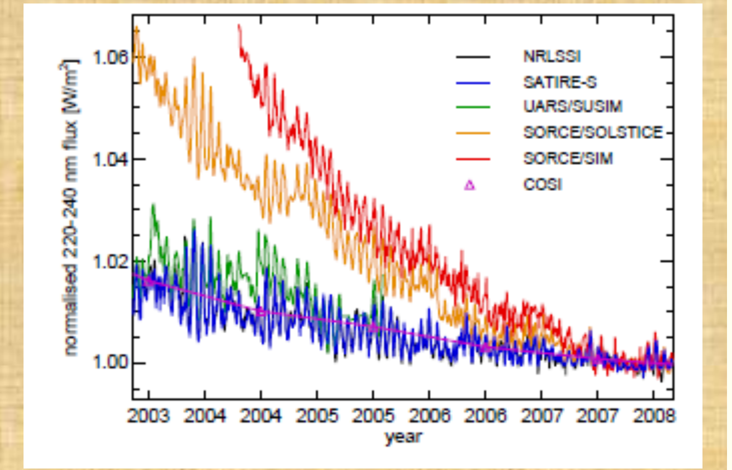
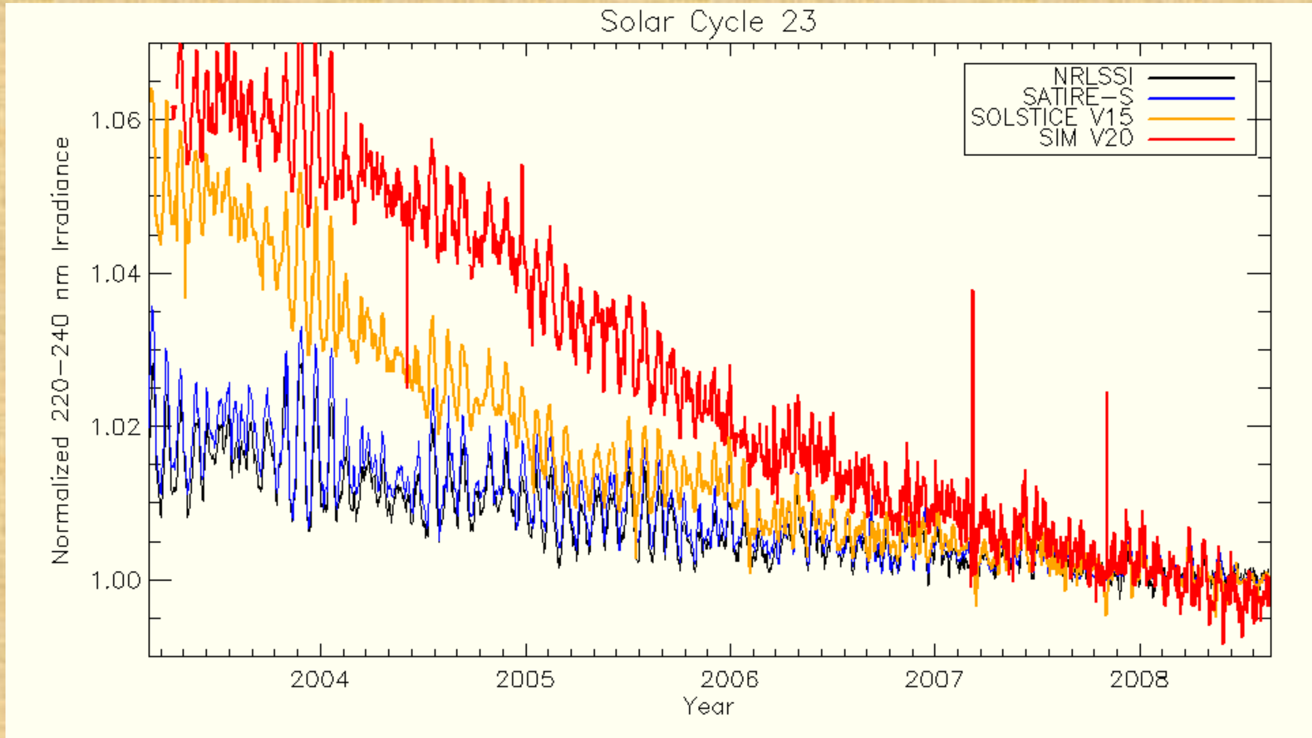
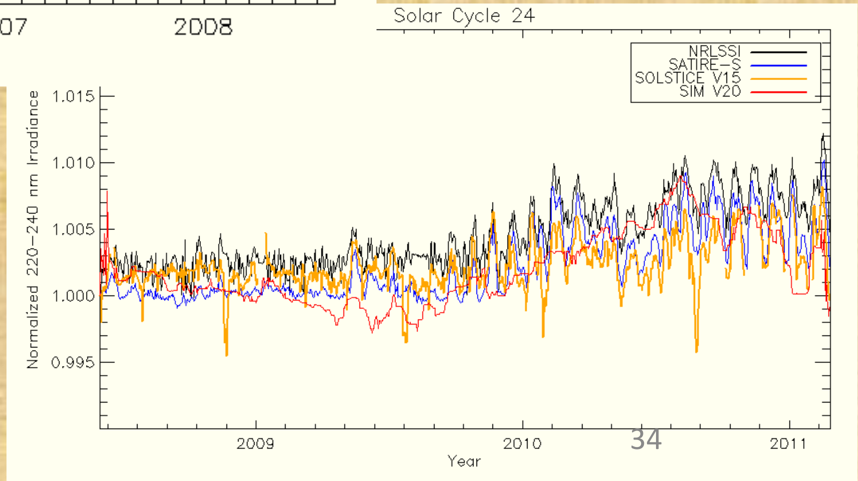


