New Shortwave Solar Radiometer with Information-Based Sparse Sampling

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A new concept for a real-time shortwave solar radiometer is presented, based on the premise that high resolution measurements of the shortwave solar spectrum are needed only in wavelength regions where the atmospheric physics are changing rapidly with respect to l. The design features holographic optical elements (HOEs) for nonuniform sampling of the spectrum, customized photocells, and temperature-compensated monolithic wide dynamic range amplifiers. Preliminary results show full spectrum reconstruction accuracies to < 3% with a 10:1 reduction in the number of photocells required.

Shortwave solar radiometry in the wavelength region from 0.3 to 1 µm is important for characterizing atmospheric aerosols, trace gases, and cloud radiative phenomena.[1] Although scanning monochromator, shortwave radiometers working in this region of the solar spectrum are commercially available, limitations in speed of response affect their usefulness under rapidly time-varying atmospheric conditions.[2] An alternate implementation is a shortwave radiometer with a dispersive element and a charge-coupled device (CCD) array,[3] where the processing of the shortwave solar spectrum is performed in parallel by each channel of the array. There are also problems with this approach: although with available CCD array sizes (256/512/1024) high spectral resolution can be attained, problems with calibration, temperature stability, cross-talk, and quantum efficiency reduce the overall performance specifications of the instrument (considering the 10^7 dynamic range of the shortwave solar spectrum).[4] A new approach taken by Michalsky and Harrison (S.U.N.Y. Albany) uses a small number of discrete photodetectors (five to seven) with carefully chosen, narrow-band, interference filters. The center frequencies of the filters are customized for measurements of selected aerosol, water, ozone, and CO_2 absorption lines. This technique works well for certain experiments; however, the ability to reconstruct higher resolution spectra from the small data set is limited.[5]

This letter presents a new concept for a shortwave solar radiometer that addresses many of the problem areas encountered in the development of CCD array radiometers and preserves the necessary information to reconstruct spectral content with approximately the same resolution as a CCD array. This concept is based on the premise that high resolution measurements of the shortwave solar spectrum are needed only in the wavelength regions where the atmospheric physics are changing rapidly with λ. This premise reduces the number of required waveband channels significantly over the CCD element implementation, thereby enhancing the overall instrument accuracy, yet retaining the ability to reconstruct full spectral curves from the resulting sparse data set. Full spectral reconstruction is possible through the use of contiguous sample bands in conjunction with a spectral model.

Our choice of wavebands is data-driven,[6] based on equalization of the variance of the "information" in each waveband in the spectrum caused by a wide range of atmospheric conditions. If the variance of the "information" in a wavelength band, $\lambda_{k-1} \leq \lambda \leq \lambda_k$, is small and the mean spectral irradiance, $I(\lambda)$ is known, one does not need to subdivide that band into finer intervals. Therefore, the solar spectrum is sampled with finer resolution in areas where the atmospheric physics change substantially and with coarser resolution in regions where there are smaller changes.

Treating $I(\lambda)$ incident on a photocell as a random variable, we define the variance of "information," σ_k, in waveband k in terms of the normalized autocovariance,

$$\sigma_k^2 = \int_{\lambda_{k-1}}^{\lambda_k} \int_{\lambda_{k-1}}^{\lambda_k} \frac{C_{II}(\gamma,\alpha)}{\bar{I}(\gamma)\bar{I}(\alpha)} d\alpha d\gamma \tag{1}$$

where the autocovariance, $C_{II}(\gamma,\alpha)$, can be stated in terms of the statistical expectation operator $\zeta\,\{\}$:

$$C_{II}(\gamma,\alpha) \equiv \zeta\,\{\,[I(\gamma) - \bar{I}(\gamma)]\,[\bar{I}(\alpha) - \bar{I}(\alpha)]\}$$

We use the normalized autocovariance rather than a simple autocovariance to eliminate any "weighting" of a particular waveband due to the absolute magnitude of the mean irradiance in that region. The criterion for selecting the radiometer wavebands is then equating the square of the variance in each waveband over the whole spectral range; thus,

$$\sigma_{\cdot}^2 = \quad = \sigma_k^2 = \quad = \sigma_{N-1}^2 = \sigma_N^2 \tag{2}$$

