Measured solar spectral irradiance variability using the SORCE SIM

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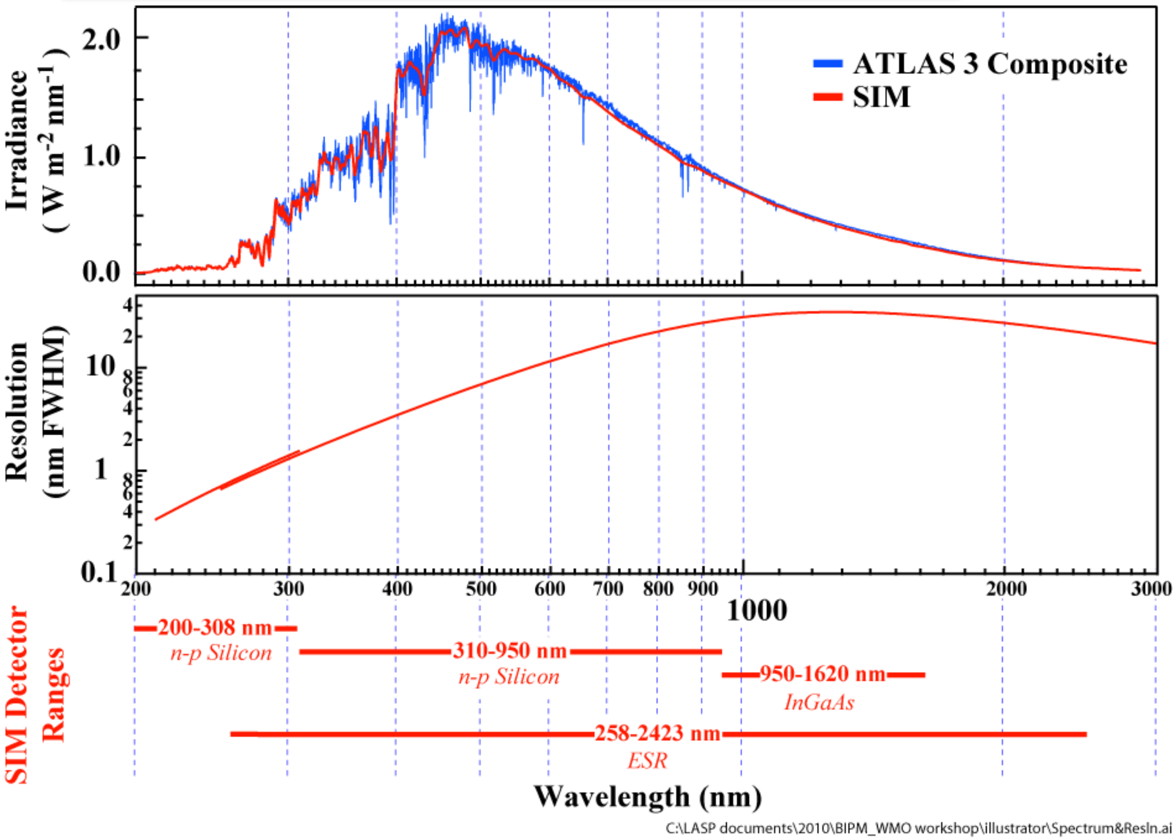
Discussion Topics

- **Review of the SIM instrument**
  - Detectors and spectral ranges, resolution, sampling
  - Instrument configuration
- **The SIM measurement equation**
- **Sources of noise**
  - ADC noise limited performance on photodiodes
  - Noise spectrum of the ESR
- **Sources of irreversible time dependent degradation**
  - Prism degradation – the dominant source of instrument sensitivity loss
  - Effects of spacecraft safe-hold events

Instrument Overview

- **Instrument Type**: Féry Prism Spectrometer
- **Wavelength Range**: 200-2400 nm
- **Wavelength Resolution**: 0.24-34 nm
- **Detector**: ESR, n-p silicon, InGaAs
- **Absolute Accuracy**: 2-8%
- **Relative Accuracy** : ~0.5-0.02% (210-2400 nm)
- **Long-term Accuracy**: 0.3-0.02%/yr (210-2400 nm)
- **Field of View**: 1.5x2.5˚ total
- **Pointing Accuracy/Knowledge**: 0.016˚/0.008˚
- **Mass**: 21.9kg
- **Dimensions**: 88 x 40 x 19 cm
- **Orbit Average Power** : 17.5 W
- **Orbit Average Data Rate**: 1.5 kbits/s
- **Redundancy**: 2 Redundant Channels



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

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

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

Harder J. W., G. Thuillier, E.C. Richard, S.W. Brown, K.R. Lykke, M. Snow, W.E. McClintock, J.M. Fontenla, T.N. Woods, P. Pilewskie, 'The SORCE SIM Solar Spectrum: Comparison with Recent Observations' , *Solar Physics*, **263**, Issue 1 (2010), pp 3, doi:10.1007/s11207-010-9555-y

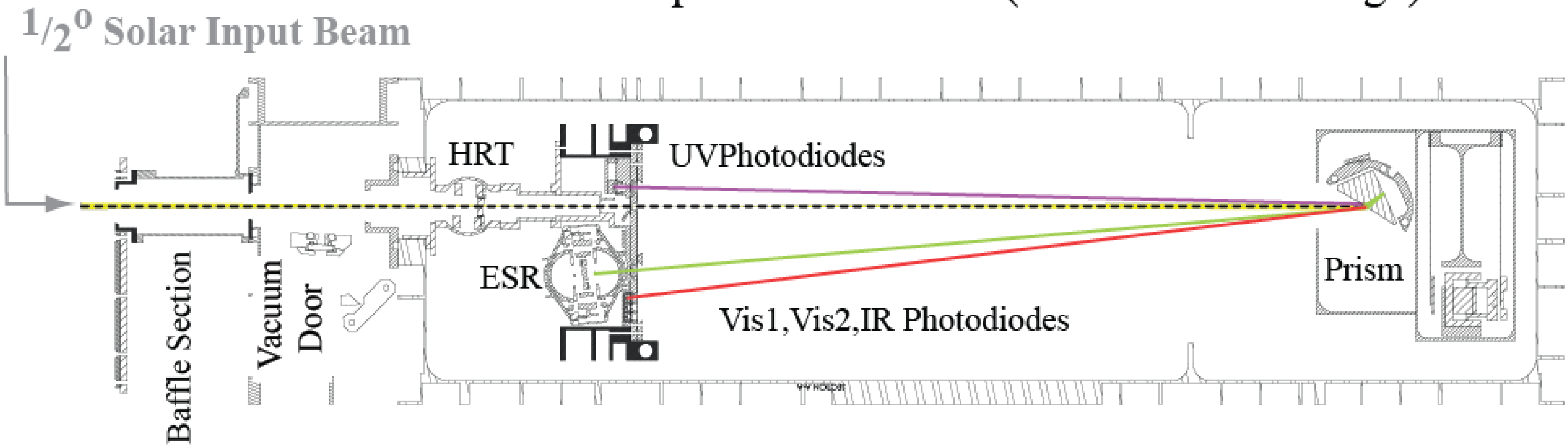
Pagaran, J., J. W. Harder, M. Weber, L. E. Floyd, and J. P. Burrows, 'Intercomparison of SCIAMACHY and SIM vis-IR irradiance over several solar rotational timescales', A&A, 528, A67 (2011), doi: 10.1051/0004-6361/201015632, 2011.

Corrections based on *measured* telemetry

- **No assumptions are made about magnitude, slope, or time dependent behavior of SSI.**
- **Method of degradation correction is similar to the method used to correct TSI instruments but done as a function of wavelength.**
- **Degradation Corrections:**
  - **Exposure-related prism transmission loss accounts for the majority of sensitivity loss in SIM**
    - Correct by comparing two spectrometers at different exposure rates
    - These spectrometers are in the same, physical, chemical, and thermal environments, so instrument changes are common mode.
  - **Non-exposure related effects from space and spacecraft environment must be handled independently from prism transmission.**
    - Correct ESR gain changes through routine gain measurement experiments
    - Correct photodiode detectors by comparing with the ESR's
    - Identify time periods when the instrument is affected by spacecraft disturbances

Instrument Configuration

SIM A: Cross section in dispersion direction (SIM B mirror image)



- **Stability of the ESR anchors the corrections for SIM**
  - Energetic photons do not make it to the ESR
  - Input flux is very small (<60 µW)
  - Critical power replacement resistors and 7.1 V reference are radiation hard
  - Weekly ESR gain measurements test and correct the 'softer' ESR electronics
- **Only one optical element to degrade through transmission loss**
- **Transmission loss probably arises from exposure of the prism to energetic solar photons:**
  - Directly induce compositional changes in the first few monolayers of the glass
  - transmission losses due to polymerization of trace amounts of organic materials on the surface

Fundamental SIM Measurement Equation

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$$E(\lambda)=\frac{measuredDetectorCounts(\lambda)}{\int entranceApertureArea\times detectorResponseFunction(\lambda)\times spectralBandwidth(\lambda)\times OpticalTransmission(\lambda)\,d\lambda}$$ (units of $Wm^{-2}nm^{-1}$)

$$E_{ESR}(\lambda_s,t)=\frac{\overbrace{\frac{1}{M}\frac{V_7^2R_h}{(R_h+R_s)^2}\left\{\frac{1+\tilde{G}(t)}{\tilde{G}(t)}\frac{\vec{p}\bullet\vec{D}}{\vec{p}\bullet\vec{Q}}\right\}}^{\text{ESR Power (phase sensitive detection)}}}{A_{slit}(T)\int\alpha(\lambda)Tr_0(\lambda)\Phi(\lambda)S(\lambda_s,\lambda)\,d\lambda}\frac{1}{\left((1-a_{ESR})\exp(-\kappa(\lambda)C(t))+(a_{ESR})\exp\left(-\frac{\kappa(\lambda)C(t)}{2}\right)\right)}\overbrace{\frac{1}{f_{1au}}\frac{1}{f_{doppler}}}^{\text{Orbit Correction}}$$

$$E_{Diode}(\lambda_s,t)=\frac{\overbrace{\frac{V_{\max}}{M}\left\{\frac{D-D_0}{R_f}\right\}}^{\text{Detector photocurrent}}}{\underbrace{A_{slit}\int Rs(\lambda,t,T)Tr_0(\lambda)\Phi(\lambda)S(\lambda_s,\lambda)\,d\lambda}_{\text{Profile Integral}}}\underbrace{\frac{1}{\left((1-a_{diode})\exp(-\kappa(\lambda)C(t))+(a_{diode})\exp\left(-\frac{\kappa(\lambda)C(t)}{2}\right)\right)}}_{\text{Prism Transmission Degradation Factor}}\frac{1}{f_{1au}}\frac{1}{f_{doppler}}$$