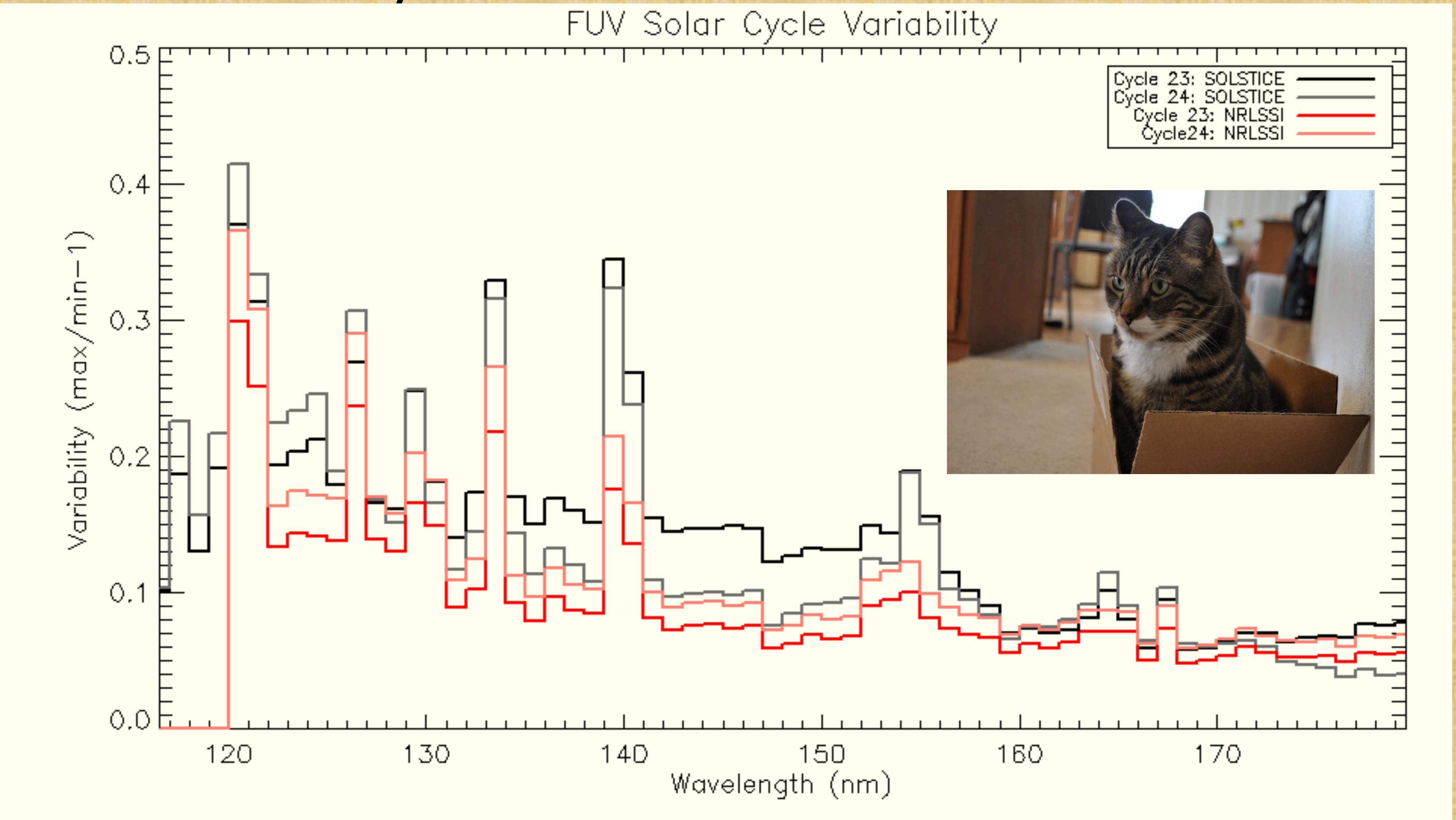
Fig. 8 from Ermolli et al. 2013



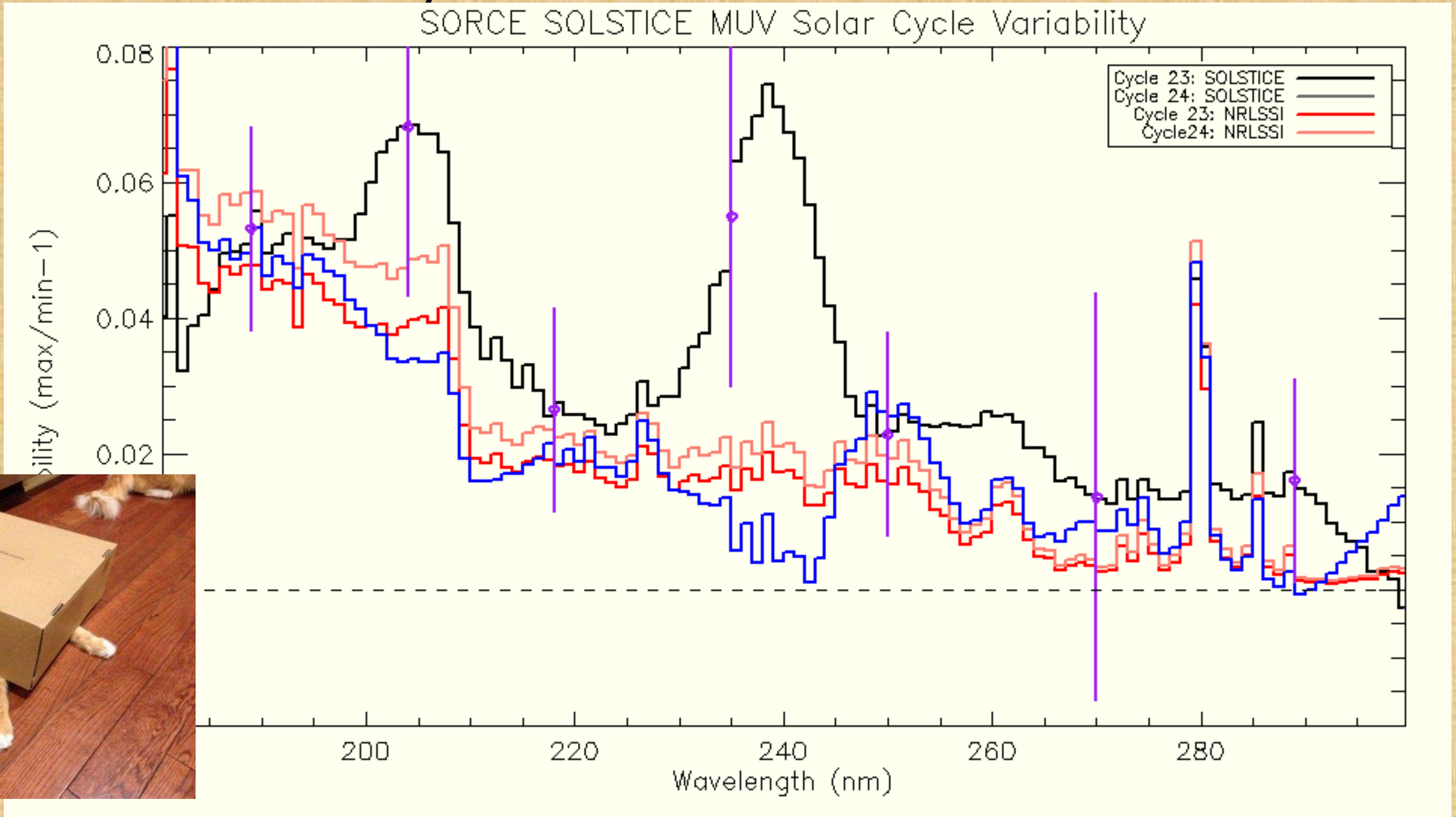
SIM V20 includes only 240 nm. SOLSTICE and models show integrated 220-240 nm band.



