A PHYSICAL METHOD FOR CALCULATING SURFACE RADIATION FROM GEOSTATIONARY SATELLITES

Manajit Sengupta,
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden CO 80401
Manajit.Sengupta@nrel.gov

Andrew Heidinger
UW/CIMSS/NOAA
1225 West Dayton St.
Madison, Wisconsin 53706
heidinger@ssec.wisc.edu

Steven Miller
CIRA
Colorado State University
Fort Collins, CO 80523-1375
miller@cira.colostate.edu

David Renne
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden CO 80401
David.Renne@nrel.gov

ABSTRACT:

High temporal and spatial resolution global horizontal irradiance (GHI) and direct normal irradiance (DNI) is essential for determining solar resource for both photovoltaic (PV) and concentrated solar power (CSP). While long term surface measurements are the best source of such information it is impossible to create and maintain such a dense network in the US and globally. Satellite based resource assessment is perhaps the best method and various techniques have been investigated and used over the years. Semi-empirical methods using the visible information from a single satellite channel are currently the most used. With the availability of faster computational capabilities it has now become possible to create such solar resources using multiple channels from geostationary satellites. It has also become possible to use physical based algorithms that have hitherto been too computationally expensive. The Global Solar Insolation Product (GSIP) is one such algorithm that has been developed over the years and is currently capable of operational computation of solar resource.

GSIP is a two stage algorithm that retrieves cloud properties using visible and infrared satellite channels as well as ancillary datasets such as topography, surface albedo and snow cover in the first stage. The second stage uses the cloud properties in a radiative transfer model to compute surface radiation. Figures 1(a) and 1(b) show the reflectance and brightness temperature from the 0.64 µm and 10.7 µm channels for July 15, 2009 UTC. Figures 1(c) and 1(d) show the cloud properties and GHI that are retrieved from the 2 steps of the algorithm.

In this paper we will present details of the methodology behind this two step process and results from comparisons with surface based measurements at multiple sites.

1. INTRODUCTION:

The cost of developing utility scale solar thermal power plants runs into the hundreds of millions of dollars. Determination of new power plant sites requires detailed analyses of multiple considerations, including the availability of transmission lines, amenable terrain and accessibility. Perhaps the most important factor in site-selection involves the availability of sufficient solar energy at the surface. This is true for both the Concentrated Solar Power (CSP) technology that requires energy from direct (solar disk) radiation and Photovoltaic (PV) technology that uses both direct and diffuse (scattered by the atmosphere) solar radiation for operating the energy collection devices.

Addressing the challenge of solar energy availability requires a comprehensive long term analysis of multiyear surface solar radiation estimates rendered at high spatial and temporal resolution. The most straightforward method is to have well calibrated instruments such as radiometers located at the surface to take multiyear measurements. These instruments, if maintained well, can provide high quality datasets. However, the high cost of running surface networks limits their use to selected locations. The Baseline Solar Radiation Network (BSRN) (Ohmura et al. 1998) under the auspices of the World Meteorological Organization, Surface Radiation (SURFRAD) (Augustine et al 2000) under the National Oceanic and Atmospheric Administration (NOAA) and United States Department of Energy (DoE) Atmospheric Radiation Program (ARM) (Ackerman and Stokes 2003) operate networks of surface radiometers for various research and operational purposes. As these networks are sparsely distributed, they cannot serve the needs of the solar energy industry. The National Solar Radiation Database (NSRDB) provides simulated solar radiation at the surface based on observations from 293 sites (Renne et al. 2008).

An alternative method for obtaining long term surface solar radiation data involves retrieving surface flux from satellite measurements. The geostationary satellites used for this purpose offer broad spatial coverage and high temporal resolution. The current Geostationary Operational Environmental (GOES) series of satellites, operated by the National Oceanic and Atmospheric Administration, provides nominal 4 km resolution coverage of the continental United States at every half-hour (Weinreb *et al*. 1997). Such coverage from the current series of satellites has been available from 1994 therefore providing the potential to develop a long term, high temporal and spatial resolution surface radiation dataset that will be of utmost necessity to the solar energy companies.

2. CURRENT METHODS:

Surface radiation can be derived from satellite measurements in two ways. One method is to form empirical relationships between multi-spectral satellite radiances and surface radiation as measured from terrestrial-based instrumentation (hereafter referred to as the empirical method) (Perez *et al*. 2002). These empirical relationships are used to compute surface flux directly from satellite measurements.