Exposure related degradation

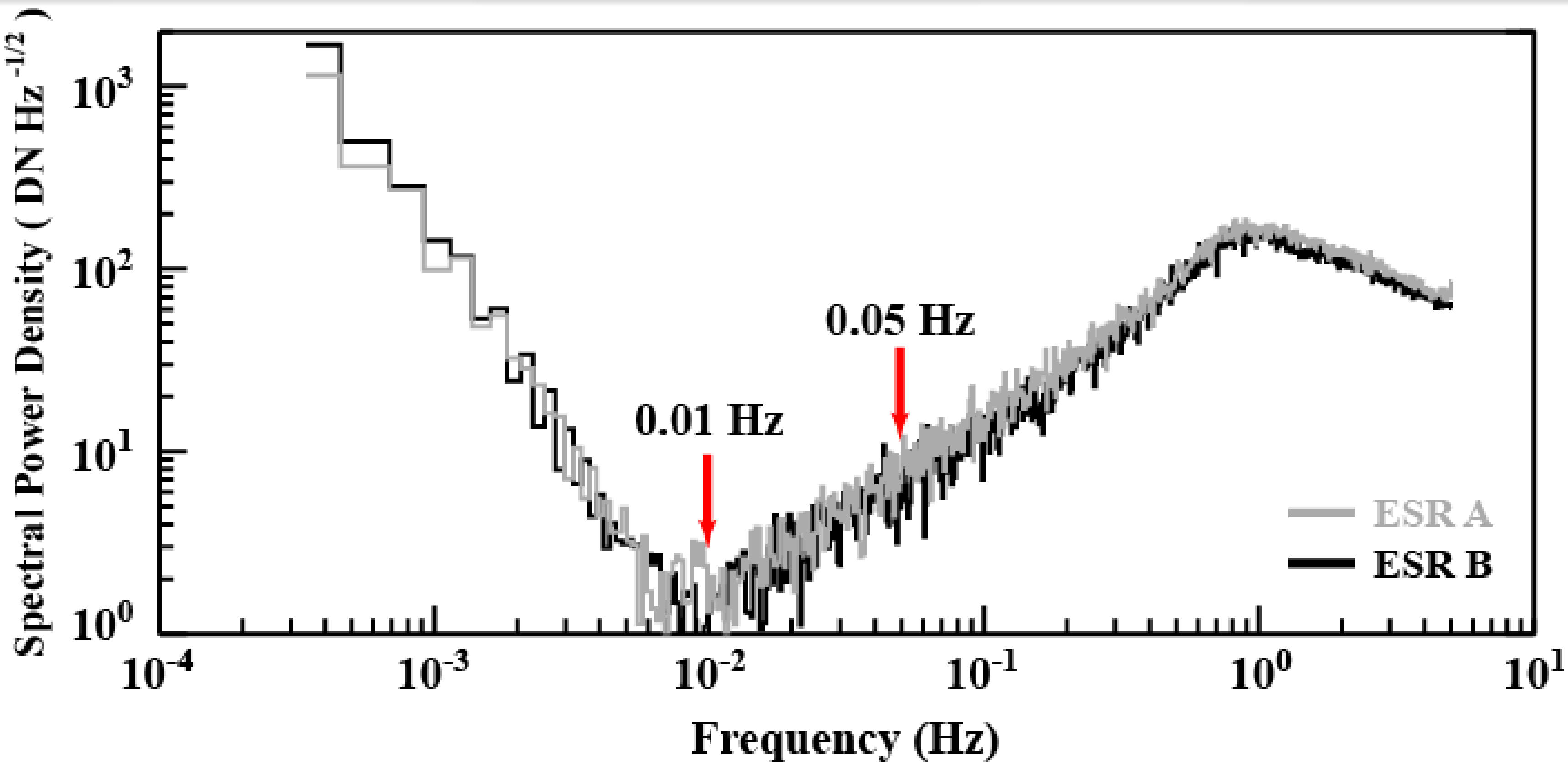
Non-exposure related degradation

Sources of Uncertainty in the SIM Time Series

Rank	Cause	Effect	Mitigation/magnitude of effect
Short-term effects – do not accumulate with time			
1	Detector Noise	Ultimate limit of comparison of two spectra	ESR :10^{-3} to 10^{-5} Diodes; 3×10^{-3} to 5×10^{-5}
2	Spacecraft pointing	Local perturbation in prism transmission/wavelength shift	Can produce spurious noise on the order of 1%, problem fixed through data masking
3	Detector Temperature	Spurious structure to photodiode data (700-900 nm range)	Adds about 500 ppm of noise at these wavelengths, refinements needed in processing.
4	Prism Temperature	Wavelength shift	Corrected to ~150 ppm in data processing
5	Scattered light	Increases apparent irradiance – decreases contrast in 'lines'	<100 ppm in ESR, VIS, IR detectors, <0.5% in UV photodiode, not corrected
Long-term effects – accumulate with time			
1	Prism Transmission	Long-term reduction in instrument response.	Residual uncertainty 0.3-0.01%/yr
2	Optical alignment changes	Produces 'jumps' in the data at well-defined times	Problem significant after 2009/01/01 uncertainty ~0.1% in certain wavelength bands
3	Photodiode Radiant sensitivity	Reduction in photodiode sensitivity (750-950 nm range)	Comparisons to ESR; Comparable to diode noise ~10^{-4}
4	ESR servo gain degradation	Reduction in responsivity of the ESR detector	7 ppm/year, uncertainty ~1 ppm/year

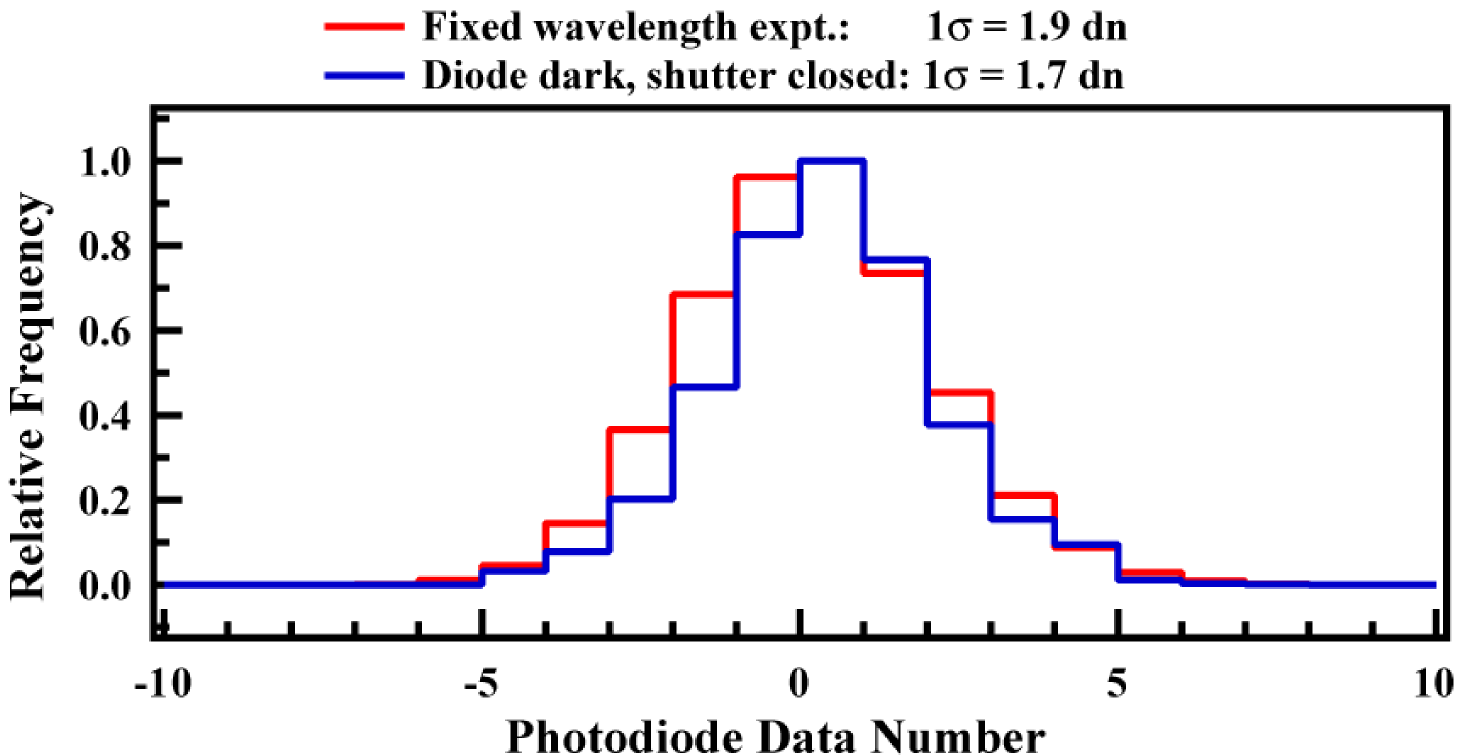
Detector Noise

Short Term effects: ESR Detector Noise



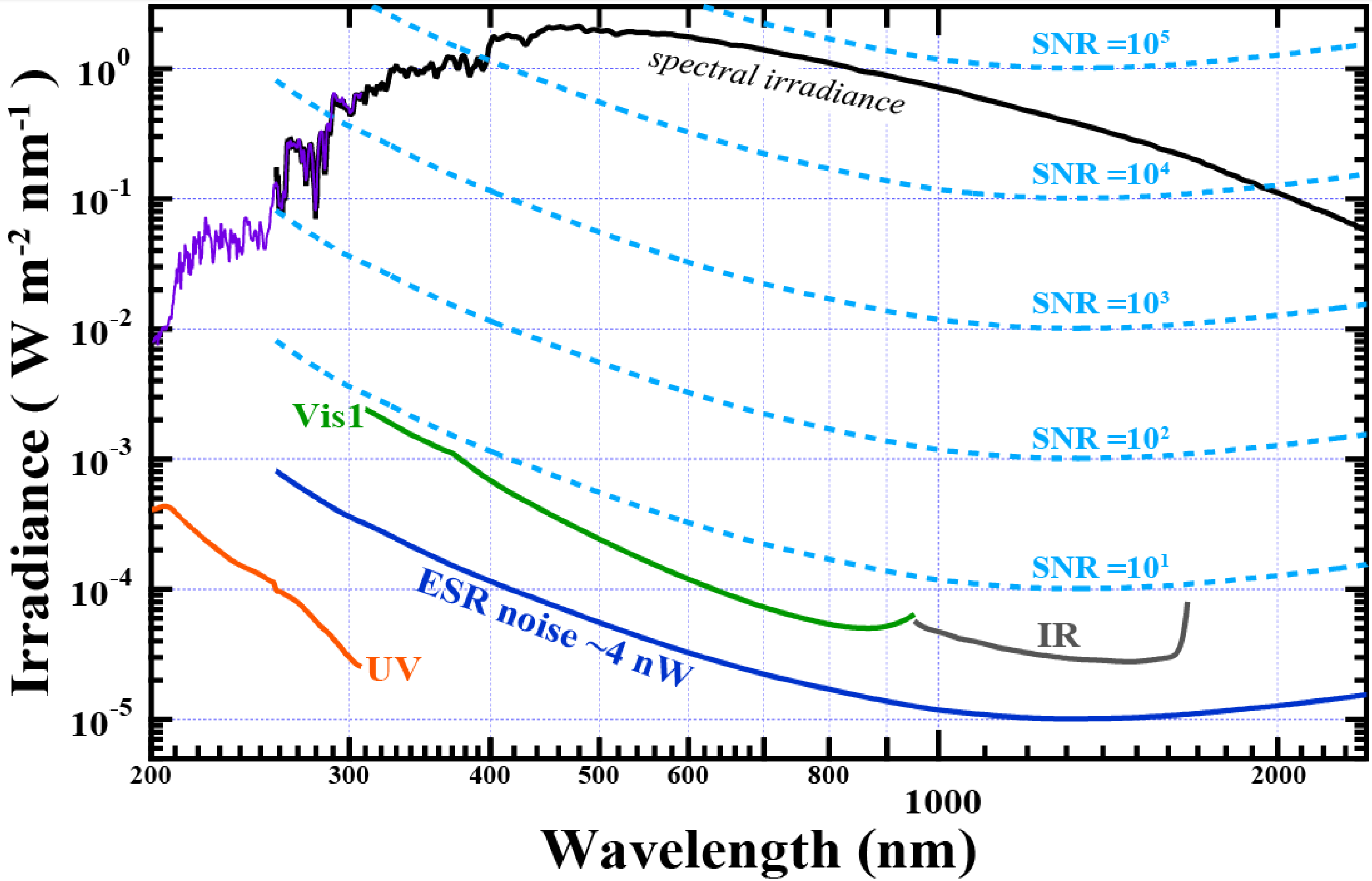
- **Noise spectrum invariant with time**
- **Other effects (λ-shift, roll effects) can reduce the effective precision of the measurement**
  - **Typical noise level ~ 4 nW, 50 sec half cycle, 2 cycles**

Short Term effects: Photodiode Noise



- Photodiode noise determined by noise on the ADC - not photon noise.
  - Output of photodiode detectors multiplex and read-out by the same ADC, therefore noise level is common to all photodiode detectors.
- Noise levels have not changed over the course of the mission, independent of where in the orbit the spectrum is taken (i.e. no SAA effects)
- Distribution of noise independent of whether shutter is opened or closed.
  - Determined from daily darks and 2005/2006 fixed wavelength experiments

Noise Equivalent Irradiance



Contours of signal-to-noise ratio are relative to the ESR 50 sec half-cycle, 200 sec integration

Prism Degradation

Working assumption for prism/ESR degradation correction

- **Degradation is proportional to exposure**
  - **SIM B has only ~1/4 of the exposure of SIM A**
  - **A function *F*(*t*) can be found that produces the same trends in A&B channels**
    - This is reasonable since the two instruments are in the same physical enclosure and their environment cannot evolve independently

Determination of the Degradation Function

Lambert's Law: $I(\lambda) = E(\lambda) e^{-\tau}$

For a single wavelength, λ. At two times 0 and 1.

$$\ln(I_{A0}) = \ln(E_0) - \tau_{A0}\ , \quad \ln(I_{A1}) = \ln(E_1) - \tau_{A1}$$
$$\ln(I_{B0}) = \ln(E_0) - \tau_{B0}\ , \quad \ln(I_{B1}) = \ln(E_1) - \tau_{B1}$$

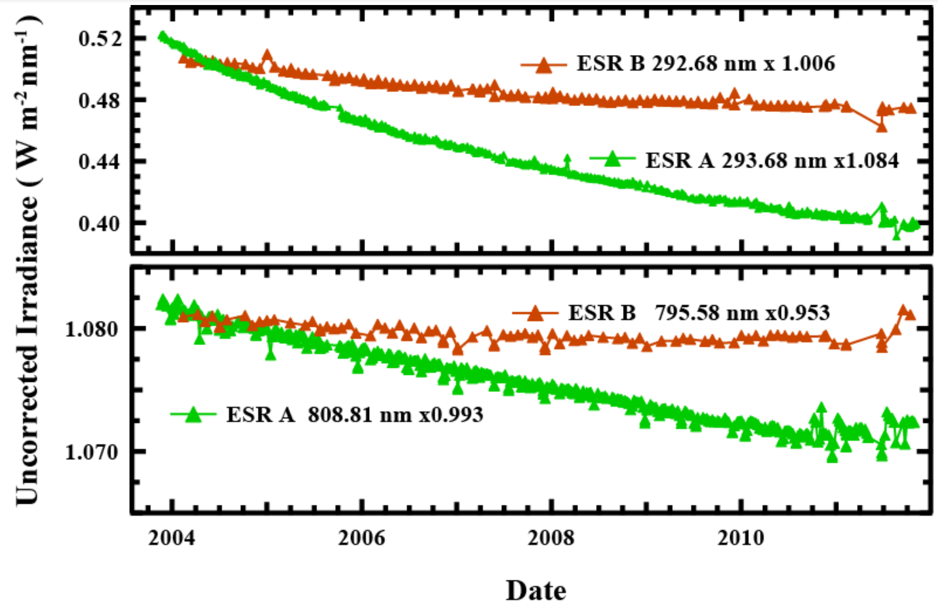
Combine and recase equations for SIM A & B in terms of measured quantities:

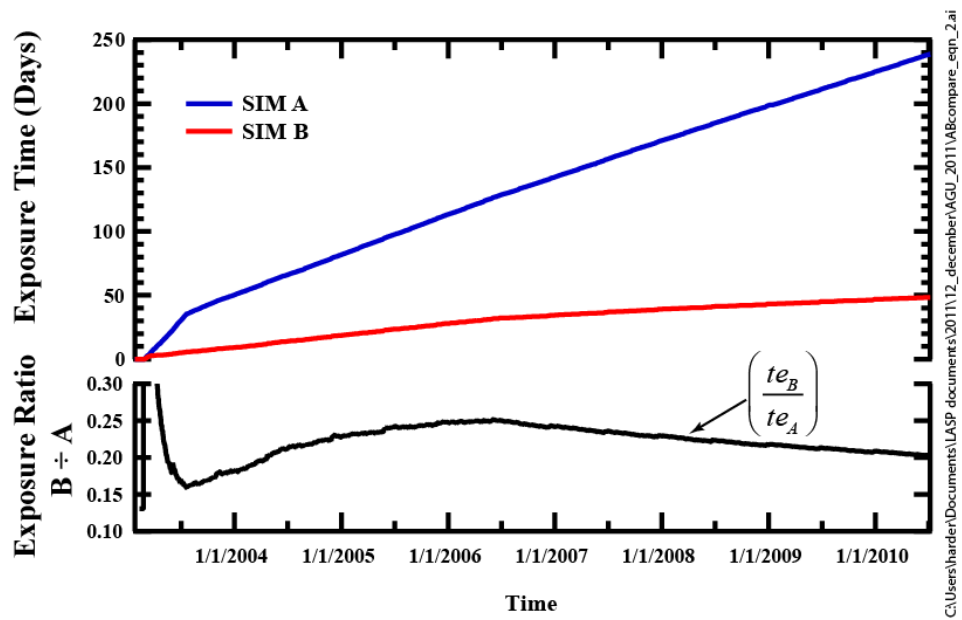
For SIM A: $\ln\left(\frac{I_{A1}}{I_{A0}}\right) = \ln\left(\frac{E_1}{E_0}\right) - F(t) \bullet \Delta X_{A_{0\to1}}$

For SIM B: $\ln\left(\frac{I_{B1}}{I_{B0}}\right) = \ln\left(\frac{E_1}{E_0}\right) - F(t) \bullet \Delta X_{B_{0\to1}}$

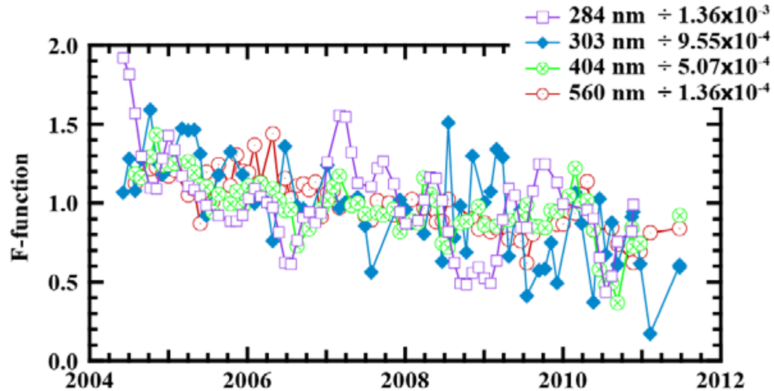
$F(t)$ = Time dependent degradation factor

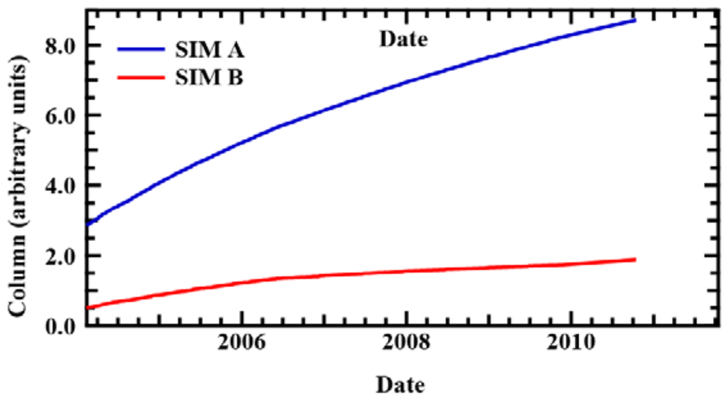
$\Delta X_{A_{0\to1} \text{ or } B_{0\to1}}$ = Measured exposure time between times t=0 and t=1

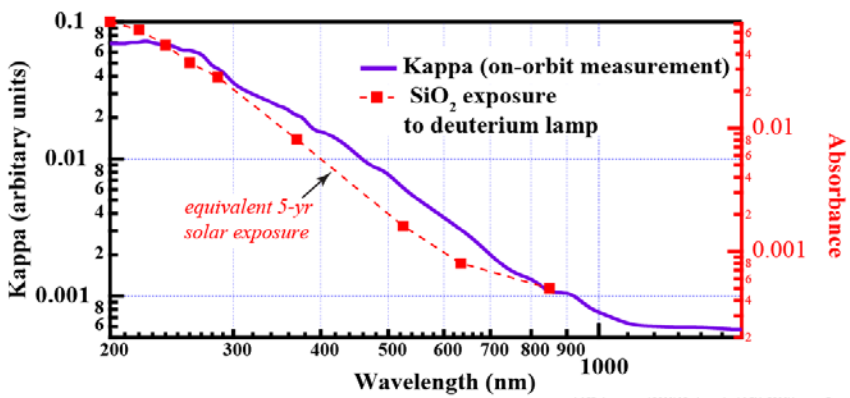




Determination of the Degradation Function







$$F=\frac{\ln\left(\frac{I_{B1}}{I_{B0}}\right)-\ln\left(\frac{I_{A1}}{I_{A0}}\right)}{\Delta X_{A_{0\to1}}-\Delta X_{B_{0\to1}}}$$

Degradation accumulates with time and must be determined for each wavelength.

$$\tau_A(\lambda,t_1-t_0)=\int_{t_0}^{t}F(\lambda,t')\frac{\partial X_{A_{0\to1}}}{\partial t'}dt \quad +Const.$$

(analogous for SIM B)

Decompose $\tau(\lambda,t_1-t_0)$ into two components:

$C(t_1-t_0)$ a time dependent part

$\kappa(\lambda)$ a wavelength dependent part

Then:

$$\tau_{AorB}(\lambda,t_1-t_0)=\kappa(\lambda)C_{AorB}(t_1-t_0)$$

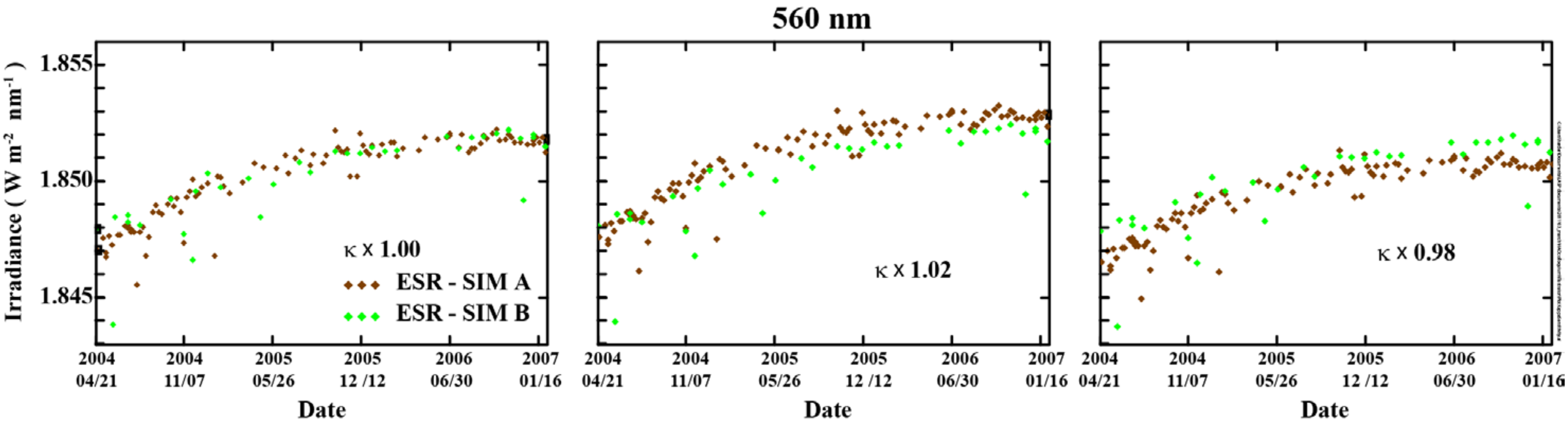
The degradation correction is:

$$E_{AorB}(\lambda,t)=\frac{I_{AorB}(\lambda,t)}{\exp\left(-\kappa(\lambda)C_{AorB}(t_1-t_0)\right)}$$

Time Series of Degradation Corrected Irradiance

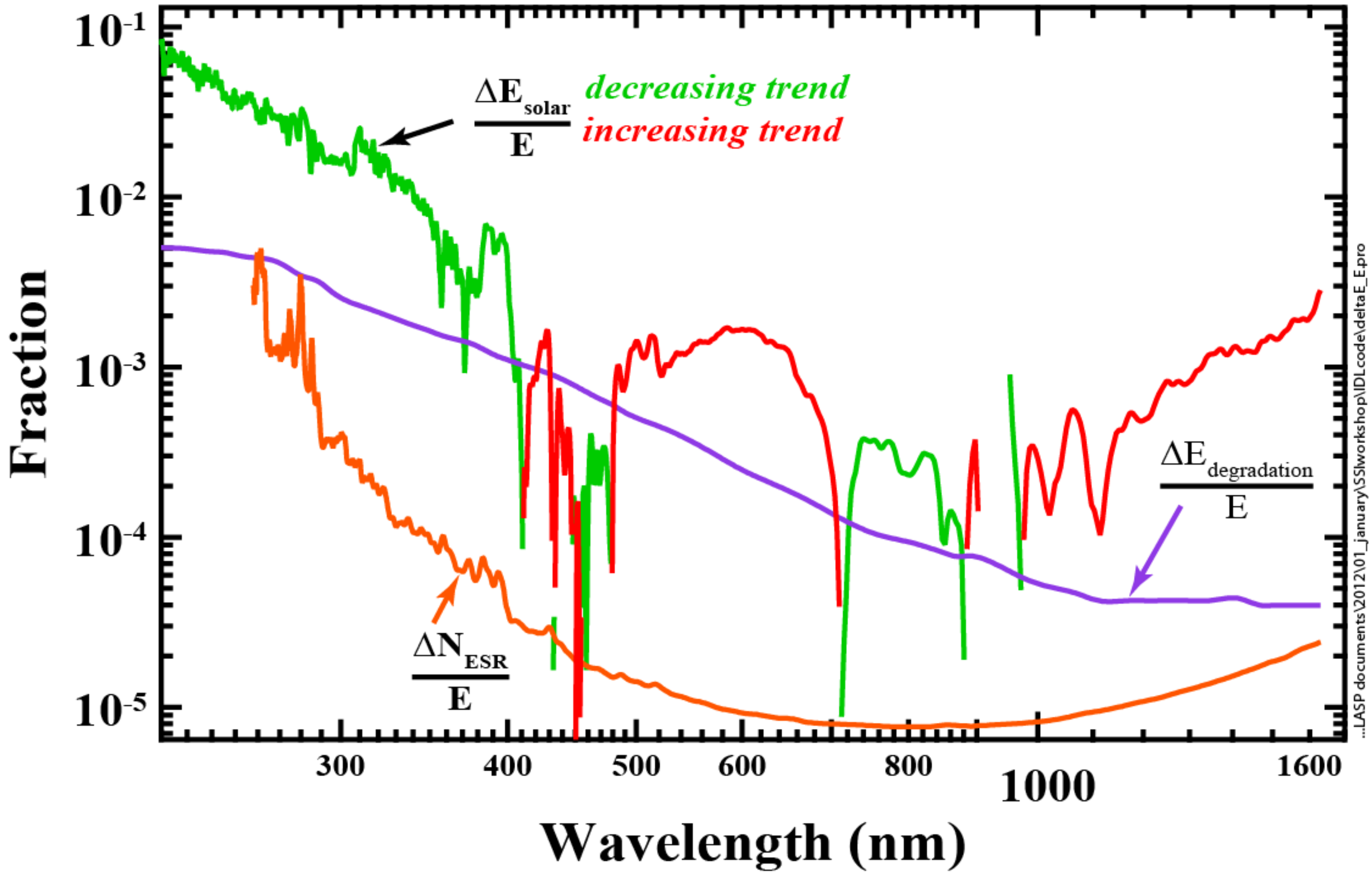
- Perturb the value of $\kappa(\lambda)$, apply to both SIM A & B
- Time series for the two instruments will diverge because the rates of exposure are different
  - Provides a method to estimate the uncertainty in $\kappa(\lambda)$

$$\frac{\Delta\tau}{\tau} = \frac{\Delta\kappa}{\kappa} \qquad \frac{\Delta\kappa}{\kappa} \le 0.02 \qquad (\pm 2\sigma)$$



$$\frac{\Delta E_{degradation}}{E} = \Delta\tau = \kappa(\lambda)\left(C_{t_1} - C_{t_0}\right)\frac{\Delta\kappa}{\kappa}$$

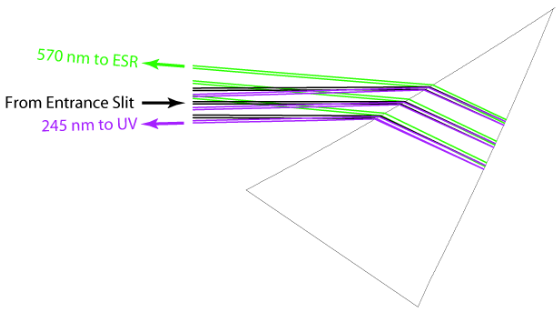
Contributions of Uncertainty to trend



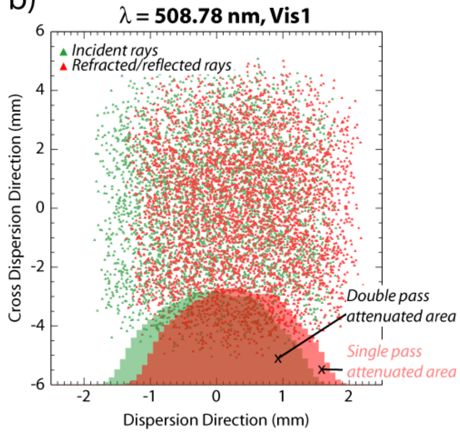
- Time range 2004/06/1-2007/11/15, 1262 days,3.45 years
- ΔN_{esr} = 4nW