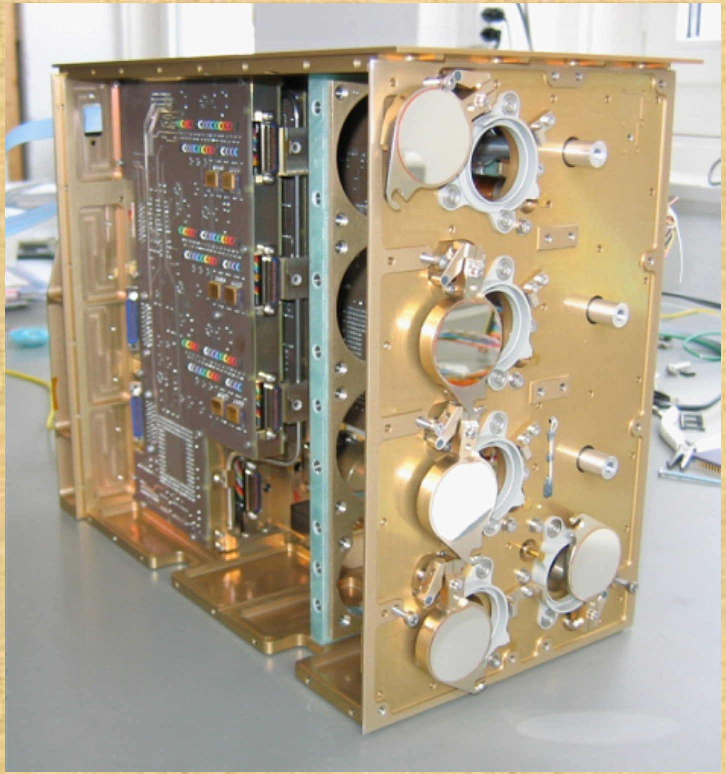
FUV Variability



MUV Variability



Cycle 24 Comparisons: Picard / PREMOS

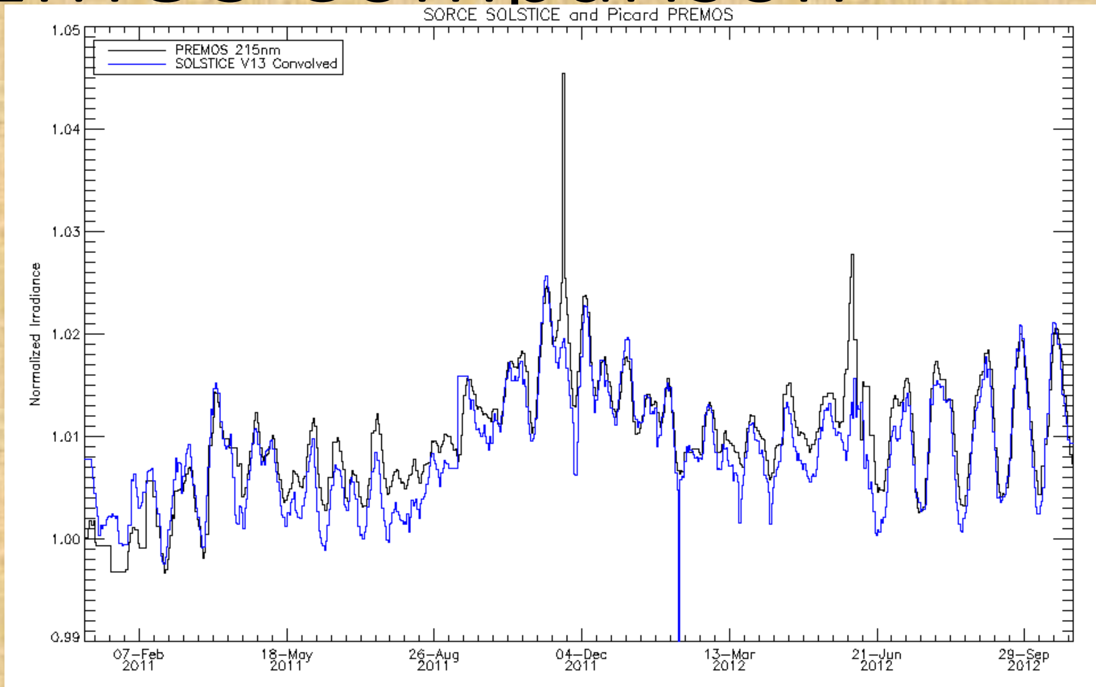


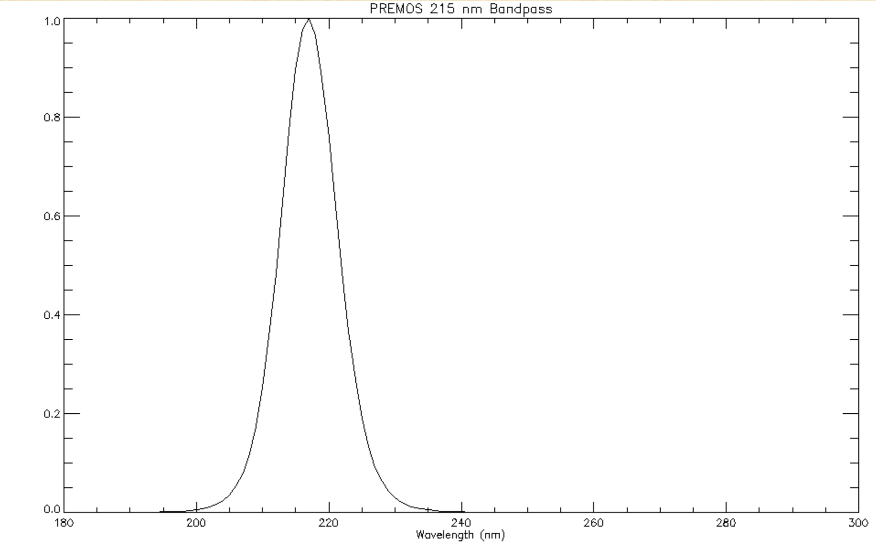
Launched in June, 2010, one of the instruments has two filter radiometer channels that overlap the SOLSTICE wavelength domain at 215 nm and 268 nm.

