Modeling Spectral Degradation of MODIS and VIIRS Solar Diffusers

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Outline

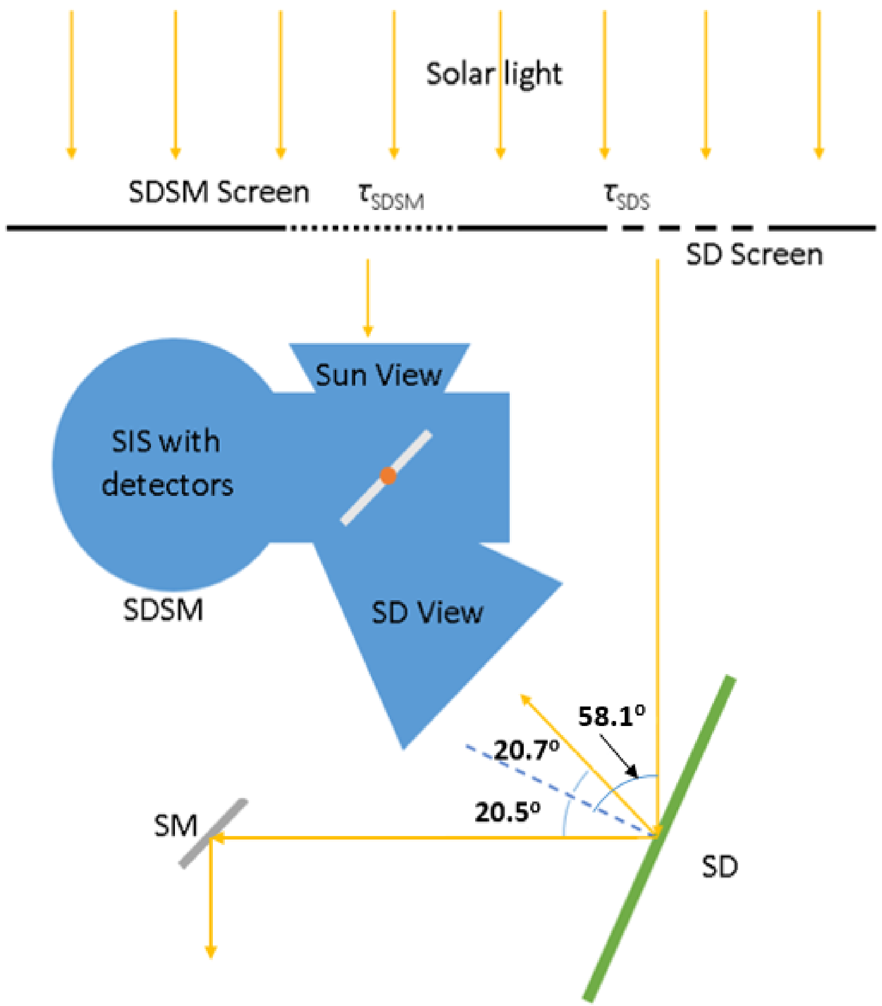
- MODIS/VIIRS solar calibration: Solar Diffuser (SD) and Solar Diffuser Stability Monitor (SDSM)
- Solar Diffuser degradation as monitored by MODIS/VIIRS SDSM
- Radiation-induced solar diffuser degradation and roughness development on polymers
- Surface Roughness-induced Rayleigh Scattering (SRRS) Model
- Comparison of SD surface roughness development from MODIS/VIIRS SDSM data
- Discussion and Summary

MODIS and VIIRS

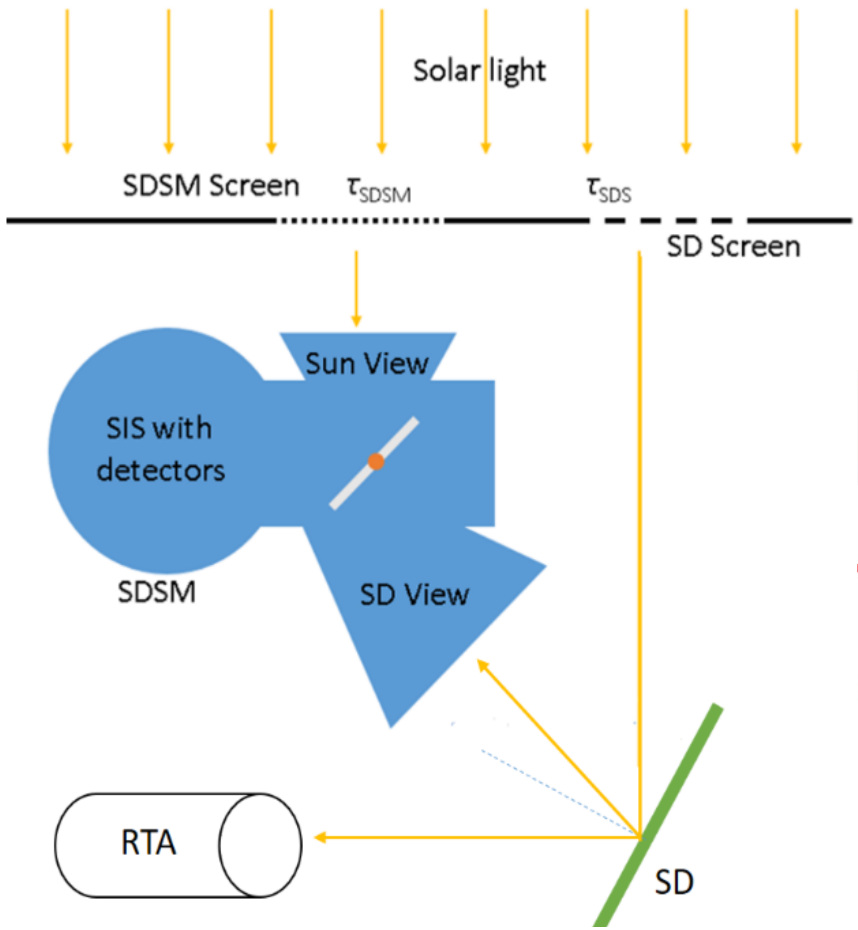
- Terra and Aqua spacecraft launched on December 18, 1999 and May 4, 2002, respectively
  - Moderate Resolution Imaging Spectroradiometer (MODIS)
    - RSBs: Channels 1–19 and 26 with wavelengths from 0.41 µm to 2.2 µm
    - TEBs: Channels 20–25 and 27–36 with wavelengths from 3.7 µm to 14.5 µm
- SNPP and NOAA-20 launched on October 28, 2011 and November 18, 2017, respectively
  - Visible Infrared Imaging Radiometer Suite (VIIRS)
    - 16 moderate resolution bands (M-bands),
      - 11 Reflective Solar Bands (RSB)
      - 5 Thermal Emissive Bands (TEB)
    - 5 imaging resolution
      - 3 RSB
      - 2 TEB
    - 1 Day Night Band (DNB) broadband