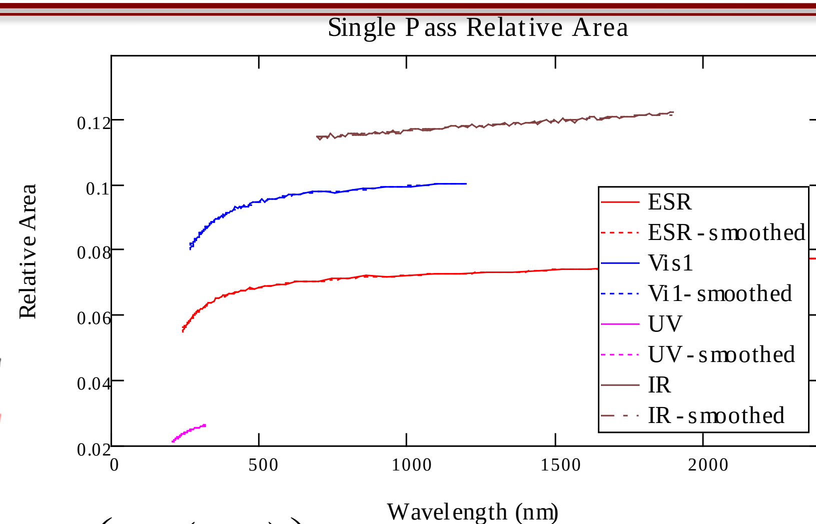
Transfer ESR correction onto adjacent photodiodes

a)



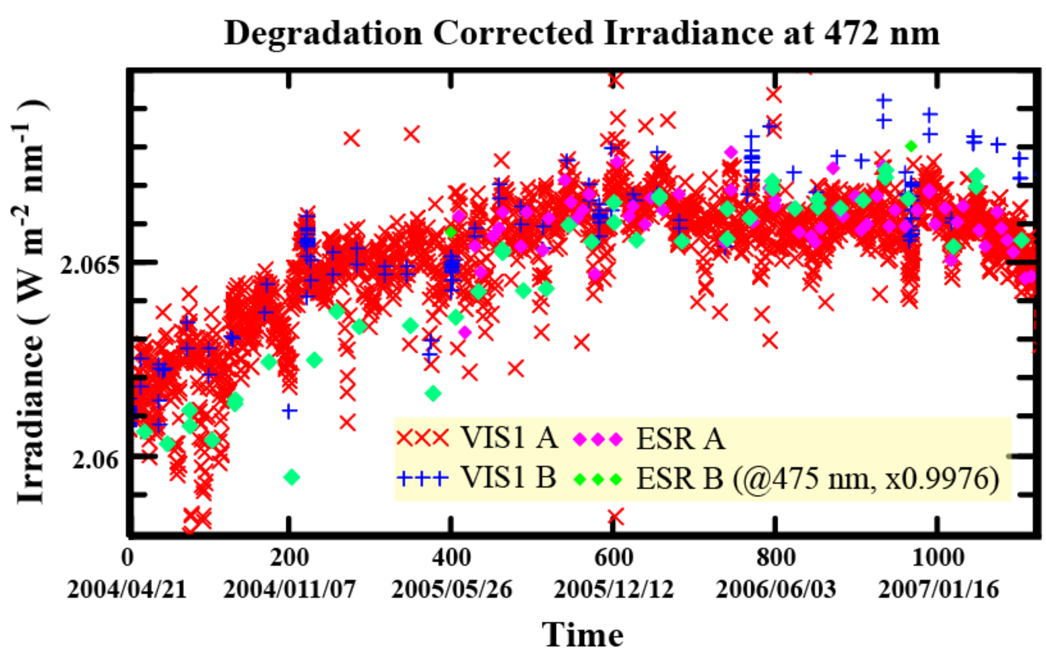
b)





$$\frac{E_{corrected}}{E_{uncorrected}} = (1-a_d)\exp(-\tau(\lambda,t)) + (a_d)\exp\left(\frac{-\tau(\lambda,t)}{2}\right)$$

- **No pristine area on the surface of the prism and different light paths through the prism encounter different amounts of absorbing material.**
- ***a_d* initially estimated from ray traces and then adjusted to match the trends seen in the ESR**



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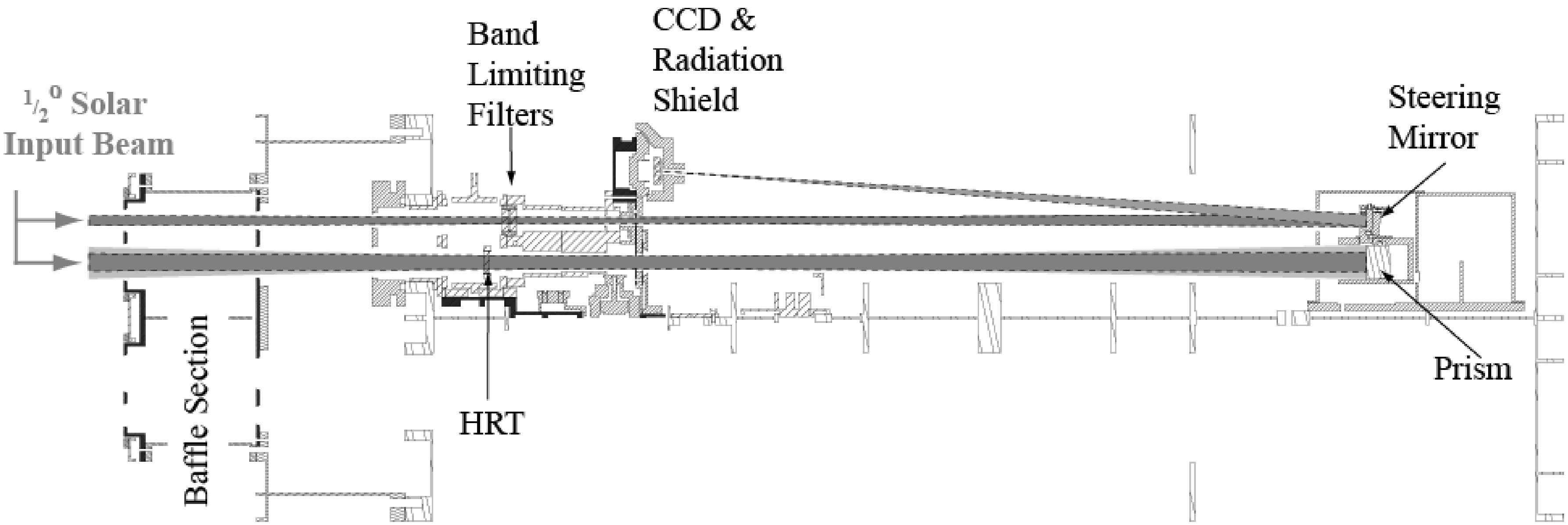
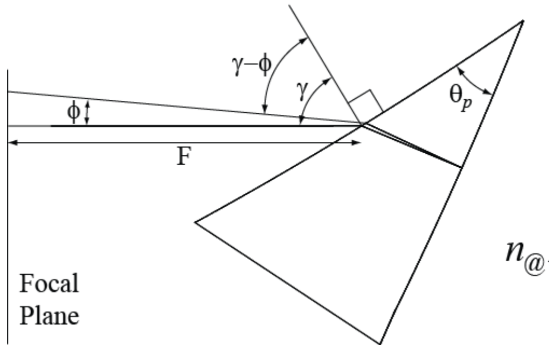
Effects of OBC Anomalies and Wavelength Stability

SIM in Cross Dispersion

SIM A: Cross Dispersion Direction





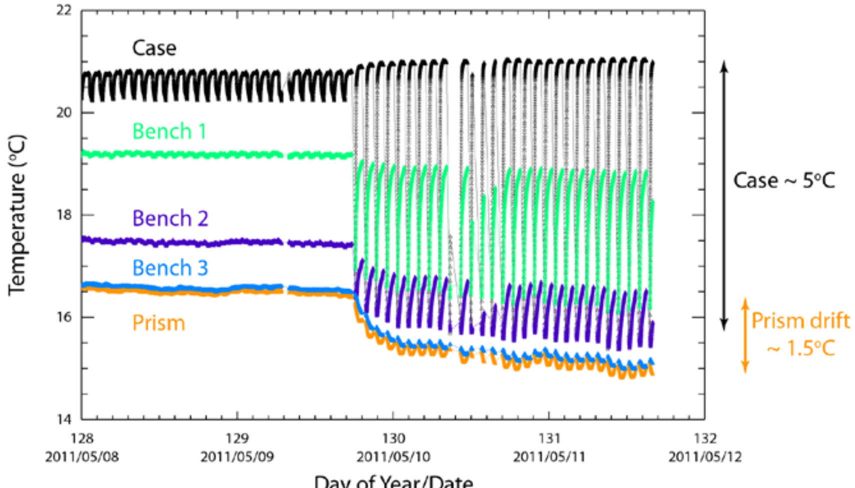
Date

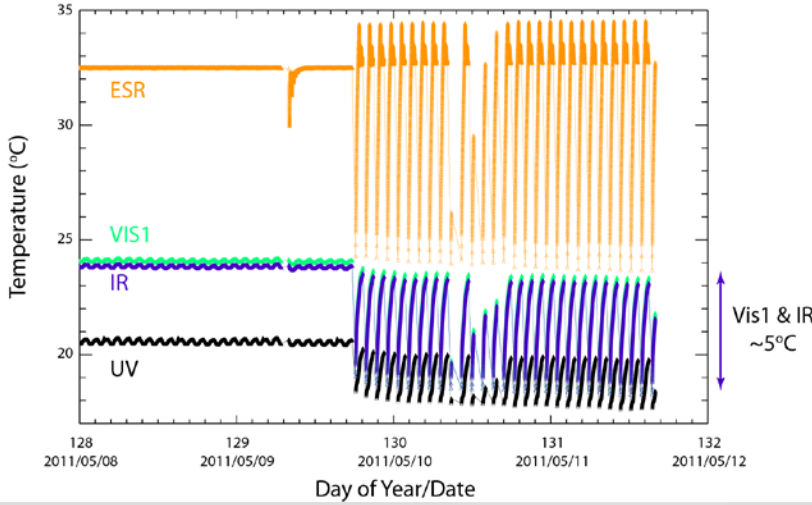
$$\gamma = (1+\alpha)\gamma_z + \frac{1}{2}tan^{-1}\left(\frac{(C-C_z)\times px(1+\beta)}{F_{REF}}\right)$$

$$n_{@vis1} = \frac{1}{\sin(2\theta_P)}\sqrt{\sin^2(\gamma)+2\cos(2\theta_P)\sin(\gamma)\sin(\gamma-\phi)+\sin^2(\gamma-\phi)}$$

Status of SIM after October 2010

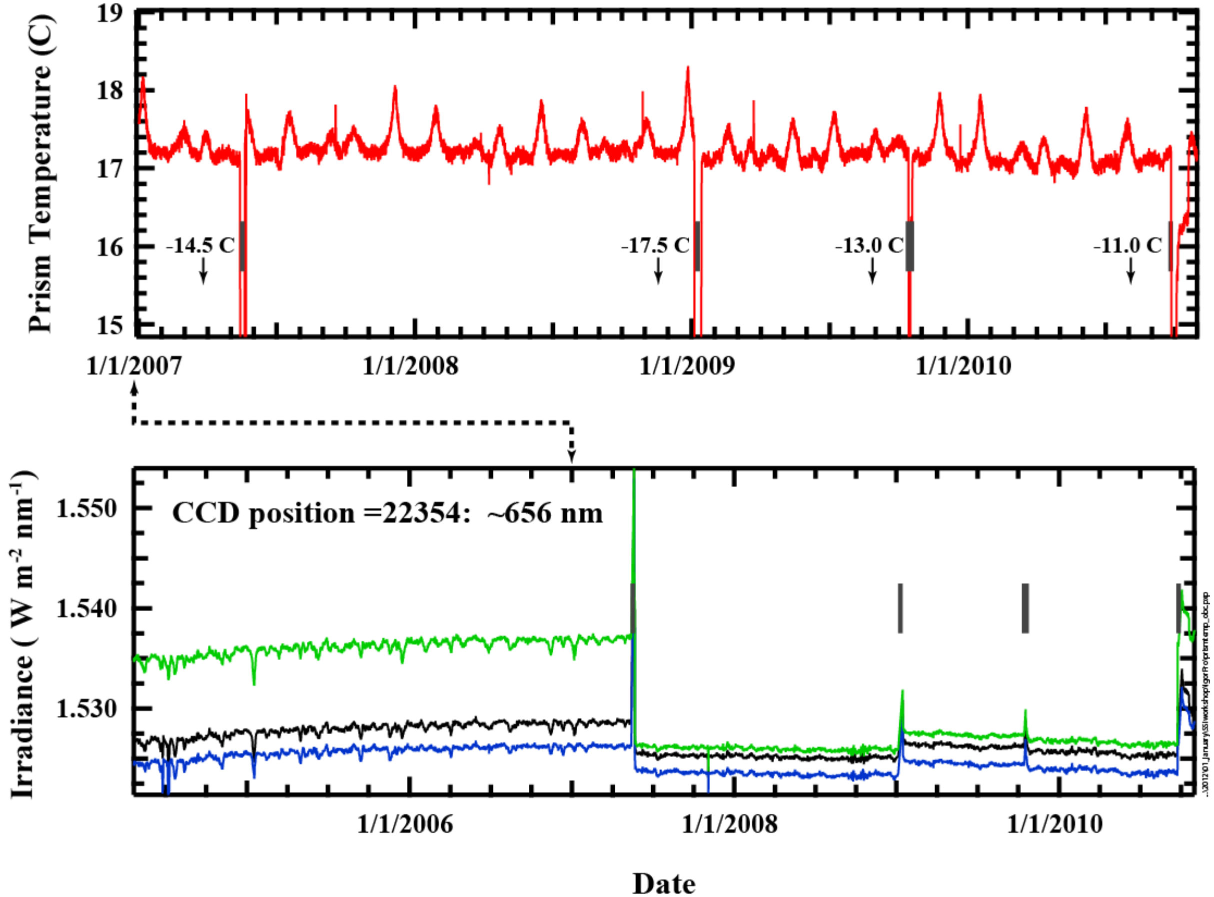
- 4 different safe-hold events since September 26, 2010 caused observatory temperatures to drop below -15°C producing small be noticeable changes in the responsivity of SIM.
  - The cause of these anomalies has been corrected in flight software
- Because of decreased battery capacity, power cycling on every orbit started on 2011/05/04
  - Power cycling has no instrument safety issues and has not disrupted normal data acquisition
  - Detectors have 3-5 degree temperature swings
  - Prism temperature drifts continuously (~1.5°C) but does not effect data processing
  - ~1 year of data may be needed to detect second order effects





