Solar Irradiance Curves, Cirrus Contamination, and Sun Glint

Bo-Cai Gao\(^1\), Rong-Rong Li\(^1\), David Thompson\(^2\), and Robert O. Green\(^2\)

June 2014

\(^1\)Remote Sensing Division, Naval Research Laboratory, Washington, DC
\(^2\)Jet Propulsion Lab, California Institute of Technology, Pasadena, CA
INTRODUCTION

• Solar irradiance curves – In the mid-1990s, we started to question the validity of the 1985 standard solar irradiance curve by C. Wehrli of World Radiation Center in Switzerland. A paper on the subject was published in 1996 (Applied Optics)

• Cirrus contamination – We began to address the cirrus detection and correction issue in early 1990s.

• Sun glint – By analyzing the AVIRIS data acquired over Salton Sea in California in the summer of 1988, we realized that the sunglint effects in the 0.4 – 2.5 micron wavelength range are spectrally flat, and the sunglint effects should, in principle, be correctable.
Relevant Equations and Definitions

In the absence of gas absorption, the radiance at the satellite level is:

\[ L_{obs}^* = L_0^* + L_g t_u' + L_w t_u, \]  \hspace{1cm} (1)

- \( L_{0}^* \): path radiance;
- \( L_w \): water leaving radiance;
- \( L_g \): radiance reflected at water surface;
- \( t_u' \) & \( t_u \): upward transmittances

Multiply Eq. (1) by \( \pi \) and divide by \( (\mu_0 E_0) \), Eq. (1) becomes:

\[ \pi L_{obs} / (\mu_0 E_0) = \pi L_0^* / (\mu_0 E_0) + \pi L_g t_u' \left[ t_d / (\mu_0 E_0 t_d) \right] + \pi L_w t_u \left[ t_d / (\mu_0 E_0 t_d) \right] \] \hspace{1cm} (2)

where \( E_0 \) = solar irr., \( \mu_0 \) = cosine of solar zenith angle. We define:

- **Satellite apparent reflectance**: \( \rho_{obs}^* = \pi L_{obs} / (\mu_0 E_0) \), \hspace{1cm} (3)
- **Glint reflectance**: \( \rho_g = \pi L_g / (\mu_0 E_0 t_d) \) \hspace{1cm} (5)

Water leaving reflectance: \( \rho_w = \pi L_w / (\mu_0 E_0 t_d) = \pi L_w / E_d \) \hspace{1cm} (6)

Remote sensing reflectance: \( R_{rs} = \rho_w / \pi = L_w / E_d \) \hspace{1cm} (6')

Substitute Eqs (3) – (6) into Eq. (2), we get:

\[ \rho_{obs}^* = \rho_{atm}^* + \rho_g t_d t_u + \rho_w t_d t_u \] \hspace{1cm} (7)

After consideration of gas absorption and multiple reflection between the atmosphere and surface, & denoting \( \rho_{atm+glint}^* = \rho_{atm}^* + \rho_g t_d t_u \), we can get:

\[ \rho_w = (\rho_{obs}^*/T_g - \rho_{atm+glint}^*) / [t_d t_u + s (\rho_{obs}^*/T_g - \rho_{atm+glint}^*)] \] \hspace{1cm} (8)

Problems with the 1985 Wehrli Solar Irradiance Curve – Atmospheric water vapor contamination

Fig. 8. Extraterrestrial solar irradiance curves from Wehrli\textsuperscript{10} and from Neckel and Labs\textsuperscript{7} between 0.8 and 1.1 \textmu m.

20 September 1995 / Vol. 34, No. 27 / APPLIED OPTICS 6267

Fig. 1. Extraterrestrial solar irradiance curves between 2 and 2.5 \textmu m from Wehrli\textsuperscript{10} and from Neckel and Labs\textsuperscript{7}.