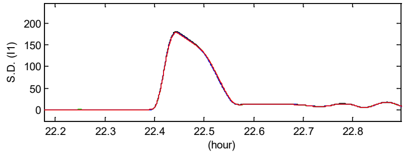
Onboard Solar Calibration

MODIS

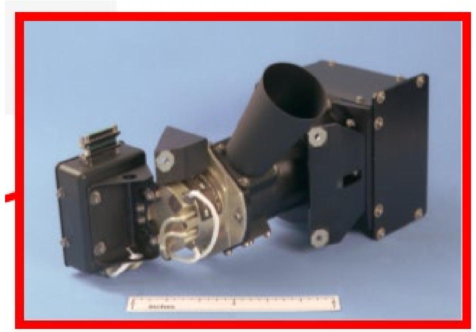


VIIRS





- For the RSBs (0.4 um to 2.2 um), the calibration uncertainty in spectral reflectance: less than 2%.
- Onboard calibration relies on the solar diffuser (SD), solar diffuser stability monitor (SDSM), space view (SV)



SDSM

(Spectralon ®)

Solar Diffuser

Solar Calibration and SD-exposure Frequency

Time Span	Terra MODIS Calibration Frequency	Terra MODIS Exposure of SD to Solar Radiation
02/24/2000-03/21/2000	Daily	During Scheduled Solar Calibration[a]
03/24/2000-07/02/2003	Weekly or Biweekly	During Scheduled Solar Calibration[a]
07/02/2003-02/18/2009	Weekly or Biweekly	During Each Orbit[b]
02/24/2009-Present	Triweekly	During Each Orbit[b]

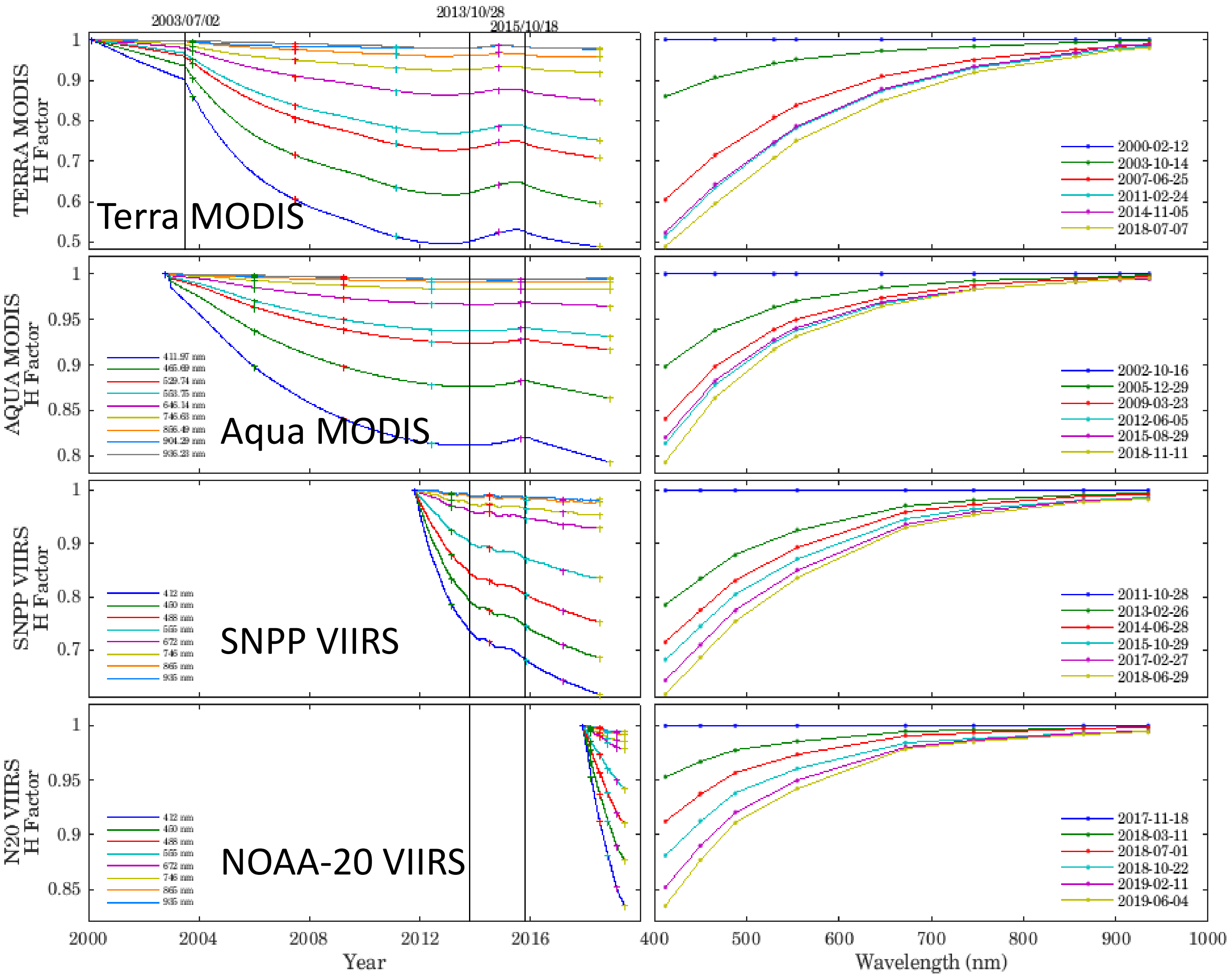
	Aqua MODIS Calibration Frequency	Aqua MODIS Exposure of SD to Solar Radiation
06/13/2002-06/30/2002	Weekly	During Scheduled Solar Calibration[a]
07/07/2002-12/26/2005	Biweekly	Mostly During Scheduled Solar Calibration[c]
01/09/2006-04/28/2008	Triweekly	During Scheduled Solar Calibration[a]
05/20/2008-Present	Once per 6 Weeks without SDS and Triweekly with SDS	During Scheduled Solar Calibration[a]

	Exposure of SD to Solar Radiation
SNPP VIIRS	During Each Orbit
NOAA-20 VIIRS	During Each Orbit

MODIS and VIIRS SDSM Detector Wavelength

Band	VIIRS Center Wavelength (µm)	MODIS Center Wavelength (µm)
D1	0.412	0.412
D2	0.450	0.466
D3	0.488	0.530
D4	0.555	0.554
D5	0.672	0.646
D6	0.746	0.747
D7	0.865	0.857
D8	0.935	0.904
D9	N/A	0.936

Spectral Degradation of Multiple Space-borne Solar Diffusers

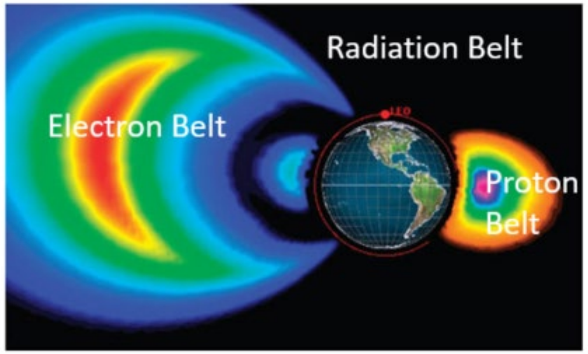


- Degradation is maximum at the blue end with virtually no degradation at the long wavelength end of the wavelength range.
- Terra MODIS degradation transition on 07/03/2003
- SNPP and NOAA-20 VIIRS SD degradation is faster than Aqua MODIS
- Degradation of SNPP VIIRS SD over 6 years is more than the lifetime degradation of Aqua MODIS SD
- Flattening or reverse degradation trend during Oct. 2013 to Oct. 2015 visible for Aqua/Terra MODIS and SNPP VIIRS.