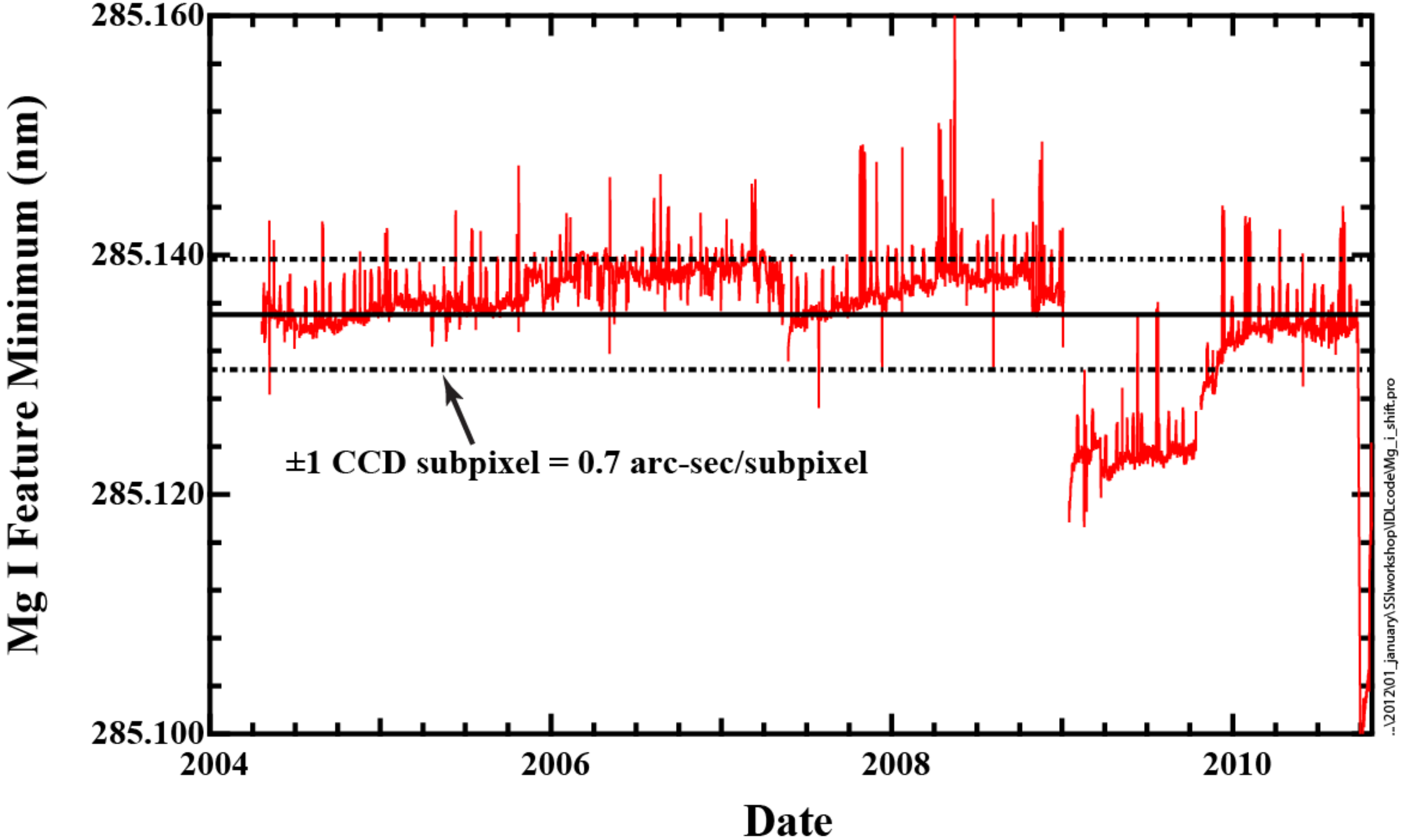
Effects of SORCE Anomalies

Spacecraft Events
05/18/2007
01/09/2009
10/19/2009
10/14/2009
09/26/2010
12/26/2010
01/28/2011
05/13/2011
09/06/2011



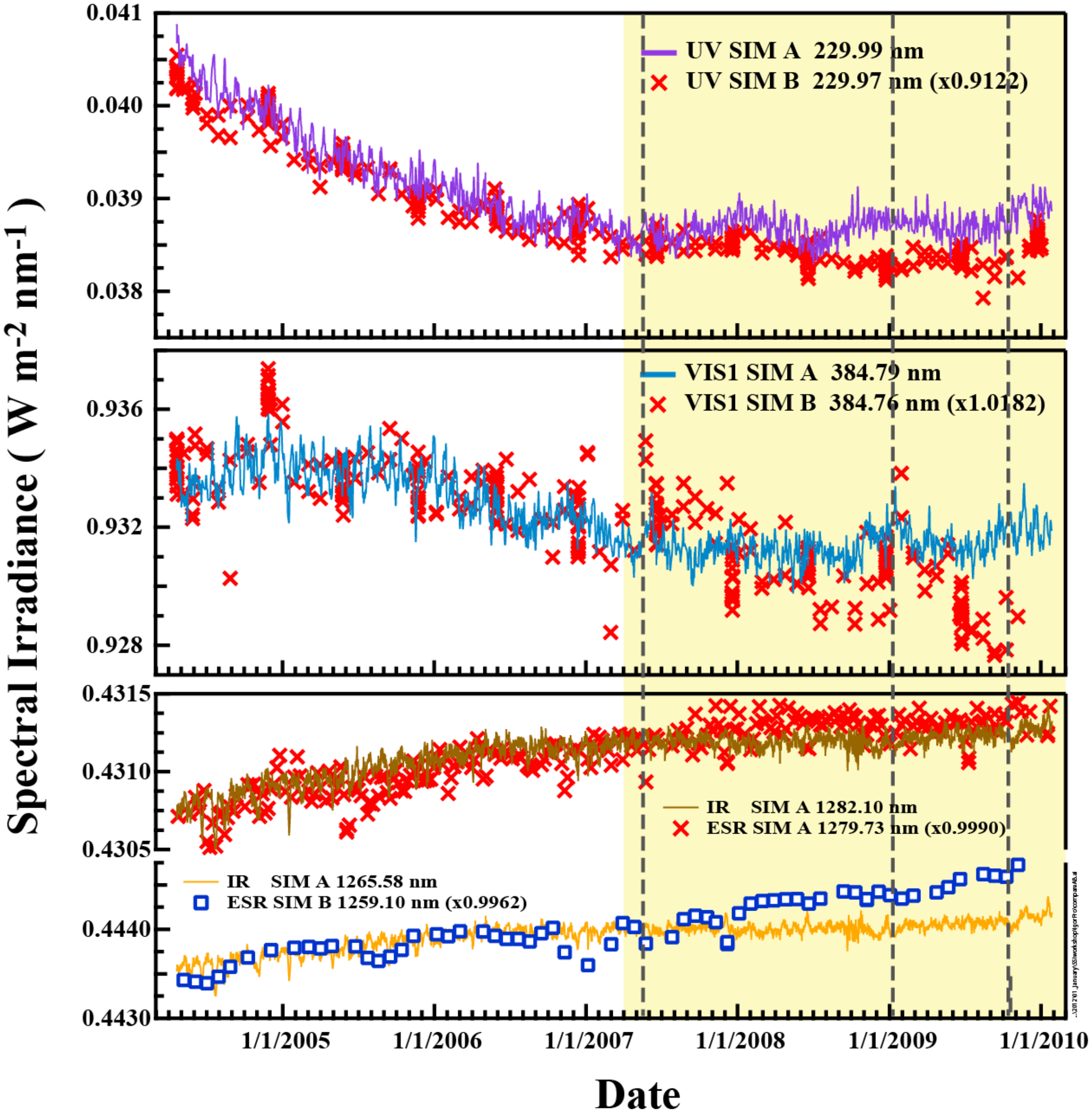
- **OBC events cause a change in the orientation of the steering mirror relative to prism face, wavelength correction performed but it re-maps the CCD pixels onto the wavelength scale**

Optical alignment changes



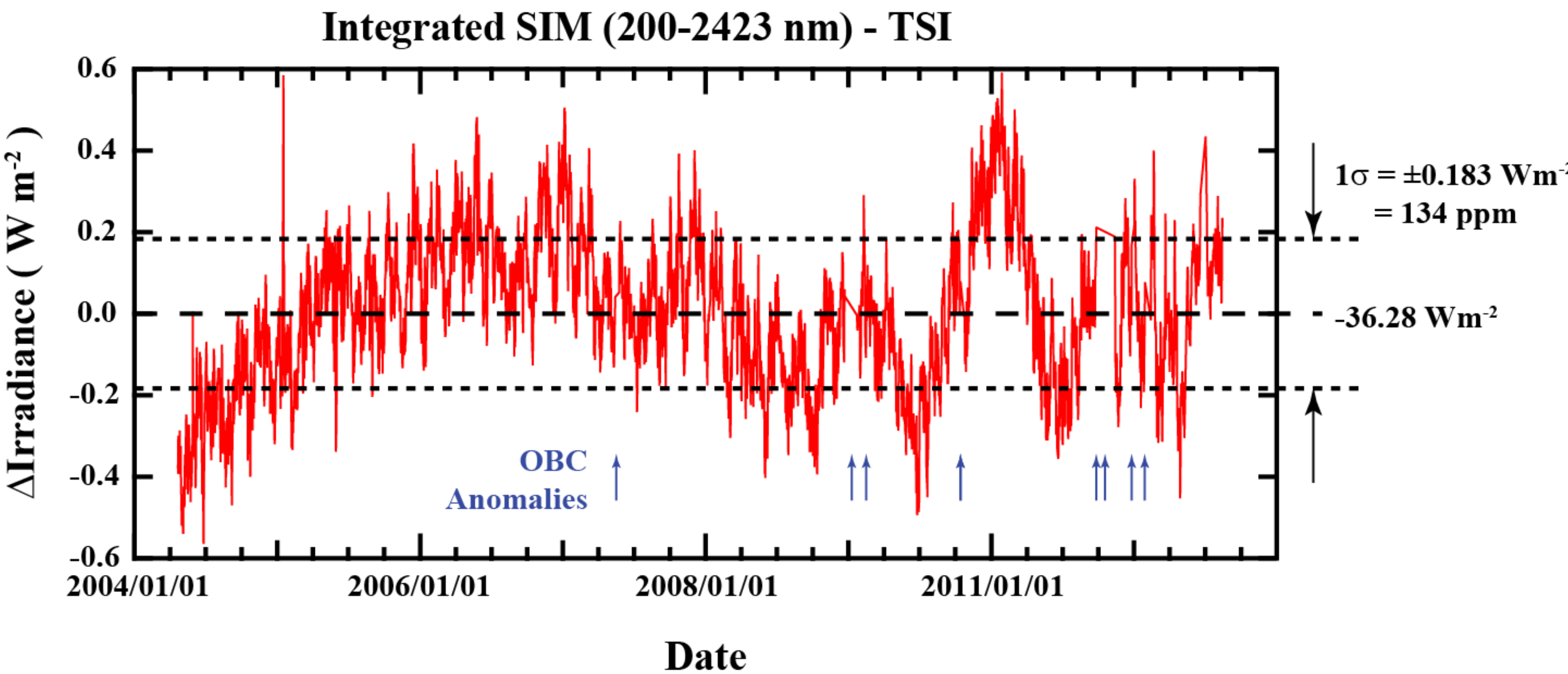
- **Wavelength drive exhibits remarkable precision over very long time periods**
  - **Wavelength registration within the limits set by hardware**
  - **Cardinal wavelength step = 38 subpixel steps, precision ~ 1/38 of a step**

Current SIM Data Composite



- OBC anomalies after 2007 disrupt the continuity of the A-to-B data
- Spectra from the two channels are valid in a piecewise sense
- Connecting data sets after OBC events is a ‘compositing’ activity and induces discontinuous uncertainty beyond AB comparisons
- Alternate/improved methods are understudy to correct and effectively concatenate the pieces.