The second method (hereafter referred to as the physical method) uses a two-stage process. The first stage involves creation of a cloudy/clear-sky mask and cloud type (e.g., cirrus, cumulus, stratocumulus, etc.) from multi-spectral satellite measurements (Stowe et al. 1999, Heidinger *et al*. 2003, Pavolonis *et al*. 2005). The second stage involves the use of the cloud information in a fast radiative transfer model to compute the downwelling surface flux properties with physical account for cloud transmittance (Pinker *et al*. 2002; Lazlo *et al*. 2008).

Whereas the empirical method is attractive because of its speed, there is the potential for large inaccuracies due to the non-linear relationships that exist between the satellite-measured radiance fields, the cloud properties, and the surface radiation. Therefore the physical method is expected to produce more accurate results as the two stage process deals explicitly with these non-linear interactions between clouds and radiation.

2.1 Empirical method

The currently available surface solar radiation datasets used by industry involve empirical fits to the satellite data (Perez *et al*. 2002). Computations are done on the central pixel of a 10 km X 10 km grid box and the result is then taken as being representative of that box. The data are available hourly (Renne *et al*. 2008) for an 8 year period (1998-2005), and are provided by the NOAA National Data Centers (NNDC) for use by the community. This data is also part of the NSRDB.

2.2 The physical method

The first stage of the physical method introduced above includes the physical retrieval of cloud microphysical and optical properties via a complex multi-stage algorithm that is applicable to multiple satellites. The retrieval algorithm first creates a cloud mask and cloud type using ancillary information including surface type, land-sea masking, surface elevation and monthly climatologies of Sea Surface Temperature and Normalized Vegetation Index over land. The algorithms vary according to satellite, based on channel characteristics and availability for a given radiometer. These methods have been applied to the Advanced Very High-Resolution Radiometer (AVHRR; e.g., Stowe *et al*. 1999), the Moderate-resolution Imaging Spectroradiometer (MODIS; e.g., Ackerman *et al*. 2002) and most recently to anticipating capabilities of the future GOES-R Advanced Baseline Imager (ABI; e.g., Heidinger *et al*. 2008). Among the above algorithms the "Clouds from AVHRR" (CLAVR) algorithm for AVHRR (Stowe et al. 1999) is perhaps the most rigorously tested, as it has been used operationally for multiple years.

Full radiative transfer computations are slow and cannot be adopted for operational purposes. As such, the second stage involves a fast computation of surface radiation using the cloud information obtained from the first stage (Pinker *et al*. 1992, Pinker *et al.* 2002, Lazlo *et al*. 2008).

An extended version of the CLAVR algorithm, called CLAVR-x (Heidinger *et al.* 2003), has been adapted for the Global Solar Insolation Project (GSIP; developed at U. Wisconsin-Madison for operational use by NOAA) and is currently undergoing operational testing at NOAA-NESDIS. With assistance from NOAA and the Cooperative Institute for Meteorological Satellite Studies (CIMSS; U. Wisconsin-Madison), a version of the GSIP code has been installed at the Cooperative Institute for Research in the Atmosphere (CIRA; Colorado State University – Ft. Collins).

Data Type		Desert Rock, NV	Seattle, WA	Hanford, CA	Salt Lake City, UT
All	**R**	0.92	0.90	0.95	0.88
	RMSE	100	129	88	134
Overcast	**R**	0.90	0.85	0.92	0.76
	RMSE	128	80	106	137
Partly Clear	**R**	0.96	0.90	0.94	0.88
	RMSE	89	77	122	114
Partly Cloudy	**R**	0.97	0.97	0.97	0.94
	RMSE	76	58	106	77
Clear	**R**	0.98	0.97	0.99	0.98
	RMSE	50	50	47	82

Table 1: This table shows the correlation (R) and Root Mean Square Error (RMSE) (W/m^2) for comparisons between satellite derive surface GHI and measured GHI averaged to 30 minutes. 1 year of data (2009) was used for this comparison.