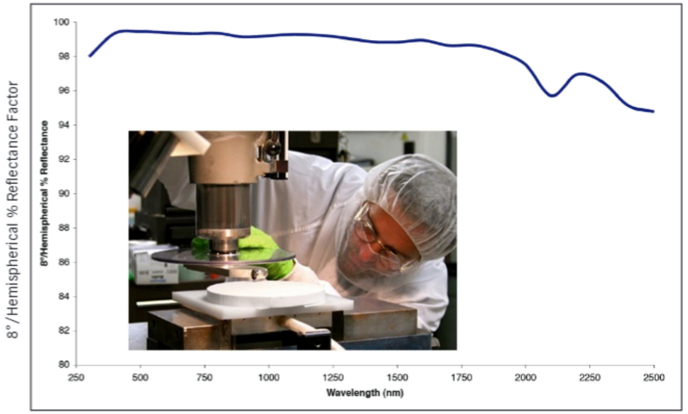
Solar Diffuser Material: Spectralon® and Space Environment Effects

- Spectralon® from Labsphere
  - Pure polytetrafluoroethylene (PTFE or Teflon) polymer; fluoropolymer (a fluorocarbon-based polymer with strong C–F bonds)
  - Diffuse reflectance generally >99% (400 to 1500 nm) and >95% (250 nm to 2.5 um). Extremely Lambertian, Chemically Inert, Thermally Stable, Environmentally Stable, NIST Traceable Calibration
  - Spectralon-based Solar diffuser has been used for calibration on Terra/Aqua MODIS, MISR, SNPP/NOAA-20-VIIRS, GO-Sat, LandSat OLI, and GOES-16/17 ABI.
- Space UV Radiation on Polymers
  - Total energy provided by solar UV radiation (100–400 nm) ~ 8% of the solar constant.
  - UV radiation is energetic enough to break polymers bonds such as C–C, C–O, C-F.
  - Scissioning, the creation of volatile fragments, and Cross linking.
- Space Energetic Particles on Polymers
  - Energetic particles effects: ionizing radiation on the polymers.
  - O^+ ions or proton (from space or outgas within instrument) can impact polymers through collisionally-induced scission of fluorocarbon-based polymers.

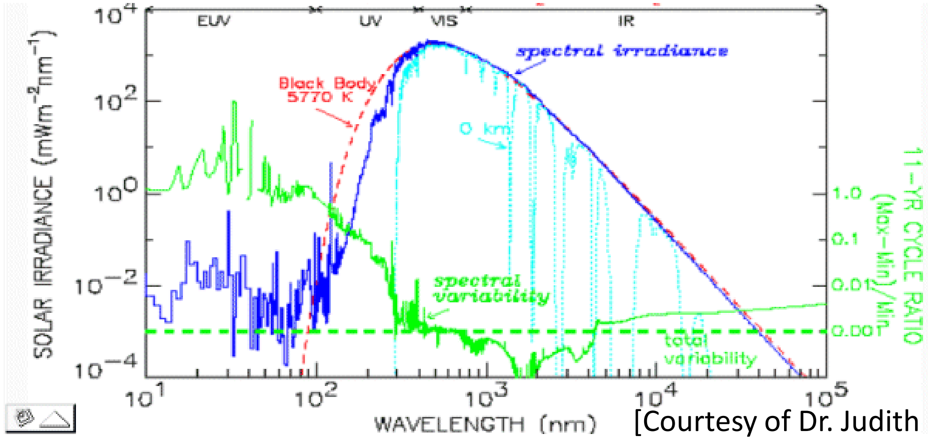
Trapped Energetic Particle



From Severe Space Weather Events--Understanding Societal and Economic Impacts: A Workshop Report - Extended Summary (2009)

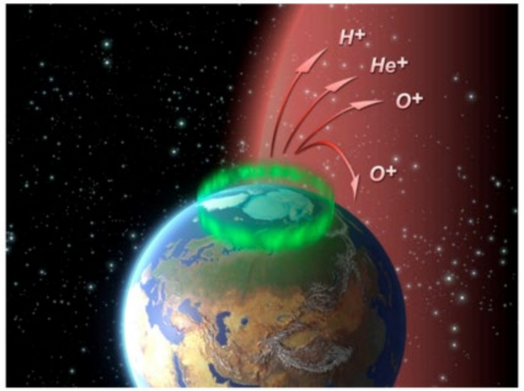


Wavelength (nm)



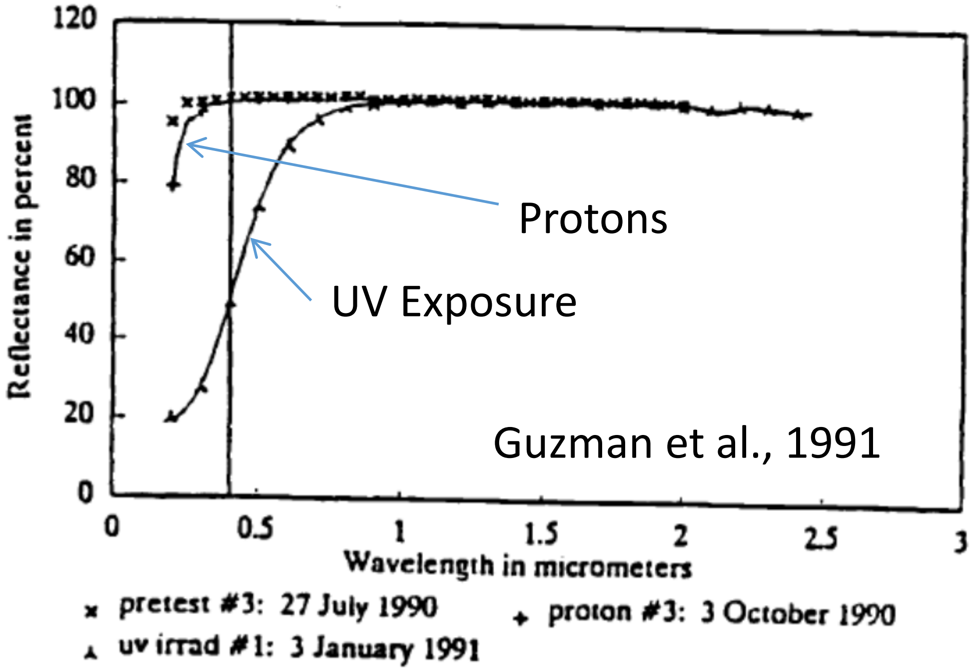
[Courtesy of Dr. Judith Lean of US Naval Research Laboratory]