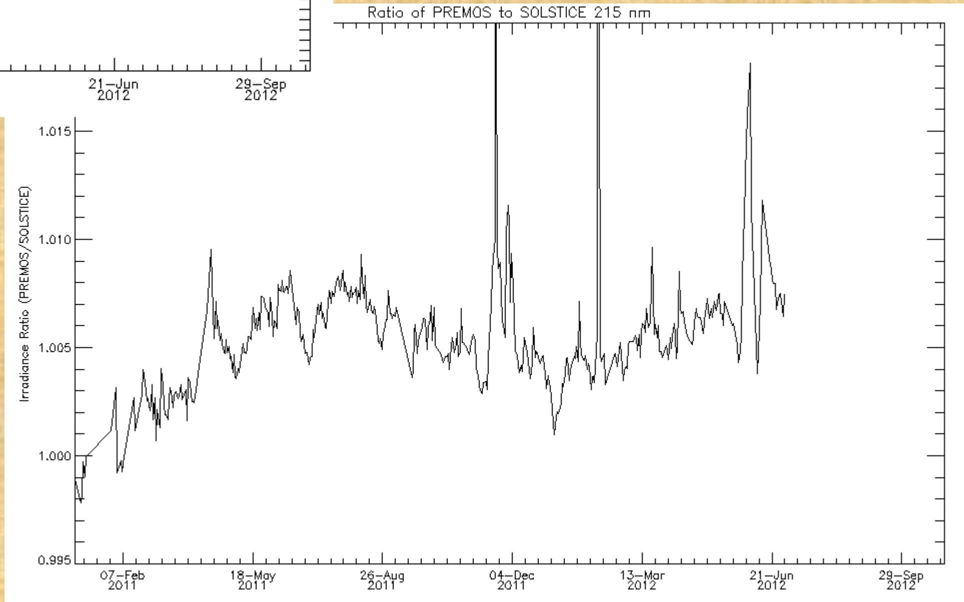
The PREMOS team have provided us with the following data from the 215 nm channel.

This data will soon be available on http://projects.pmodwrc.ch/solid/index/php/main-database but it has not yet been updated there.

PREMOS Comparison







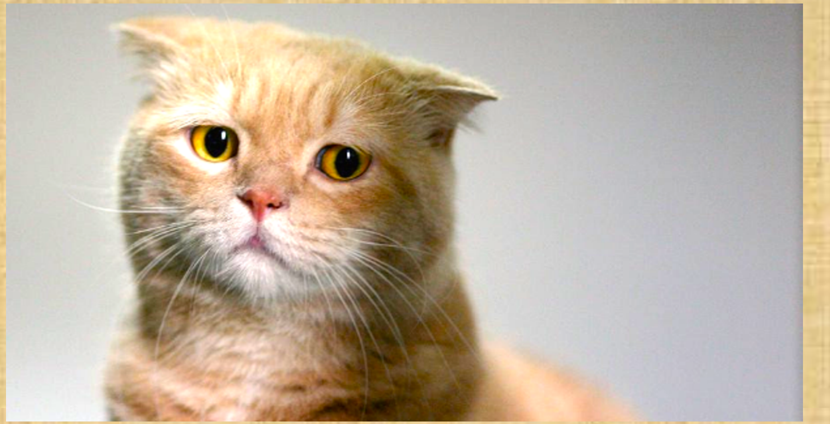
Agreement is within 0.3% apart from early in the Picard mission.

Cycle 24 Comparisons: SOLAR/SOLSPEC

Launched in 2008 to International Space Station
Grating double monochrometer – similar to ATLAS SOLSPEC

Measures 165-3100 nm. Geometry limits solar viewing to only a few days per week (average 1 spectrum every three days).