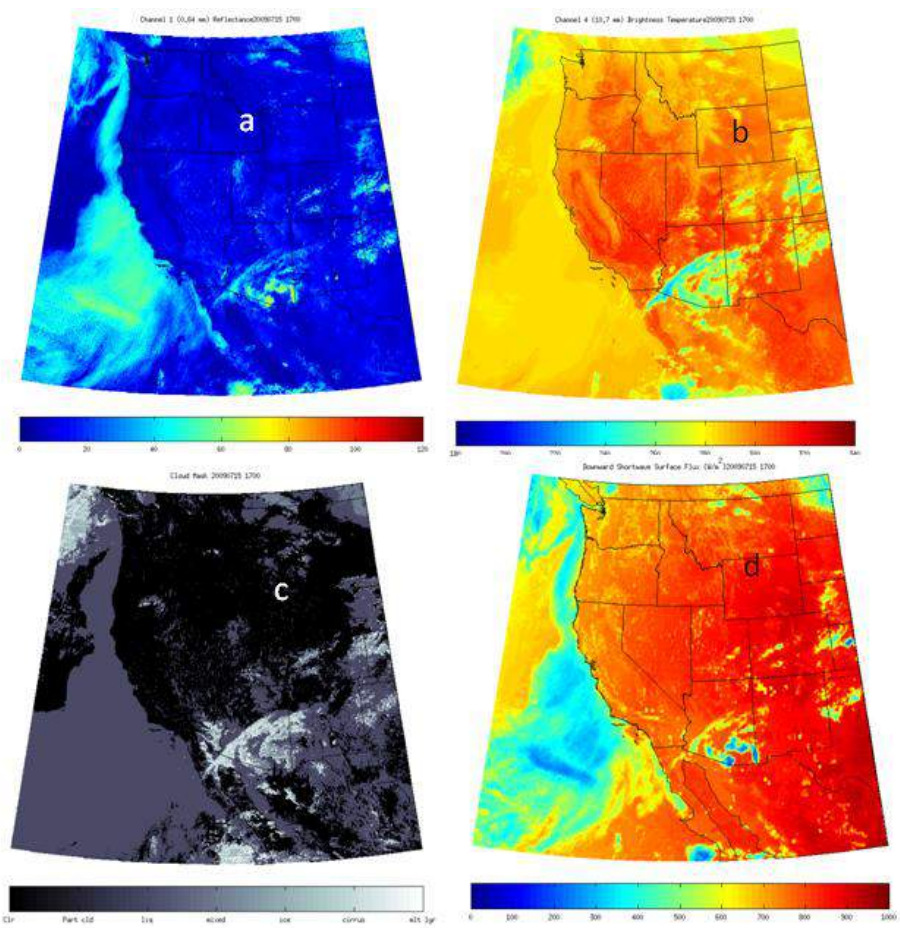

Figure 1. Visible reflectance (1(a)) and infrared brightness temperature (1(b)) from GOES 11 and the corresponding cloud (1(c)) and surface radiation (1(d)) retrievals for July 15, 2009 at 1700 UTC are shown in this figure.