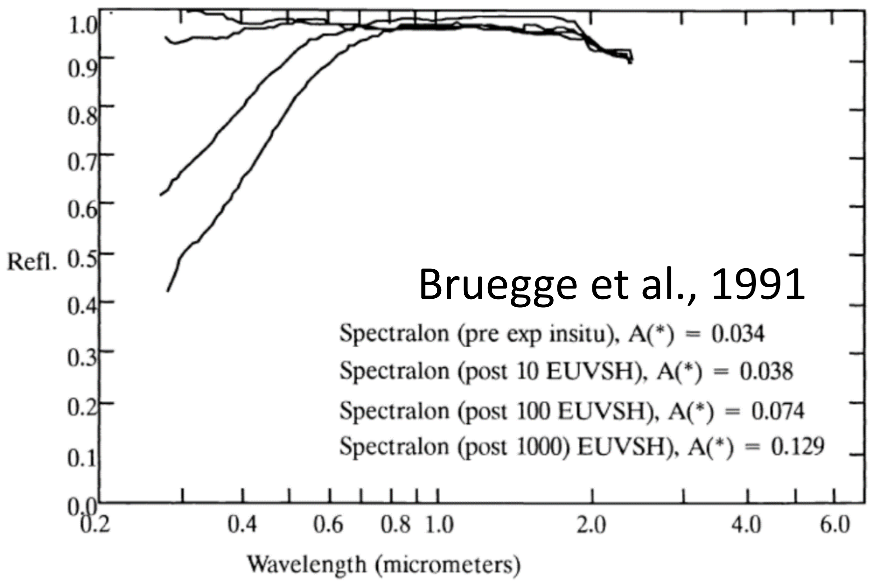
Polar Wind: Ion Outflow



Lab Experiments on Spectralon® Degradation under Radiation Exposure

UV and Proton Radiation on Spectralon ®





- Irradiated with 1.5 equivalent solar UV for 333 hours, yielding 500 equivalent hours exposure.
- Proton-accelerator facilities at JPL. A 10-cm-diameter proton beam was used to irradiate the samples with 10^{10} p/cm^2 at energy levels of 1 keV, 1 MeV and 10 MeV. Equivalent fluence accumulation for 5 year Eos mission.

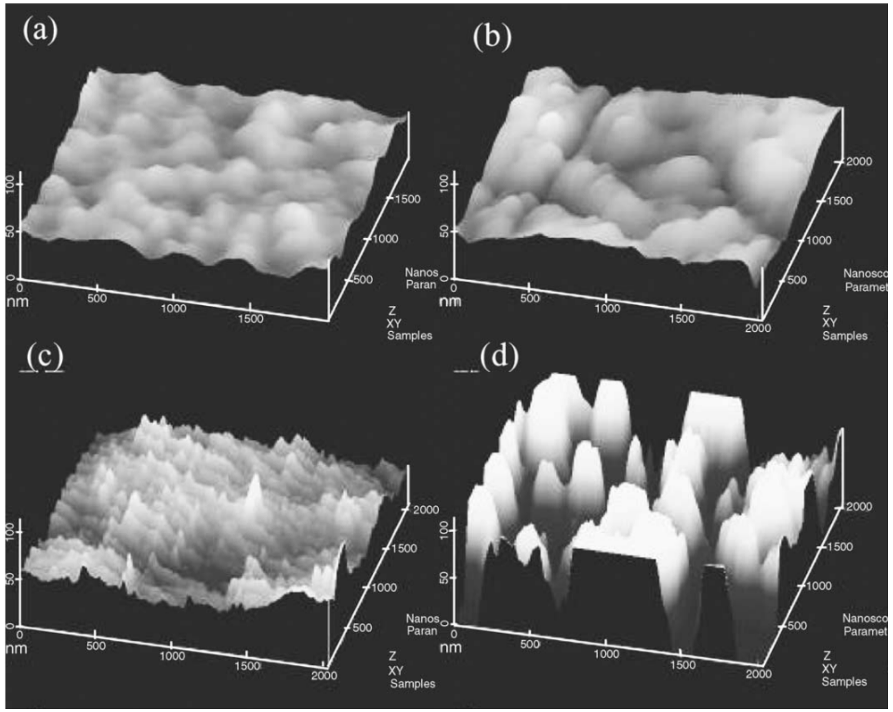
- Spectralon spectral reflectance degrades due to exposure of to UV and proton radiation .

Lab Experiment on Surface Roughness Change for Polymer under Radiation

Table 2
Surface roughness measurements (nm) (from AFM data) of fluorocarbons before and after exposure to VUV and/or O

Exposure	Polymer			
	Polyethylene	Tedlar PVF	Tefzel PTE	Teflon FEP
Unexposed	15	17	17	8
VUV	22	28	32	14
O	41	33	24	14
VUV + O	32	39	59	35

nm



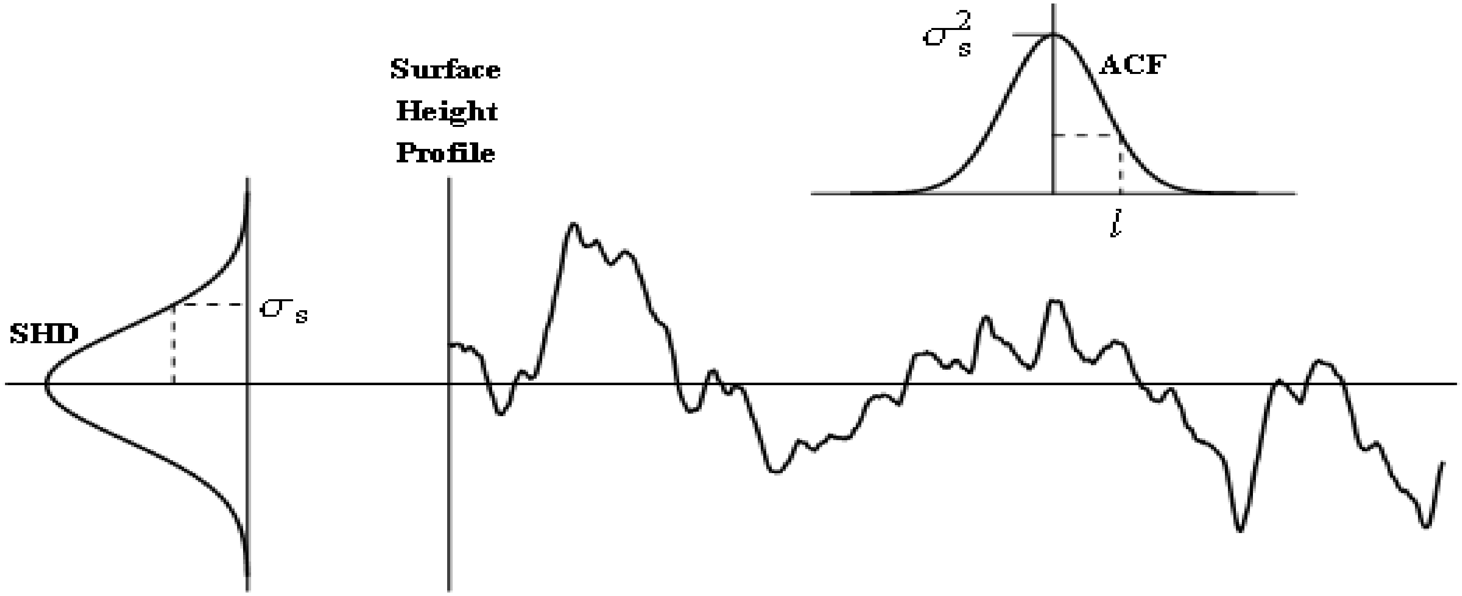
Atomic Force Microscopy (AFM) image of Teflon FEP surface