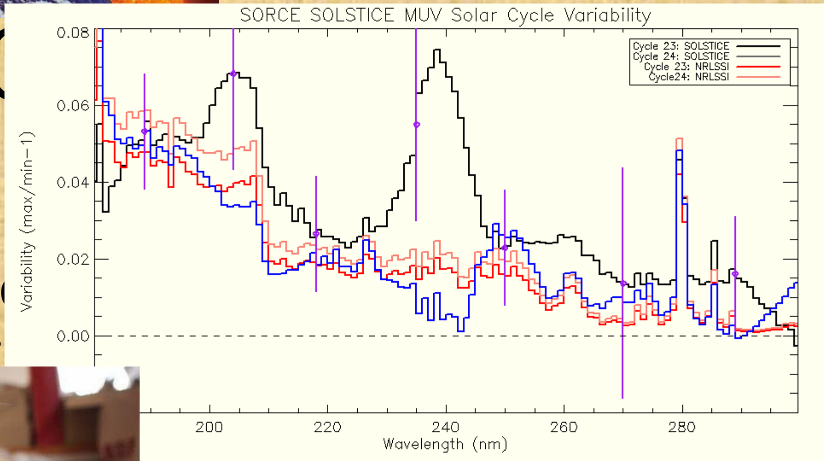
Decomissioned just a few days ago.