Integrated SIM Relative to TSI



- **No systematic slope through the data, suggests no common-mode degradation**

Conclusions

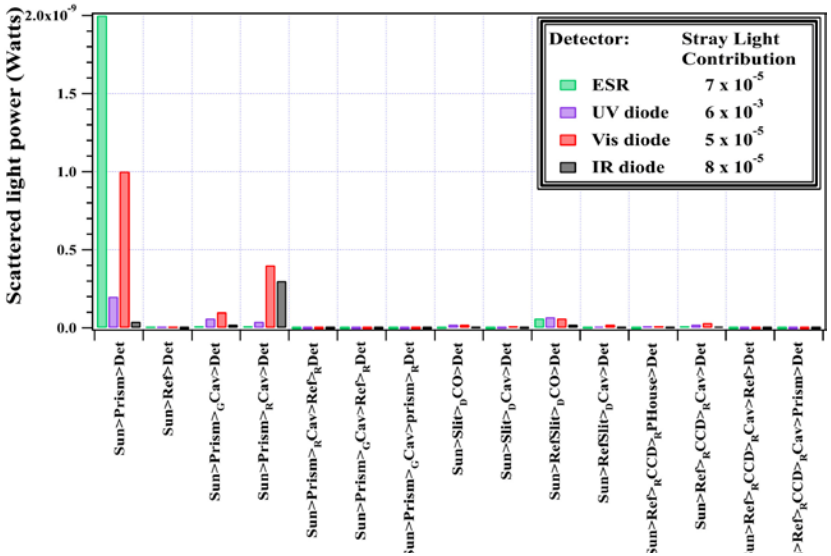
- **Long-term degradation corrections in SIM are based solely on measured instrument quantities.**
  - **Correction is based on the comparison of two identical (mirror image) spectrometers that have been exposed at different rates.**
  - **Corrections for photodiode detectors in the same channel are made by comparison with the spectrally flat ESR detector after correcting for the different optical paths through the prism.**
  - **Safe hold events decrease the precision after 2009, further work is underway to correct the influence of these events.**

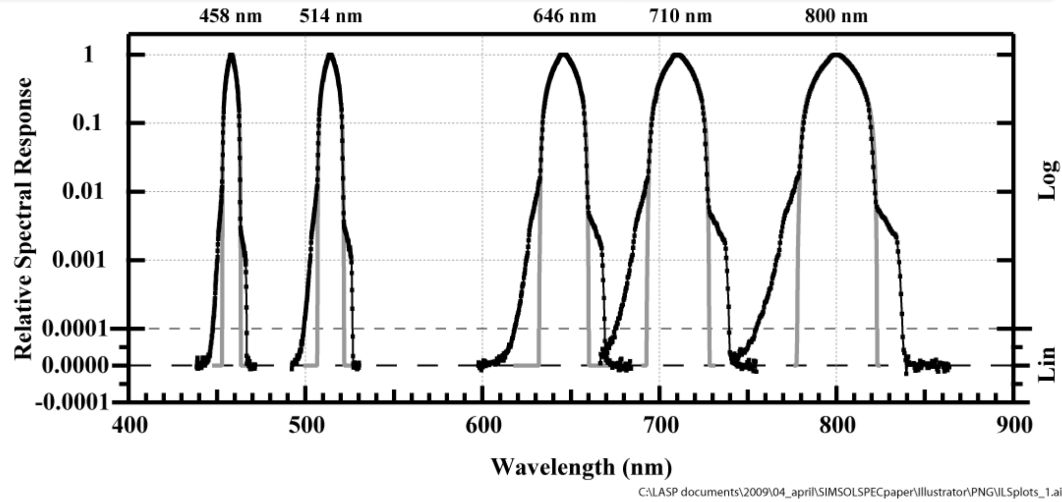
Additional Uncertainty Analyses

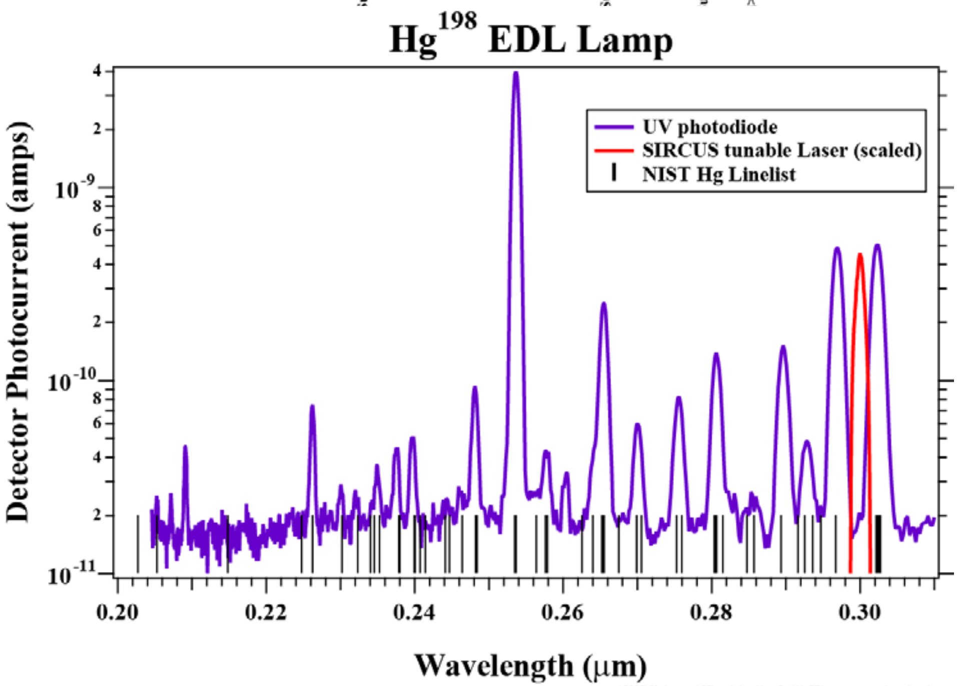
Sources of Uncertainty in the SIM Time Series

Ranking	Cause	Effect
Short-term effects – do not accumulate with time		
1	**Detector Noise**	**Ultimate limit of comparison of two spectra**
2	**Spacecraft pointing**	**Perturbation in prism transmission/wavelength shift**
3	**Detector Temperature**	**Spurious structure to photodiode data (700-900 nm range)**
4	**Prism Temperature**	**Wavelength shift**
5	**Scattered light**	**Increases apparent irradiance – decreases contrast in 'lines'**
Long-term effects – accumulate with time		
1	Prism Transmission Degradation	Long-term reduction in instrument response. Effect is irreversible
2	Photodiode Radiant sensitivity	Reduction in photodiode sensitivity (750-950 nm range)
3	Optical alignment changes	Produces 'jumps' in the data at well-defined times
4	ESR servo gain degradation	Reduction in responsivity of the ESR detector

Short Term effects: Scattered Light

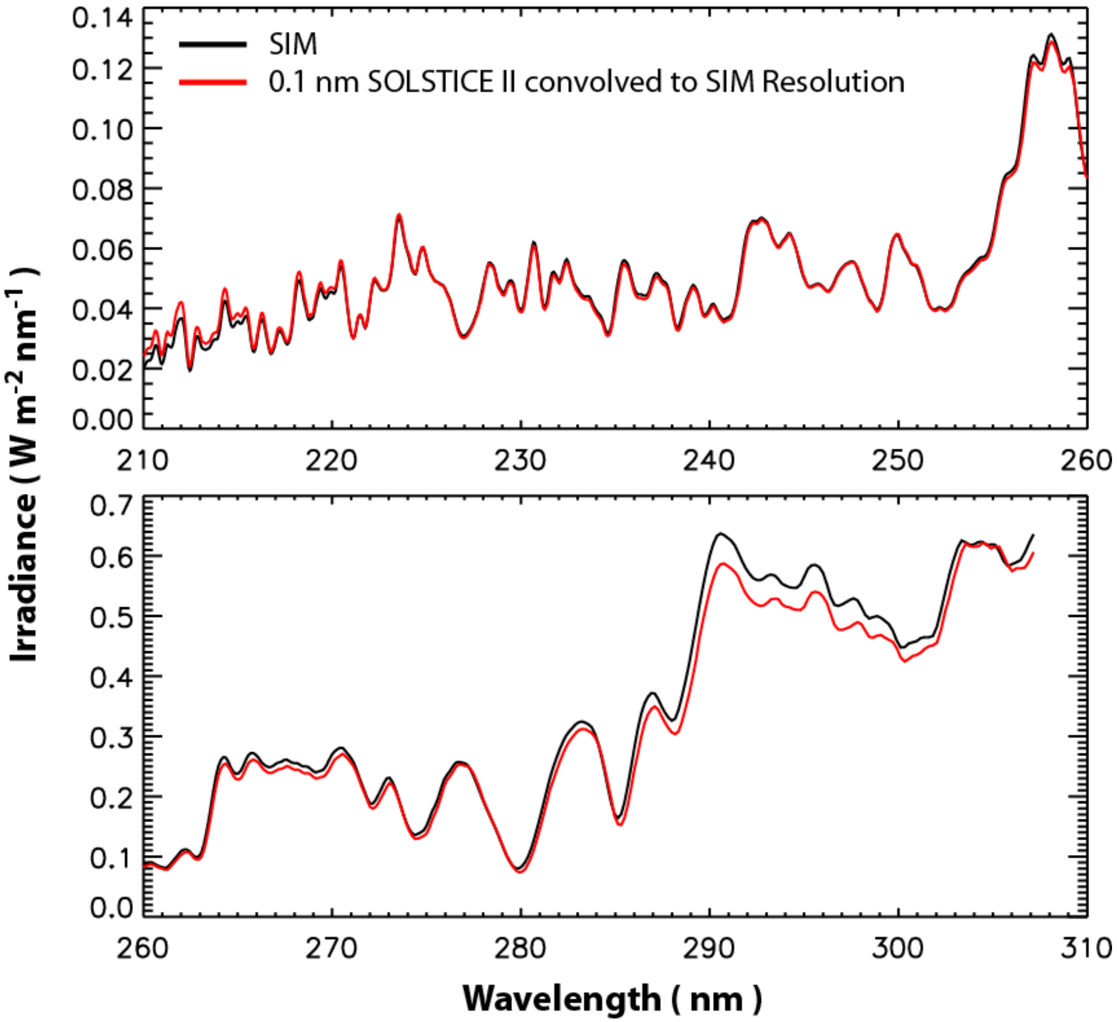






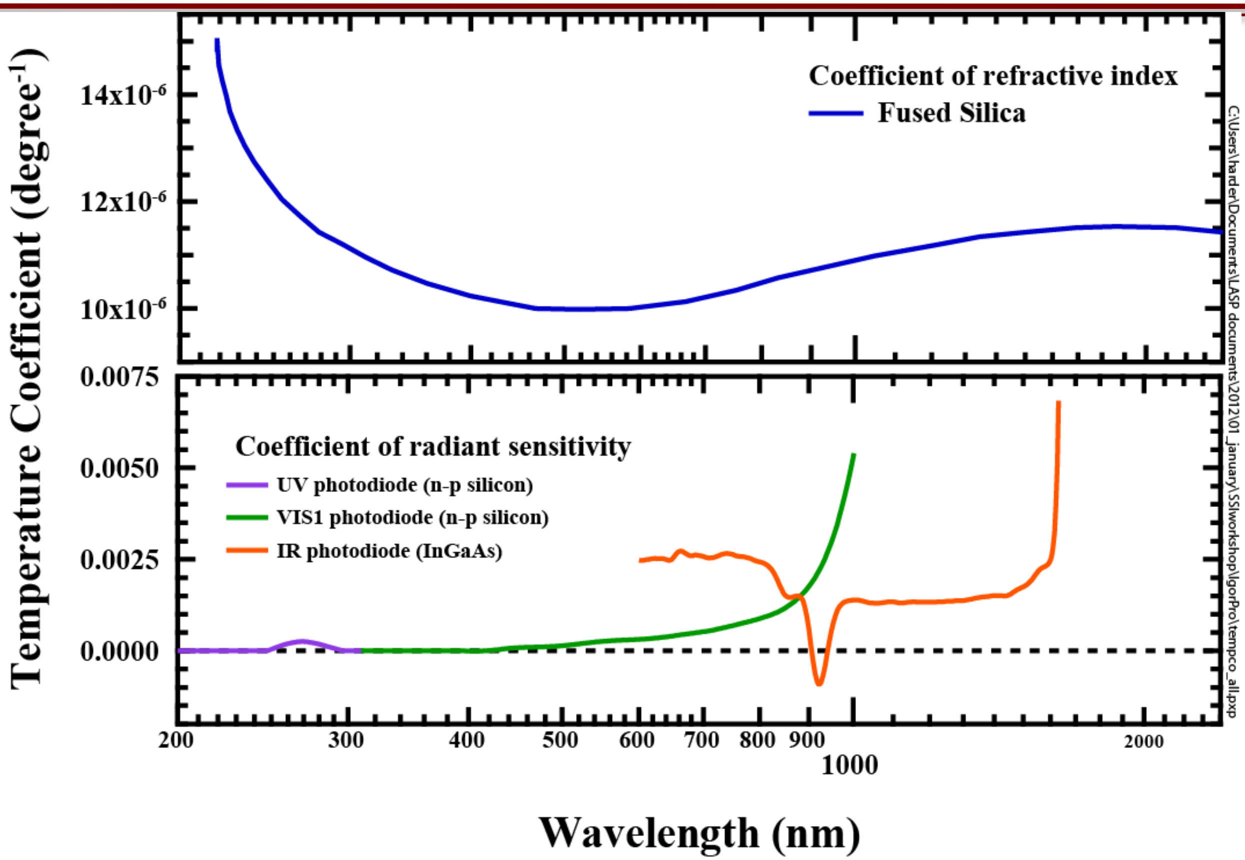
- Scattered light contribution dominated by polish on prism (near-field scattering)
- Reflections from prism⇒cavity ⇒ detector (far-field scattereing) are baffled in front of prism & in front of detectors.
- Scattered light cannot be detected above noise level of the instrument. No corrections made in data processing.