- Fluoropolymers samples: Teflon FEP, Tefzel, Tedlar and Polyethylene
- Exposed to low fluence of VUV (generated by a 30-W deuterium lamp with a MgF_2 window) and/or O^+ (50 eV O ions generated by a Kaufman source)
- 20 equivalent Sun hours (ESH) of VUV
- 5×10^{17} O^+/cm^2 at 50 eV

Grossman and Gouzman , 2003
Space environment effects on polymers in low earth orbit

Surface Roughness-induced Rayleigh Scattering (SRRS) Model for SD Degradation

Statistical Parameters Characterizing Surface Roughness



σ_s : RMS surface roughness (Standard deviation of surface height distribution)

l: Surface auto-covariance function (ACV) length (half width of *1/e* ACV)

Surface Roughness-induced Rayleigh Scattering (SRRS) Model for SD Degradation

- Total Integrated Scattering (TIS)
- ($l \gg \lambda$) [Bennett and Porteus,1961]

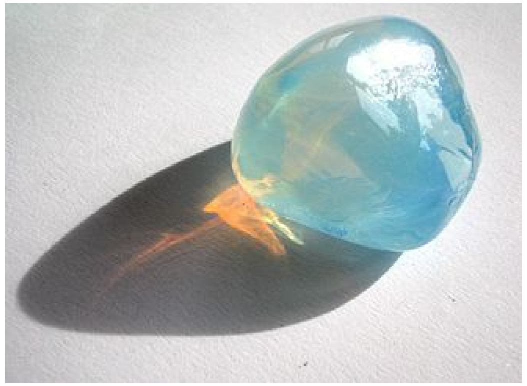
$$TIS = 1 - \exp[-(4\pi cos\theta_i \ \sigma_s \ /\lambda)^2] \approx (4\pi cos\theta_i \ \sigma_s \ /\lambda)^2$$

- ($l \ll \lambda$) Elson et al. [1983] (Rayleigh-type scattering)

$$TIS(\lambda) = \frac{64}{3}\frac{\pi^4\sigma_s^2 l^2 cos^2\theta_i}{\lambda^4}.$$

- SD Spectral Degradation Modeling with SRRS (Shao, Cao and Liu 2016, Shao et al. 2019) ($l \ll \lambda$)

$$R_m(\lambda) = R_0(\lambda)[1 - S_T(\lambda)] = R_0(\lambda)(1 - \alpha\frac{64}{3}\frac{\pi^4\sigma_s^2 l^2 cos^2\theta_i}{\lambda^4})$$

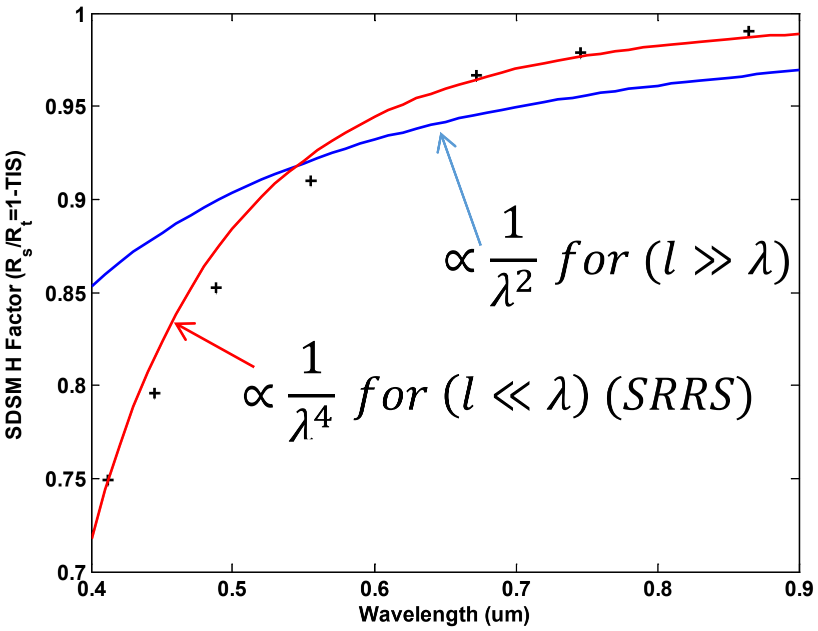


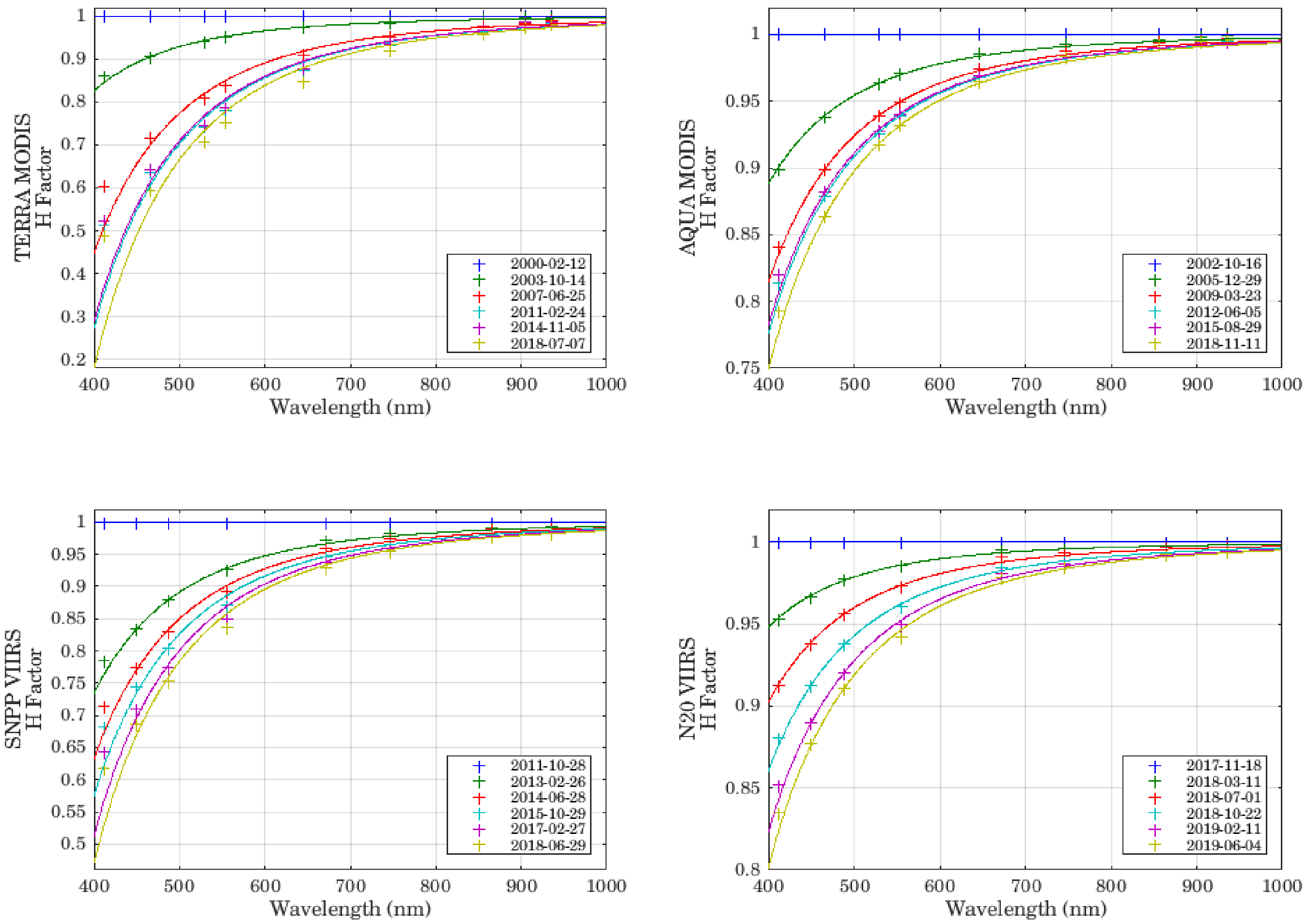
Rayleigh scattering in opalescent glass: it appears blue from the side, but orange light shines through [Webexhibits.org]