Ideally, one would like an arbitrarily large data set of high-resolution solar extinction measurements taken over a variety of atmospheric conditions as the input for the statistical analysis. For convenience, in place of this data set, we used the SPCTRL2 code developed by the Solar Energy Research Institute (SERI) and varied 1) day of the year, 2) solar zenith angle, 3) ground reflectivity, 4) surface pressure, 5) the aerosol optical path depth, 6) precipitable water vapor, and 7) site latitude and longitude. The resulting data set was processed statistically and the subsequent waveband selections are shown superimposed on a typical solar radiation spectrum in Figure 1. The number of wavebands was initially chosen to be 38 (the size of a commercially-available photodetector array) but will ultimately be determined from tradeoffs between reconstruction accuracy and cost. The waveband selection in Figure 1 is seen to be heavily weighted toward sampling in the near-UV. This is a region of the spectrum where Rayleigh scattering, ozone absorption, and the solar spectrum are all changing rapidly with λ. Therefore some confidence is gained that the data-driven statistical criteria developed in equations (1) and (2) accurately reflect the underlying atmospheric physics. The real test of the criteria, however, is how well higher resolution spectra can be reconstructed from sparse data collected via the nonuniform samples.

Implementing a prescribed nonuniform dispersion of incident solar radiation onto an array of photocells is not trivial. The most promising idea for controllable nonuniform

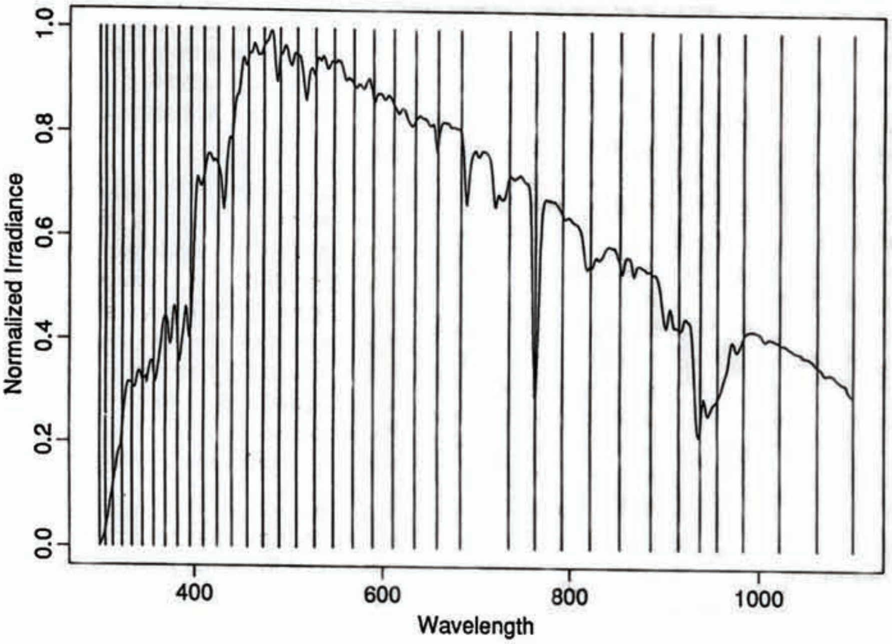

Figure 1. Nonuniform Sampling of Solar Radiation.

dispersion of incident light, derived from discussions with APA Optics Inc., is a combination of a conventional dispersive optic (i.e., prism) and HOE "amacronic optics."[7] This concept is illustrated in Figure 2 as part of the overall instrument design. The dispersive optic divides the incident light into its spectral components and directs the light toward the amacronic optic and photocell array. The amacronic optic is an array of lenslets that can be made off-axis or of varying size to provide the nonuniformly distributed wavebands without varying the photocell size or position. Each lenslet focuses a selected portion of the quasi-collimated light (spectrum) from the dispersive element onto its corresponding photocell. The amacronic lenslet array can be fabricated by reactive ion etching of fused silica and thus should not experience significant environmental degradation or aging.

One of the benefits in reducing the number of required wavebands in a shortwave solar radiometer is that the photocells and associated electronics can be individually customized. Off-the-shelf Si photodiode arrays are sensitive from ~200 to ~1150 nm, but have at least three major problems: 1) high cross-talk, resulting from monolithic separation of the photodiode elements (we measured a cross-talk of ~25% at 488 nm from a standard commercially-available photodiode array); 2) low quantum efficiency (QE) and QE degradation in the near UV (200-370 nm), resulting from surface recombination of electron-hole pairs generated near the surface; 3) broadband antireflection (AR) coatings, that reduce the total amount of reflected light, but reflect a significant fraction of the incident light, particularly in the UV and IR. Cross-talk can be eliminated by physically separating the individual photodiode elements. The UV QE can be increased and stabilized by using standard surface passivation techniques[8] used in the fabrication of high efficiency solar cells. The reflectivity can be reduced to nearly zero by varying the thickness of the Ta_2O_5 AR coatings on the individual photodiode elements. This last step increases the photogenerated current, but more importantly, reduces scattered light in the entire optical device.