Short Term effects: Scattered Light



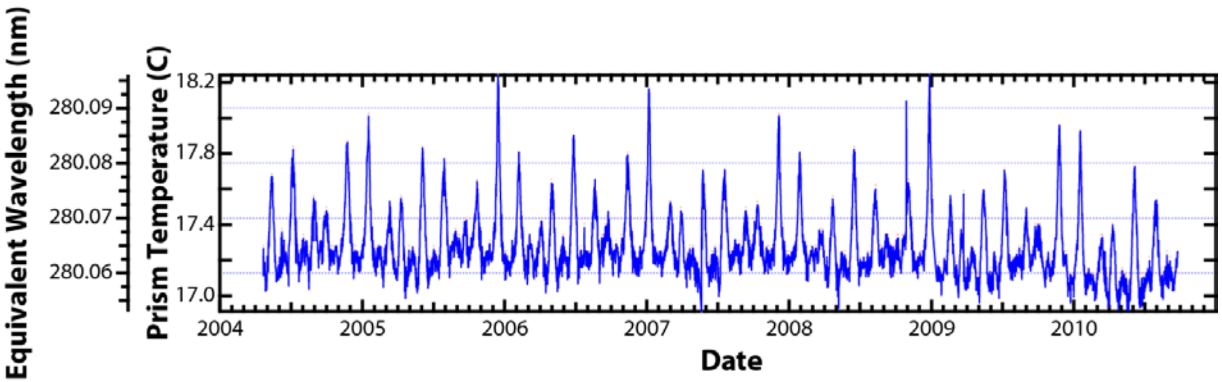
- **At the same resolution feature depths match (though absolute scales differ) indicating little discernible scattered light in either instrument.**
- **Reflects fidelity in determination of the instrument profile integral.**

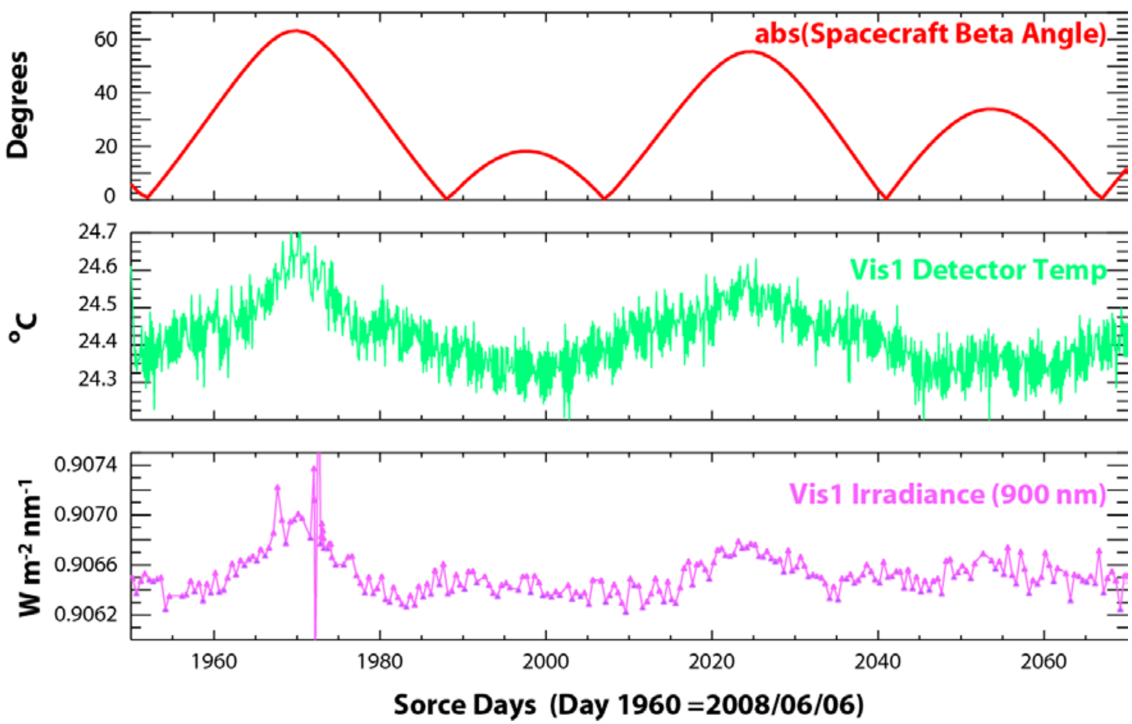
Short Term effects: Temperature



- Index of refraction a function of temperature and effects wavelength reaching the detectors – if not corrected induces wavelength shift
  - Temperature of the prism(s) monitored and corrected continuously in data processing
- Radiant sensitivity is weakly temperature dependent – induces temperature structure in irradiance in the 900-1000 nm range
  - Processing includes a temperature correction, imprecision due to gradients between temperature sensor and the photodiode.

Short Term effects: Temperature

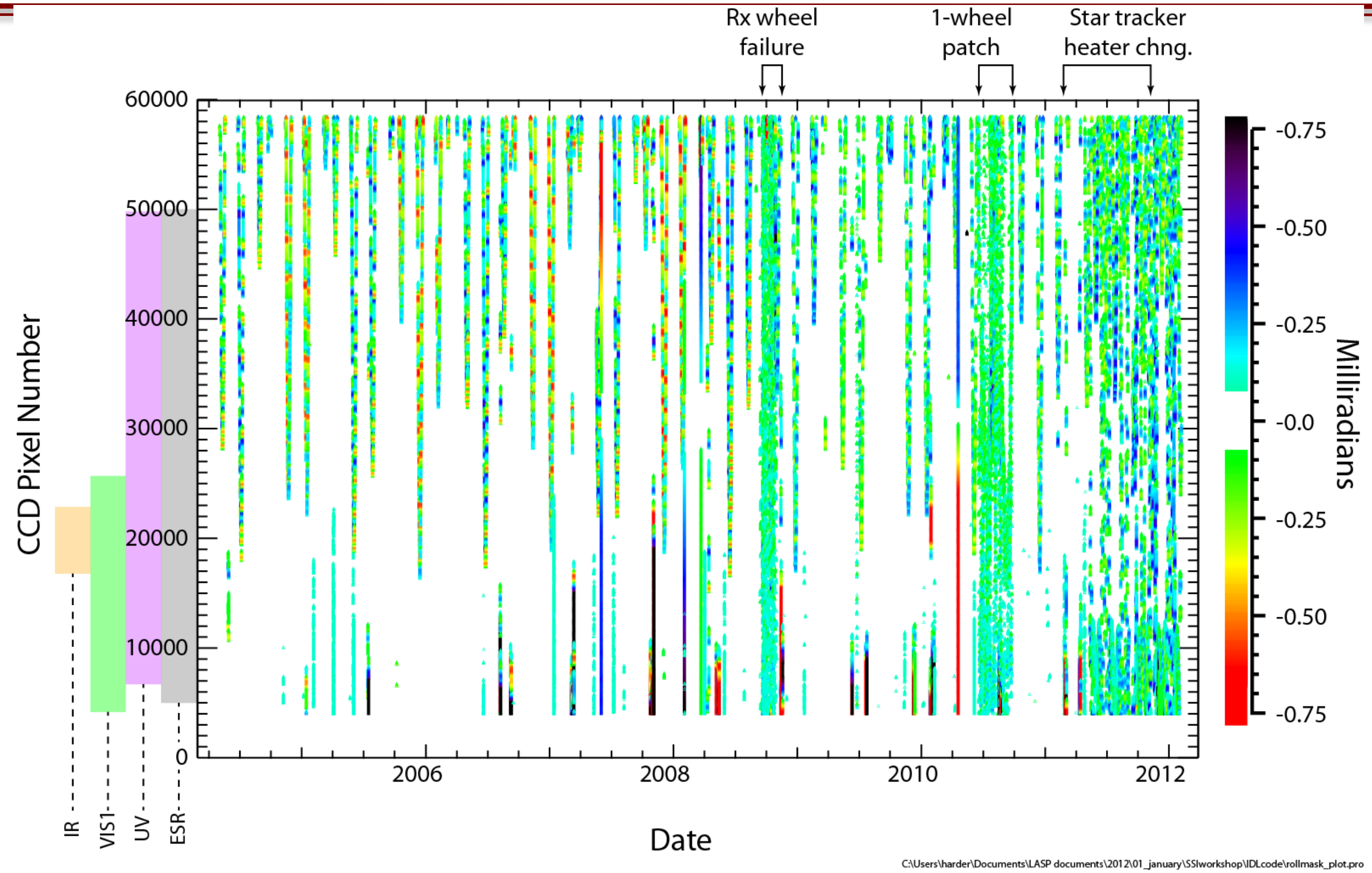




- **Prism Temperature variation of ~1.2 °C**
- **P-p λ shift ~0.04 nm**
- **less than 1/4 of cardinal prism step.**
- **Corrected in data processing**

- **Residual structure in irradiance related to inaccurate corrections for diode temperature**
- **Adds uncertainty of <0.1% to determining long-term trend in the 900-1000 bands.**

Short Term effects: Spacecraft Pointing



- **Roll maneuvers contaminate only 2.8% of the viable science data**
- **Effects of rolls tend to preferentially effect data towards the end of scans but can effect any portion of the scan.**
- **Not all 'spikes' in the data are identifiable as caused by roll maneuvers and vice versa**
  - **'De-spiking' more practical than filtering: no correction made in data processing**

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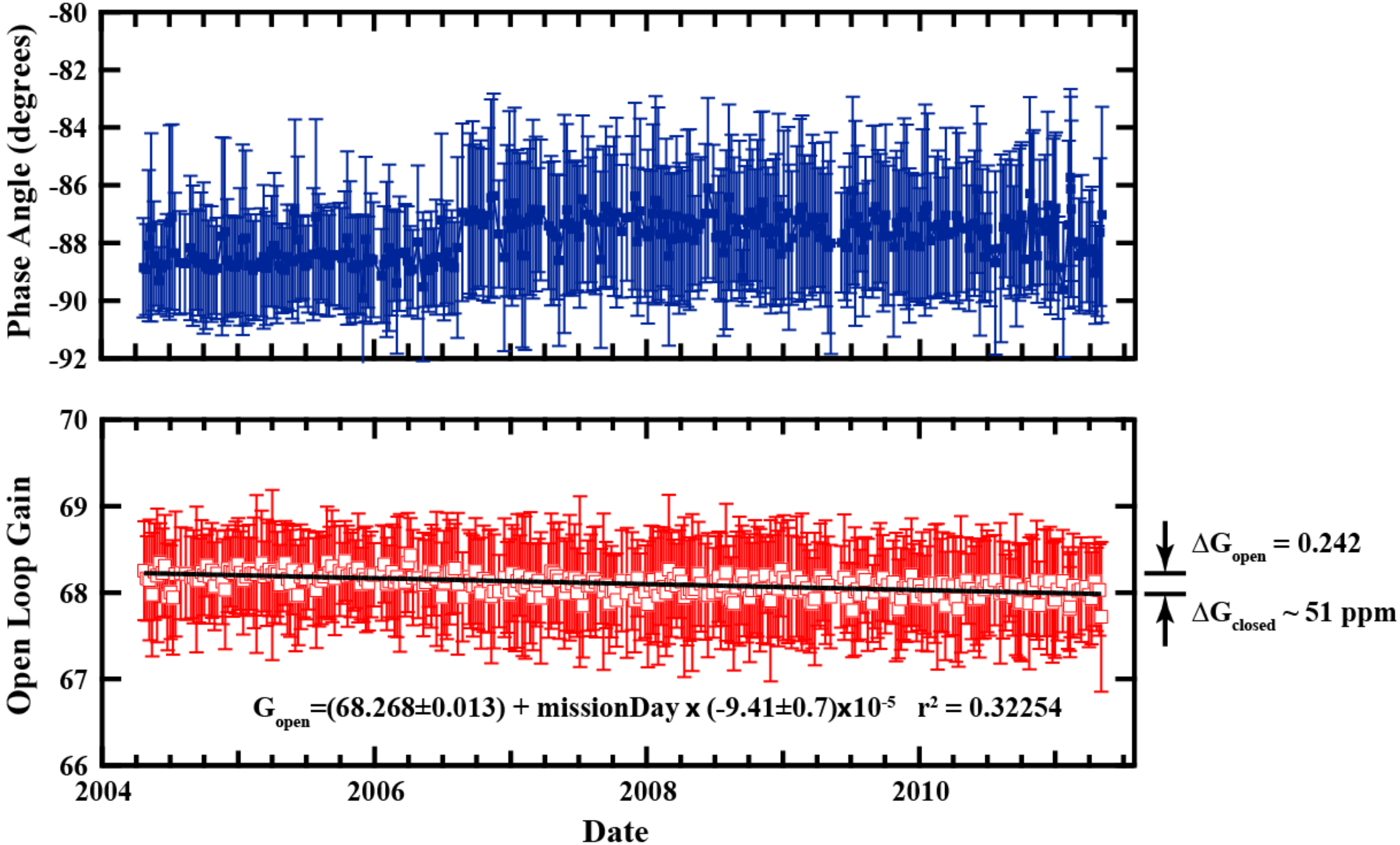
Long-term effects – accumulate with time		
1	**Prism Transmission Degradation**	**Long-term reduction in instrument response. Effect is irreversible**
2	**Optical alignment changes**	**Produces 'jumps' in the data at well-defined times**
3	**Photodiode Radiant sensitivity**	**Reduction in photodiode sensitivity (750-950 nm range)**
4	**ESR servo gain degradation**	**Reduction in responsivity of the ESR detector**