Shao, X., Cao, C., and Liu, T.-C. "Spectral Dependent Degradation of the Solar Diffuser on Suomi-NPP VIIRS Due to Surface Roughness-Induced Rayleigh Scattering." Remote Sens. 8, 254 (2016).

Shao, X., Liu, T.-C., Xiong, X., Cao, C., Choi, T., and Angal, A., "Surface Roughness-Induced Spectral Degradation of Multi-Spaceborne Solar Diffusers Due to Space Radiation Exposure," IEEE Trans. Geosci. and Remote Sens., Vol. 57 , 11 , 8658 – 8671, Nov. 2019.

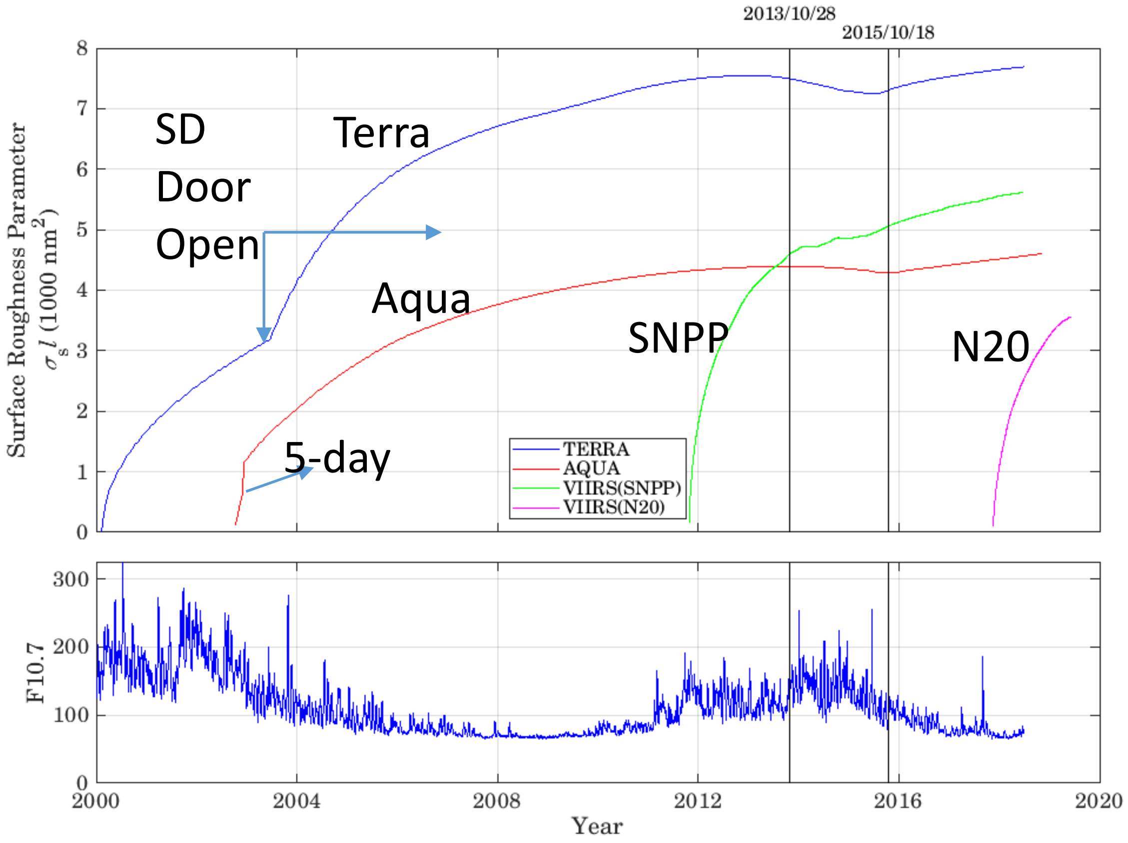
Modeling Spectral Degradation of Multiple SDs with SRRS Model