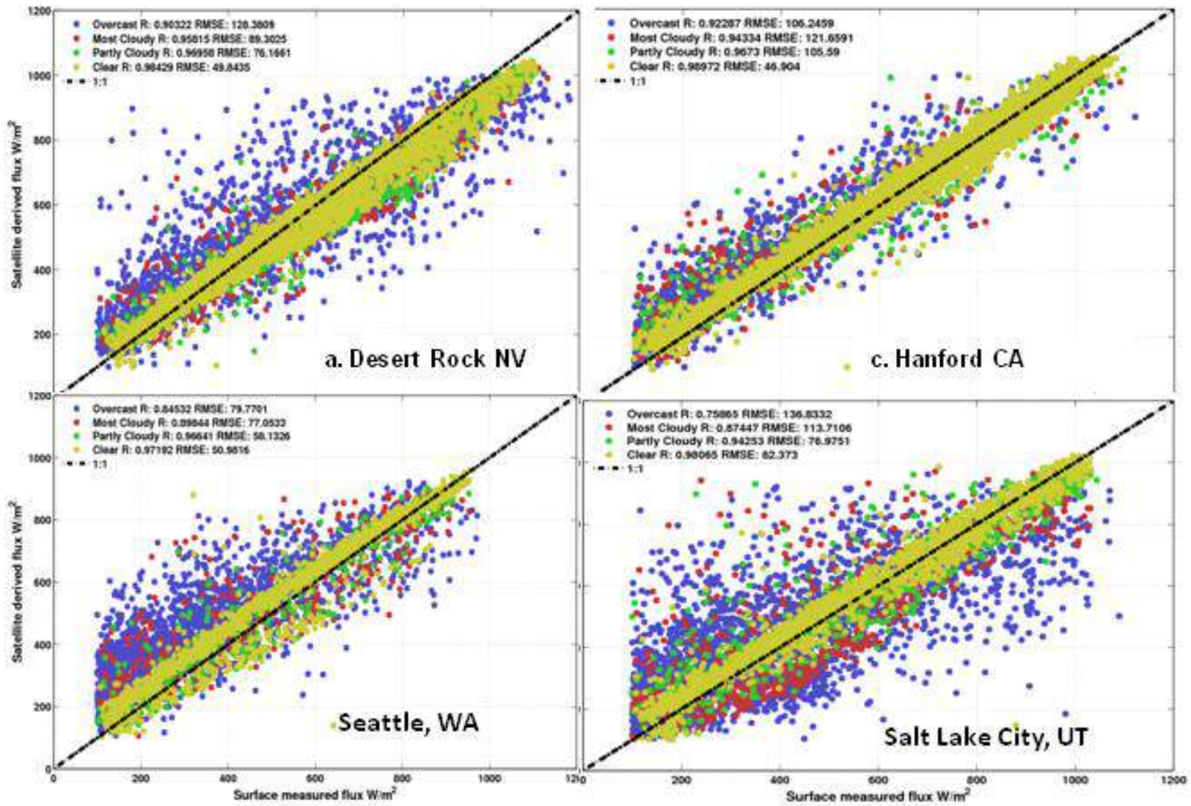

Figure 2: Comparison of Global Horizontal Irradiance measured at the SURFRAD and ISIS sites at (a) Desert Rock, NV, (b) Seattle, WA, (c) Hanford, CA and (d) Salt Lake City, UT with retrievals from the GOES-11 satellite for 2009.

3. RESULTS:

The physical based GSIP algorithm has been set up to run real time for the GOES-11 satellite. Satellite data is collected from the NOAA NESDIS servers and GFS data is collected from the National Weather Service (NWS) servers. These two datasets are combined with ancillary information about surface type, land/sea mask, surface elevation, sea surface temperature and other climatological data to produce cloud mask, type, and properties. The cloud information serves as input to a fast radiative transfer scheme that produces surface radiation for every satellite pixel in the scene (e.g. Figure 1). In these runs the cloud properties are retrieved every half-hour at a nominal resolution of 4 km to match the spatial resolution of the infrared channel on the GOES-Imager. The surface radiation, though, is computed at 1/8^{o} resolution and includes information from approximately a grid of 3X3 satellite pixels for which the cloud properties have been retrieved.

Surface based measurements provide an excellent tool for validation of the satellite based algorithm. We therefore selected multiple sites located at Desert Rock, NV, Seattle, WA, Hanford, CA and Salt Lake City, UT which are either NOAA SURFRAD or ISIS sites. These sites have quality controlled irradiance measurements available every minute. For our comparisons with the satellite retrievals surface GHI was averaged to 30 minutes. The satellite retrievals are also available every 30 minutes. Monthly and annual comparisons were made for different cloud scenes classified as (a) overcast, (b) partly clear, (c) partly cloudy and (d) clear to represent decreasing cloudiness derived from cloud fraction value. The results of the annual comparisons are shown in Figure 2 and Table 1. The GHI correlations from all the sites shows that the satellite derived values are well correlated with the surface observations with correlations ranging from 0.88 to 0.95. As expected the clear sky periods have the highest correlation ranging from 0.97-0.99.

4. CONCLUSIONS AND FUTURE WORK:

A physical based two stage algorithm for retrieving surface irradiance has be created for the GOES series of satellites but is useful for any other geostationary series of satellites. The goal of this research was to investigate the quality of the surface flux derived from GOES data using the ***physical method*** for selected locations in the United States. The desert southwest region is of particular interest to solar utility developers because of the low climatological occurrence of clouds in this region. A validation of the quality of the datasets being produced is necessary to build confidence in the user community. The retrievals were verified using surface based measurements from Desert Rock, Nevada and the results shown in Figure 2 indicated that the retrievals are realistic and useful.