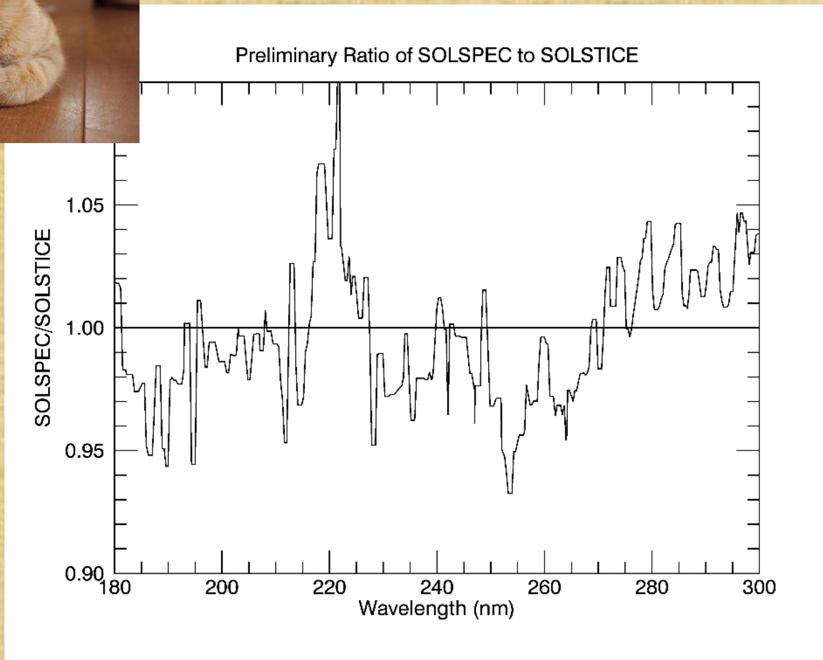


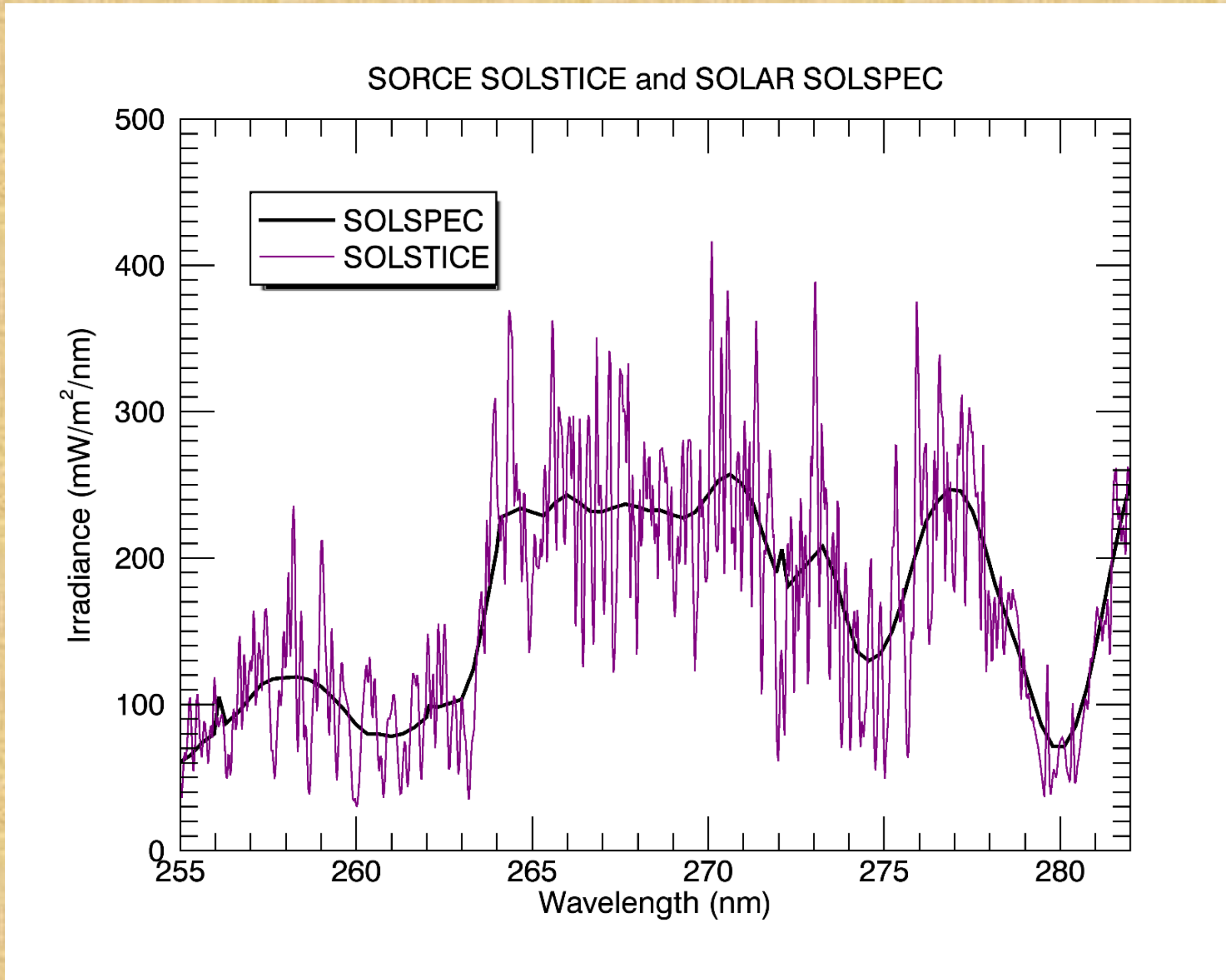
So far, only UV part of the spectrum is ready for release.

SO… on

SOLSPE… measur… m … It …RCE SOLSTICE to within a few percent.







SORCE Mission Outlook

- Degraded batteries have led to a Day Only Operations (DO-Op) mode.
  - All instruments are powered off during eclipse
  - Data recorder also reset every eclipse
  - Instruments power on autonomously every sunrise
  - Data is captured with real-time contacts or with ground station (2-4 orbits/day)
- Instruments still in good health
- NASA plans to operate SORCE for 1 year after TSIS launches (2018?)
- Compact SIM (CSIM) is a cubesat version of SIM – may also launch in 2018.
- Instrument in development at LASP for rocket flight in 2018 will provide underflight calibration of SOLSTICE FUV.

2018 may be an eventful year for SSI

SORCE SSI Summary

- Daily observations continue in DO-Op mode:
  - SOLSTICE gets occasional stellar and solar/stellar calibration observations.
  - Fewer spacecraft events makes SIM analysis less complex – spacecraft is currently well behaved.
- Cycle 24 observations are much closer to model predictions and other SSI observations.
- Decline of cycle 23 is larger than model predictions and other SSI observations – but analysis continues.
- Degradation rates for both SIM and SOLSTICE are now very low, giving high confidence in cycle 24 measurements.