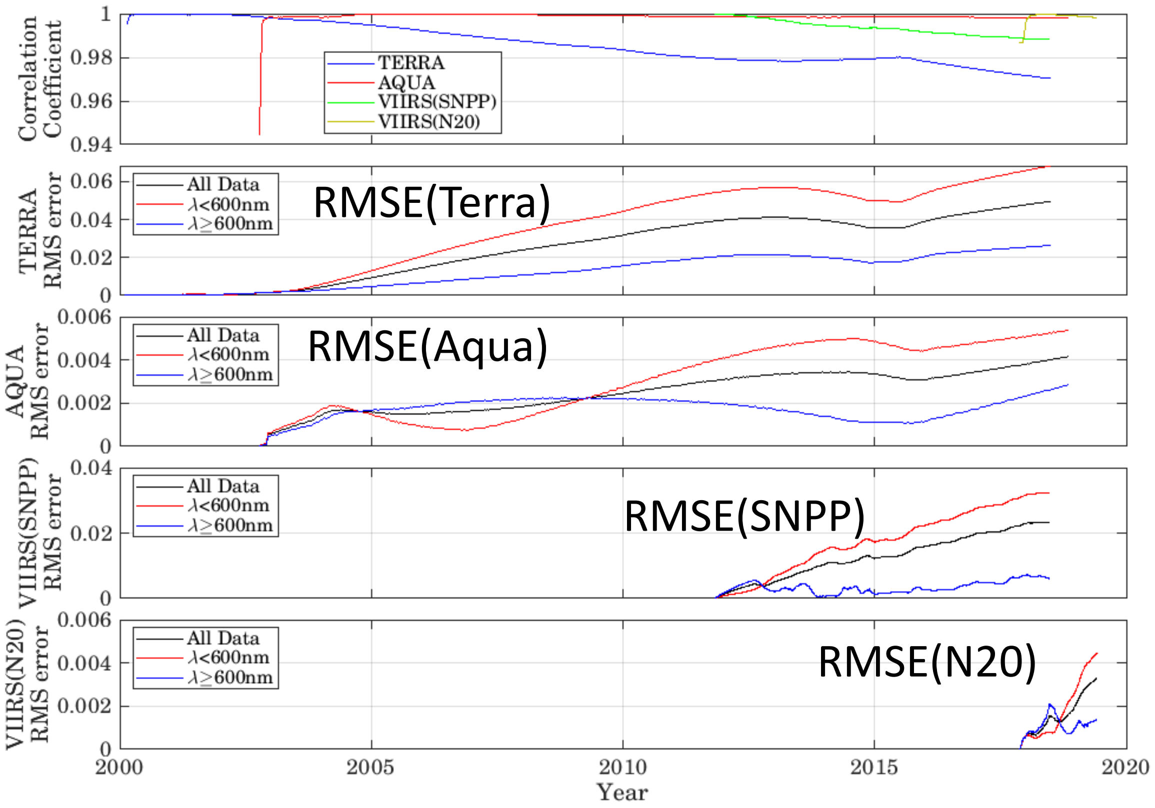




- Good agreement with SRRS model for all four SDs
- Suggest that the surface roughness grown on SD is in the roughness length scale $l \ll \lambda$ Rayleigh Scattering regime

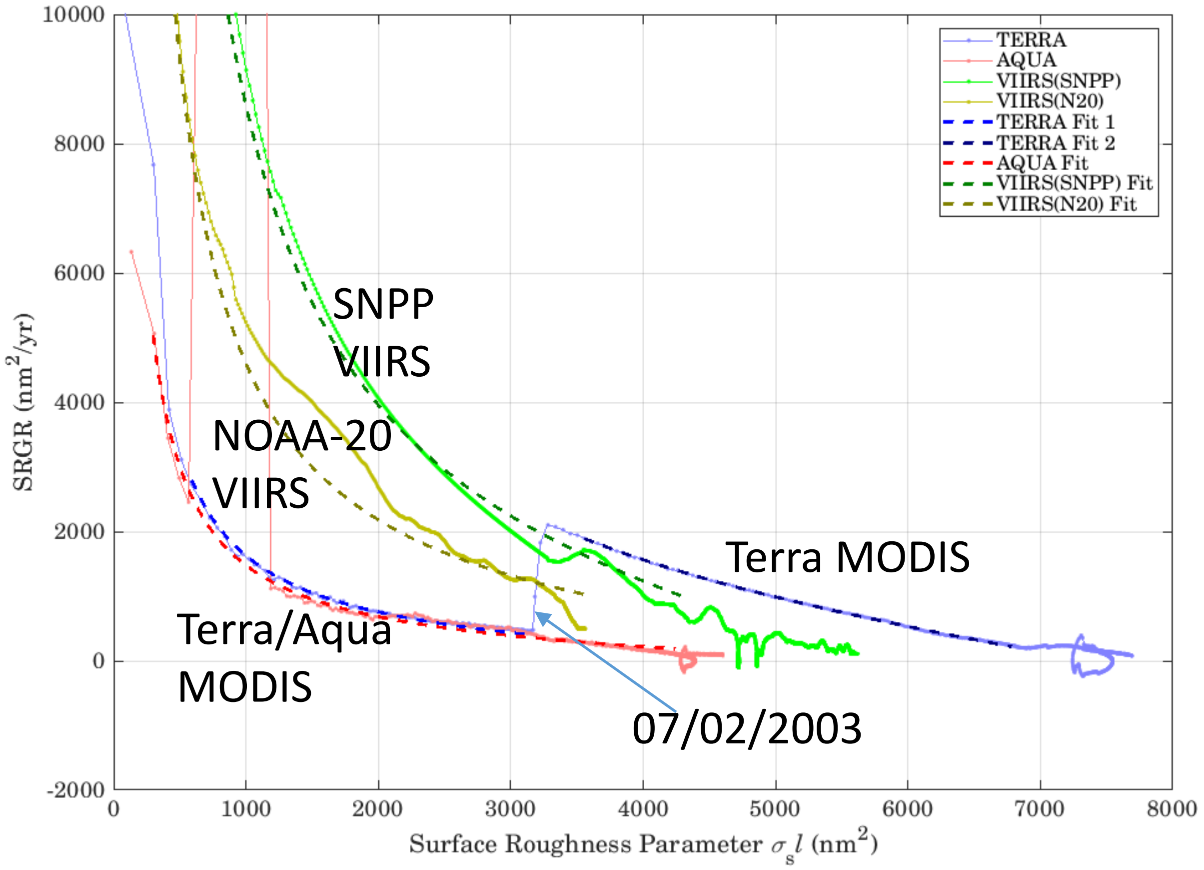
Growth of Surface Roughness on Multiple SDs





- Able to trend the surface roughness growth of multiple SDs
- High correlation between model and data; RMSE are all below 1% for Aqua, SNPP (< 600 nm) and N20.
- Consistent with the surface roughness length scale (10s nm) found from lab.
- Better fitting for λ< 600nm than λ> 600nm; RMSE is high for Terra. Can be due to the $l \ll \lambda$ *assumption* for SRRS model.
- Space-environment related slow-down/reverse of SD Degradation during Oct. 2013 to Oct. 2015 around solar maximum