Long Term effects: ESR Gain



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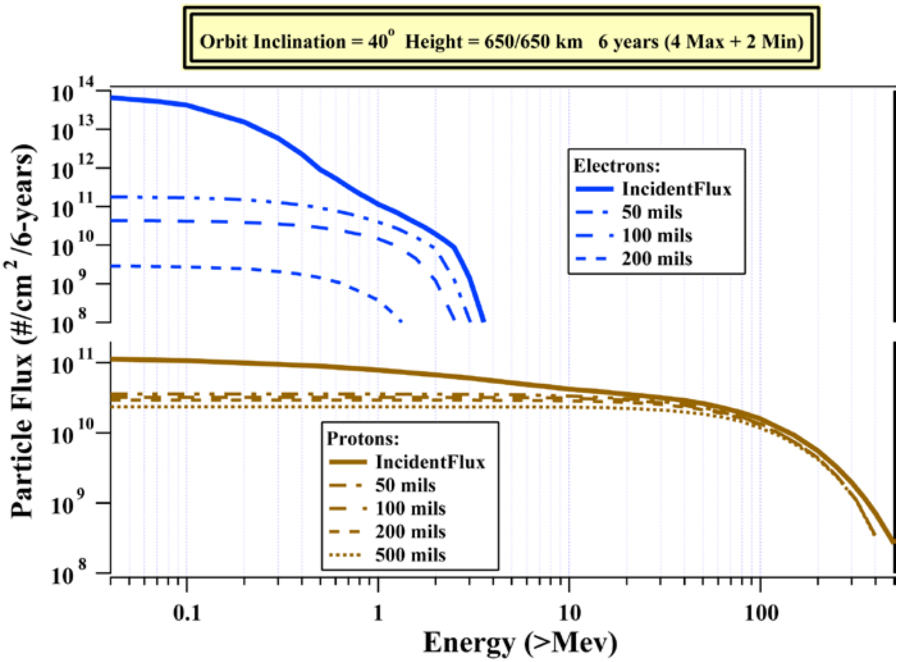
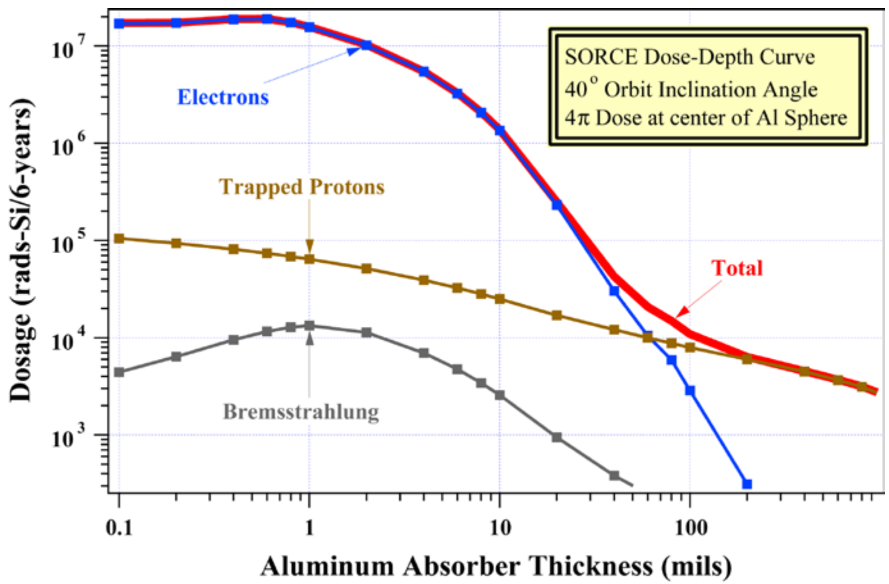
- **Gain change discernable, but small**
- **Change in SIM B comparable to SIM A**
  - **$G_{open\ B}$ = (68.541±0.018) + (-7.78±0.86)x10^{-5} r^2 = 0.16238**
- **Corrections made in data processing**

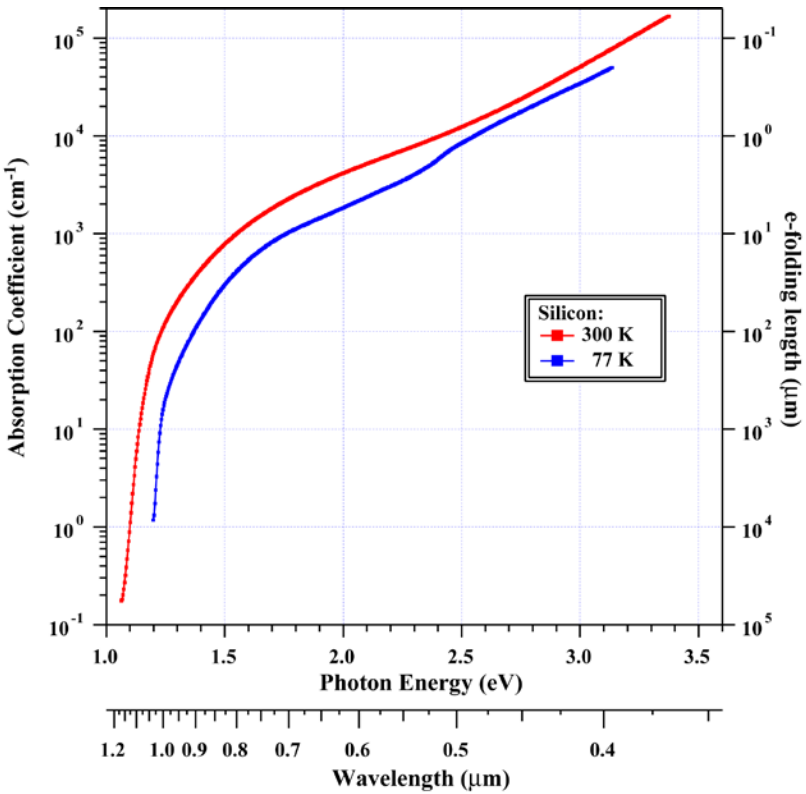
Long Term effects: Photodiode Radiant Sensitivity changes



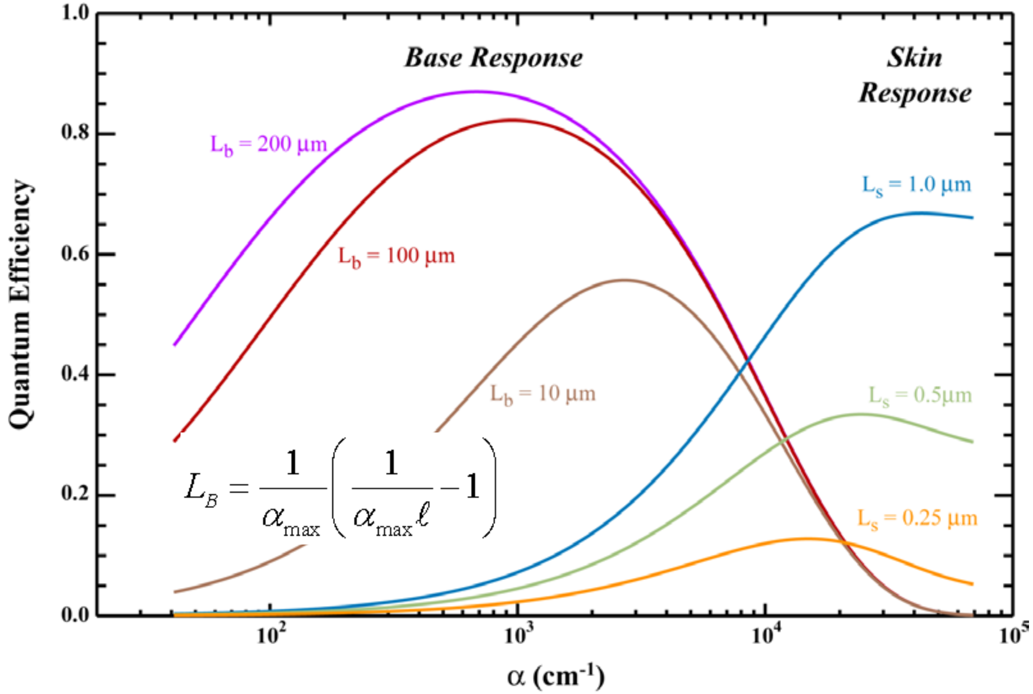


- High Energy Particle Spectrum
  - High energy particles (particularly protons) penetrate deep into the instrument case
- The majority of high energy particles will be protons
  - Shielding ineffective against proton penetration

Long Term effects: Photodiode Radiant Sensitivity changes



adapted from: Dash and Newman, *Phys. Rev.*, **99**, 1151, 1955



$$L_B = \frac{1}{\alpha_{max}}\left(\frac{1}{\alpha_{max}\ell} - 1\right)$$

J. A. Baicker and B. W. Faughnan, ***J. Appl. Phys.*** **, 33,** 1962.

- **Photon absorption is a necessary condition to produce a photoelectron**
- **The photoelectric effect occurs over a very broad depth scale:**
  - **∴ Degradation processes at the skin will behave differently than the bulk processes.**

- **Radiation damage in the *base* of the diode decreases L_b (minority carrier diffusion length) and effectively moves α_{max} to shorter wavelengths (larger α)**
- **L_{skin} dominates the diodes performance at the shorter wavelengths.**
- **Radiation testing suggests p-n diode incurs greater damage than n-p:**
  - **~100x > for electrons, ~3x > for protons**

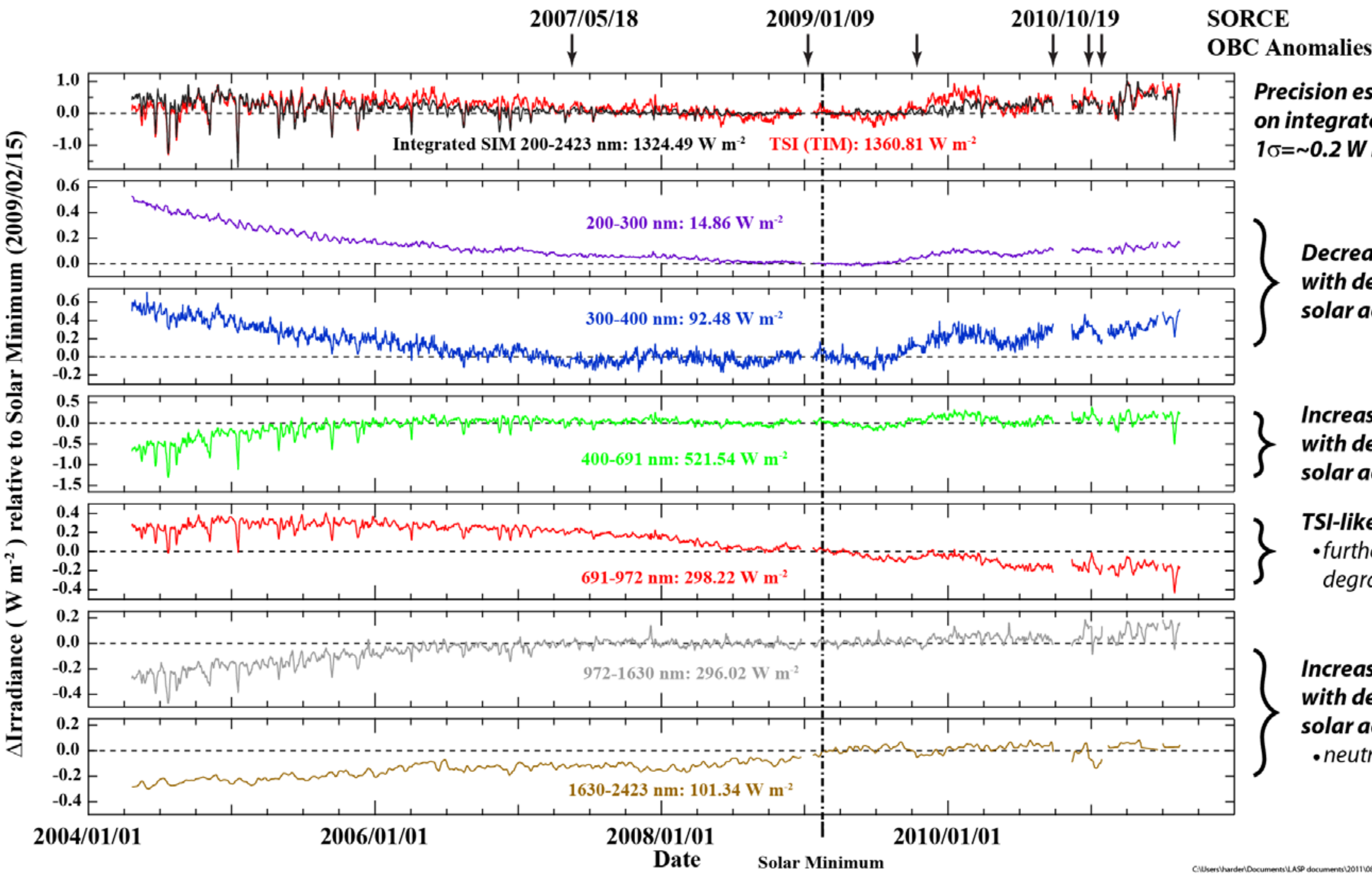
SIM Measurement Equation and Error Budget

$$E(\lambda_s) = \frac{P_{ESR}(\lambda_s)}{A_{slit}\int \alpha_\lambda T_\lambda \Phi_\lambda S(\lambda,\lambda_s)\,d\lambda} \quad or \quad E(\lambda_s) = \frac{P_{detector}(\lambda_s)}{A_{slit}\int R_\lambda T_\lambda \Phi_\lambda S(\lambda,\lambda_s)\,d\lambda}.$$

Term (units)	Symbol	Value/Range	Uncertainty	Derived from:
Wavelength (nm)	λ	265-2423	$0.2 \pm \lambda\times(150\times10^{-6})$	λ standards, solar spectrum
Power (watts) of the ESR	P	1×10^{-7} - 5×10^{-5}	$\sim2\times10^{-9}$ WHz$^{-1/2}$	Detector testing
Entrance slit area (mm^2)	A_{slit}	2.1	5×10^{-5}	Slit diffraction
ESR optical efficiency (%)	α_λ	100	+0 to -2 (200-1000 nm) +0 to-10 (1000-2700 nm)	SIRCUS, flight spare ESR (measured in power mode)
Photodiode radiant sensitivity (amps/watt)	R_λ	0.08 -1.0	2-4% (wavelength dependent)	Comparisons with ESR
Prism transmission (%)	T_λ	0.55-0.77	±0.1% 200-700 nm ≥ ±1% 700-2700 nm	Laboratory measurements (see Harder et al, 2005a)
Diffraction loss (%)	Φ_λ	0.3-2.2	~0.01	Diffraction theory
Instrument function area (nm)	S	0.58-34.5	~0.4%	Ray tracing, laser scans

See Harder *et al.*, *Solar Physics* (2005): **230** 169-204

Time series of solar spectral variability from SORCE



Precision estimate on integrated SIM:
1σ=~0.2 W m^{-2} (~130 ppm)

Decreasing trend with decreasing solar activity

Increasing trend with decreasing solar activity

TSI-like
- *further refinements in diode degradation needed*

Increasing trend with decreasing solar activity
- *neutral by ~ 2000 nm*

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