Fig. 4. (a) Solar transmittance spectrum at a resolution of 20 wave numbers, (b) ratio of the Wehrli\textsuperscript{10} curve to the curve from Neckel and Labs\textsuperscript{7} in Fig. 1.
Recent Evaluation of Solar Irradiance Curves

- Judith Lean of NRL – the data set is not good because sampling spacing is too coarse.
- Fontenla 2011 - the standard solar irradiance curve adopted by the solar research community. It is not good for our use because the solar absorption features in the UV region are too deep.
- Neckel & Labs 2004 – The spectral resolution of this data set is poor, but the magnitude of solar irradiance values is quite reasonable.
- SORCE SSI – The data below 0.4 micron is fine. Above 0.4 micron, the spectral resolution is poor.
- Thuillier (SOLSTICE, 2003) – Steve Ungar provided the digital data. The data were already binned slightly.
- Thuillier (2004) ATLAS 1 & ATLAS 3 spectra – the two data sets differ in the far UV region, and they are the same in the 0.3 – 2.4 micron spectral range. No coverage above 2.4 micron.
- Kurucz data sets built in MODTRAN 3.5, Mod 4, and Mod 5.2 – The Kurucz Mod 5.2 solar IRR values below 0.5 micron are too large.

- We constructed another new solar curve for ATREM using Thuillier (2004) ATLAS 3 data below 644.7 nm & Kurucz 2005 Modtran 5.2 data above 644.7 nm.
Comparisons of three solar irradiance curves: Atlas3, MODTRAN 5.2, & MODTRAN 3.5
(The data were smoothed to 3 nm spectral resolution for comparison)

The magnitudes and spectral shapes are very different for the 3 standard solar irradiance curves in the 350 – 600 nm wavelength range.
NASA JPL PRISM image acquired over Ivanpah, CA
(The lower right plot shows apparent reflectance spectra ($\pi L / (\mu_0 E_0)$) for 3 solar curves)

The zig-zag features are due to solar curve errors.

Blue: Mod 3.5 solar curve
Green: < 2.4 um: ATLAS3; >=2.4 um: MOD5.2*1.02
Red: < 644.7 nm: ATLAS3; >= 644.7nm: MOD5.2
Cirrus Detection and Corrections

Sample AVIRIS Images

MODIS Original RGB Image 1.38-μm MODIS Image Cirrus-Corrected RGB Image

Sample AVIRIS Cirrus Spectra & MODIS Channels
A pair of AVIRIS images acquired over Gainsville, Florida – with more cirrus (2nd pass) & less cirrus (3rd pass)
Cirrus-introduced additional radiances at the red (0.66 µm) and near-IR (0.86 µm) channels due to scattering of solar radiation.
After cirrus correction, the two NDVI images appear identical.
Histories for the Un-corrected and Cirrus-corrected NDVI Images

*Figure 7.* (A) Histograms of uncorrected NDVI images obtained from the second and the third pass AVIRIS data sets over Gainesville, Florida. (B) Similar to (A), except for cirrus-corrected NDVI images.
An Example of Cirrus Detection & Cirrus Removal Over Red Sea
An AVIRIS Scene Over Hawaii Acquired in April 2000

Sunglint effect becomes stronger from left to right
It is seen again that sunglint contributes a nearly constant reflectance value of ~ 8% above 0.8 μm.
A Case of Glint Removal Using AVIRIS Data Over Kaneohe Bay, HI

Before

After

Sample Radiance Spectra

Sample Derived Reflectance Spectra
An example of cirrus & glint removal over waters using AVIRIS channels near 1240 nm (f140423t01p00r07rdn)

Most cirrus features over water surfaces are removed after such an empirical correction.
An example of glint removal from the JPL PRISM data
SUMMARY

• In this presentation, I have covered three topics – solar irradiance curves, cirrus detection and corrections, and empirical glint removal.

• For proper retrieval of land surface reflectances and water leaving reflectances from hyperspectral imaging data, we still need an improved solar irradiance curve.

• So far, the empirical techniques presented here for removing thin cirrus and sunglint effects have not been used in operational codes. Improvements in treating the downward and upward atmospheric transmittance terms are still needed.
Un-corrected and Cirrus-corrected NDVI Images

After cirrus correction, the two NDVI images appear identical.
Second Case of Glint Removal Using AVIRIS Data Over Pearl Harbor, HI

Before

After