Future plans include 1) gathering sufficient surface radiation datasets for different sites in the U.S. to validate the GSIP results, and 2) set the stage for a comparative study of the quality of the data being produced via GSIP and those using various empirical methodologies (Sengupta et al. 2004). Our hope is to build on this analysis and create a 10-15 year high quality surface radiation dataset which can be used by industry for site location purposes. In addition to the retrospective work proposed here, we plan to examine the skill of surface solar radiation *forecasts* based on realistic regional-scale models (including explicit cloud microphysics) for the purpose of predicting future power availability. The latter is of keen interest to industry, and can be validated through the satellite tools being developed for this phase of the work.

5. REFERENCES:

Ackerman, T.P.; Stokes, G.M. (2003). “The Atmospheric Radiation Measurement Program.” *Physics Today* (**56**:1); pp. 38–44.

Ackerman, S., K. Strabala, P. Menzel, R. Frey, C. Moeller, L. Gumley, B. Baum, S. W. Seeamann, & H. Zhang, 2006: Discriminating Clear-Sky from Cloud with MODIS - Algorithm Theoretical Basis Document . *Products: MOD35. ATBD Reference Number: ATBD-MOD-06.*

Augustine, J. A., J. J. DeLuisi, and C. N. Long, 2000: SURFRAD—A national surface radiation budget network for atmospheric research. *Bull. Amer. Meteor. Soc.,* **81,** 2341–2357.

Heidinger, A. K., 2003: Rapid daytime estimation of cloud properties over a large area from radiance distributions. *J. Atm. Oceanic Tech.,* **20,** 1237-1250.

Heidinger, A. K., C. Calvert*,* 2008: Algorithm theoretical basis document -ABI Cloud Mask Version 0.8. available from: http://www.goesr.gov/procurement/ground_documents/Cloud_Mask_GOES-R_ABI_ATBD_v0.8.pdf

Lazlo, I., P. Ciren, H. Liu, S. Kondragunta , J. D. Tarpley , M. D. Goldberg, 2008: Remote sensing of aerosol and radiation from geostationary satellites. *Adv. Space Res.*, **41**, 1882–1893

Li, X., R. T. Pinker, M. M. Wonsick and Yingtao Ma, 2007: Toward improved satellite estimates of short-wave radiative fluxes-Focus on cloud detection over snow: 1. Methodology. *J. Geophys. Res.*, **112**, doi:10.1029/2005JD006698.

Ohmura A. et. al.: 1998. Baseline Surface Radiation Network (BSRN/WRMC), a new precision radiometry for climate research. *Bull. Amer. Meteor. Soc.,* **79**. 2115–2136.
Pavolonis, M., A. K. Heidinger, T. Uttal, 2005: Daytime Global Cloud Typing from AVHRR and VIIRS: Algorithm Description, Validation, and Comparisons. *J. Appl. Meteor.,* **44,** 804-826.
Perez, R., P. Ineichen, K. Moore, M. Kmiecik, C. Chain, R. George, F. Vignola, 2002: A new operational model for satellite-derived irradiances: description and validation. *Solar Energy*, **73,** 307-393.
Pinker, R. T., and I. Laszlo, 1992: Modeling of surface solar irradiance for satellite applications on a global scale. *J. Appl. Meteor*., **31**, 194–211.
Pinker, R. T., I. Laszlo, J. D. Tarpley , and K. Mitchell, 2002: Geostationary satellite parameters for surface energy balance. *Adv. Space Res.* **30**, 2427-2432.
Renné, D., R. George, S. Wilcox, T. Stoffel, D. Myers, and D. Heimiller. 2008: Solar Resource Assessment, *Technical Report,* NREL/TP-581-42301.
Sengupta, M., E. E. Clothiaux and T. P. Ackerman, 2004: Climatology of Warm Boundary Layer Clouds at the ARM SGP Site and Their Comparison to Models. J. Clim., **17**, 4760-4782.
Stowe, L. L., P. A. Davis, and E. P. McClain, 1999: Scientific basis and initial evaluation of the CLAVR-1 global clear cloud classification algorithm for the Advanced Very High Resolution Radiometer. *J. Atmos. Oceanic Technol.,* **16,** 656–681.
Weinreb, M. P., M. Jamison, N. Fulton, Y. Chen, J. X. Johnson, J. Bremer, C. Smith, and J. Baucom, 1997: Operational calibration of Geostationary Operational Environmental Satellite-8 and -9 imagers and sounders. *Appl. Opt.,* **36,** 6895–6904.