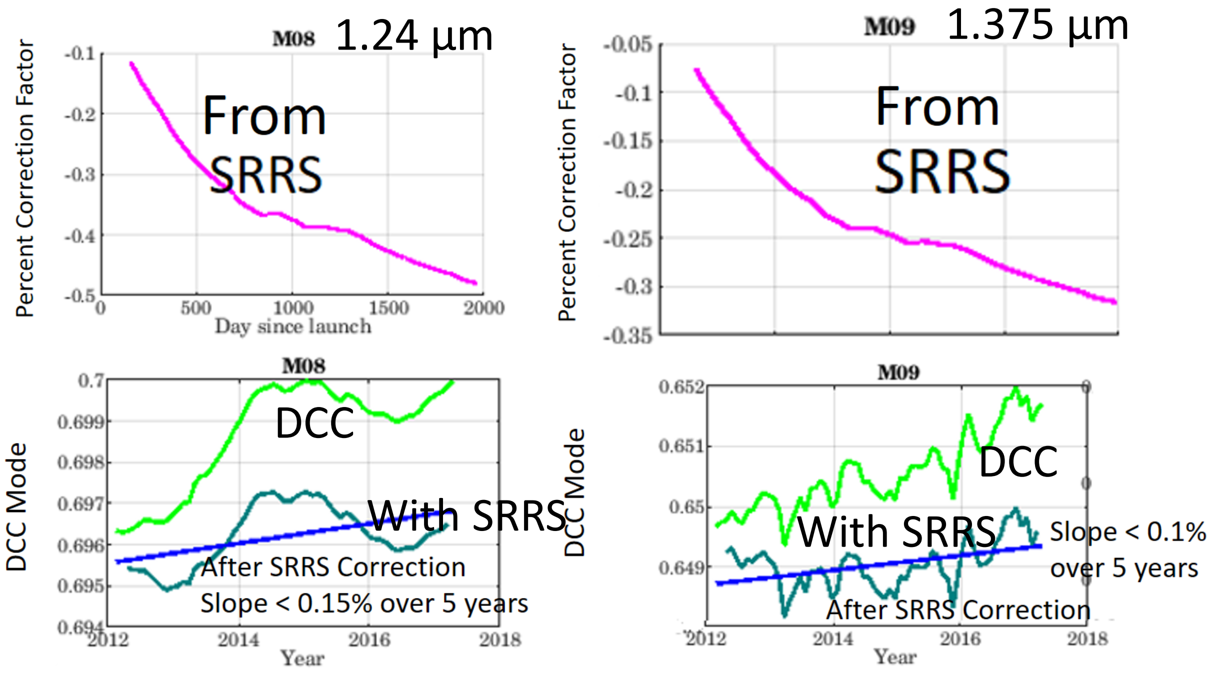
SD Surface Roughness Growth Rate SRGR



- Enable comparison of surface roughness growth of multiple SDs
- SRGR decreases as the surface roughness grows
- SRGR of Terra and Aqua MODIS matched in early lifetime given the similar exposure frequency
- SRGR of SNPP VIIRS and Terra MODIS in later time (after SD door malfunction) are aligned
- SRGR over the first ~1.5 years of NOAA-20 VIIRS is about 1.5 times slower than the SRGR of SNPP VIIRS.
- Negative or ~ 0 SRGR are identifiable for Terra/Aqua MODIS and SNPP VIIRS

Application: Enable the trending of spectral degradation of SDs at short-wavelength IR (SWIR) with SRRS Model

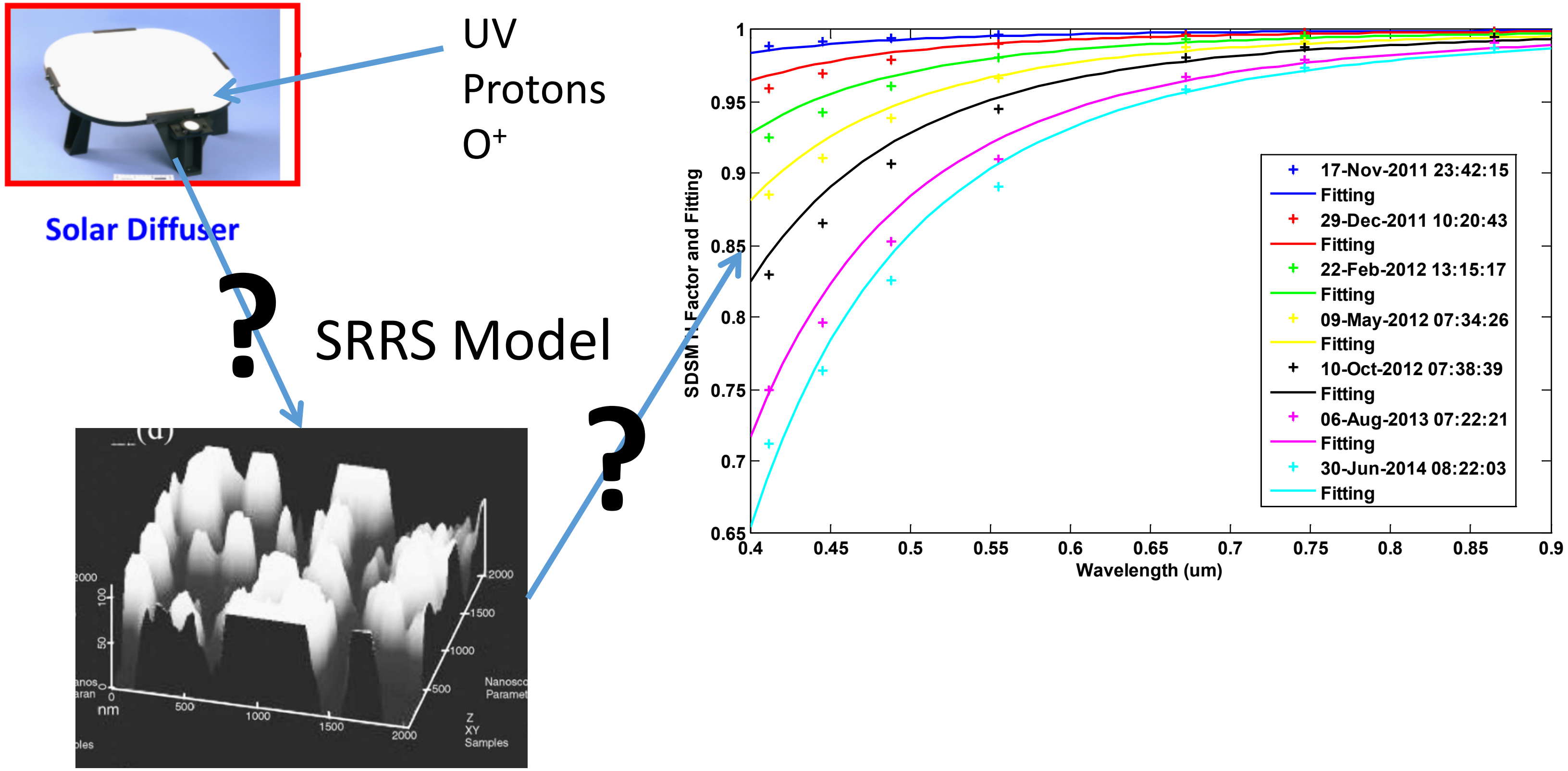
- SNPP VIIRS Data Reprocessing (SRRS model vs. DCC Results)



Courtesy of SNPP VIIRS SDR Reprocessing Team

- Lei et el. [2016] used a power law fitting with a wavelength-exponent = -4.03 to model the SWIR band degradation of SNPP VIIRS SD. Consistent with SRRS model.
- Lee et al. [2018] applied the SRRS model to estimate the spectral degradation of SD in Aqua MODIS SWIR bands.

Discussion



- RSB calibration using solar diffuser are very important Terra/Aqua MODIS, MISR, SNPP/NOAA-20-VIIRS, GO-Sat, LandSat OLI, GOES-16/17 ABI and other satellites.
- To better characterize and understand the cause of spectral degradation of SD, collaborative research in space and laboratory are needed. Connect spectral degradation with the material surface change.
- Call for standardized, traceable and inter-comparable lab irradiation experiments and physics-based modeling with various particle species, fluence levels and energies together with UV radiation onto SD

Summary

- Confirm the general applicability of the physics-based SRRS model for trending the spectral dependent degradation of the multi-spaceborne (Terra/Aqua MODIS and SNPP/NOAA-20 VIIRS) SDs under various level of solar radiation exposures
- Estimated surface roughness lengths from the reflectance data of the four SDs are all much less than the wavelength, which confirms the basis of the Rayleigh scattering model.
- Space-environment related slow-down/reverse of SD Degradation during Oct. 2013 to Oct. 2015 around solar maximum
- SD surface roughness growth rate over the first ~1.5 years of NOAA-20 VIIRS is about 1.5 times slower than that of SNPP VIIRS SD
- The SRRS model can also be applied to model the spectral degradation of SDs on other missions that perform RSB radiometric calibration with onboard SDs.
- Further study requires investigation of sample solar diffuser roughness change under various (UV and particle) radiation exposure

References

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