Important considerations in the design of an amplifier to monitor photocell current for this application are wide dynamic range, high accuracy, temperature stability, and suitability for monolithic integration. We have designed a wide-range logarithmic electrometer to operate from -15 to 65°C with input currents ranging from 1 pA to 10 µA (seven decades), ideal for monolithic integration and multichannel applications. We use a new temperature compensation method[9] which employs dual logarithmic electrometer circuits; one to measure the photocell current

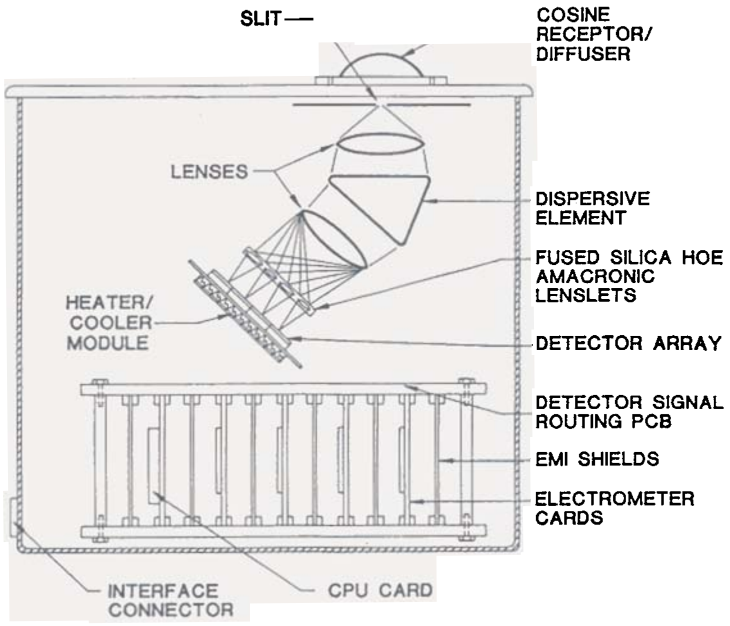

Figure 2. Radiometer Instrument Configuration

and the second to track temperature effects. A ratio of the electrometer outputs then yields a result independent of temperature. Laboratory measurements with a prototype demonstrated that accuracies to <1% were achievable over the upper five decades of signal range (-15 to 71°C). Accuracies to <1% were achieved over the full seven decades when the input device leakage current is reduced by cooling. Conventional temperature compensation methods using positive temperature coefficient resistors produce at best a 25% error over the same temperature and dynamic range.[9]

To test the overall instrument concept we made high-resolution (2 nm) measurements of diffuse solar radiation (0.325 to 1.1 µm) with a LiCor Model LI-1800/22 radiometer under clear and overcast skies. We then integrated these measurements over the wavebands shown in Figure 1 thereby simulating nonuniform sampling. We processed the simulated sparse data sets to produce an estimate of the original full-resolution measurements. This reconstruction process involved two steps: 1) extracting a general fit of the sparse data, using an available solar radiation model, and 2) fine tuning the general fit by using equations resulting from the boundary conditions of contiguous spectral samples. We used SPCTRL2 for the general fit of the sparse data and a perturbation method for an underdetermined system of equations for the fine tuning. We obtained mean rms errors <2.8% for the clear sky case and <4.9% for overcast skies, reconstructing 387 spectral data points from 38 sparse samples (a 10:1 expansion). Two large sources of error in the reconstruction were the absence of detail in the 740-nm O_2 and H_2O absorption band region and the 940-nm H_2O band of the SPCTRL2 code and the lack of sensitivity of the LiCor instrument below 400 nm. Excluding these error sources for the clear sky case with nonuniform sampling reduced the mean error to 1.9%. All else being equal, these results provide an indication of the types of accuracies one would expect comparing an ideal high-resolution CCD-based radiometer with an information-based sparse sampling radiometer. Future work will concentrate on using more detailed models such as LOWTRAN7 in the spectral reconstruction.

Acknowledgments

We would like to thank S. M. Arnold, APA Optics, Inc., for his technical suggestions and input. This research was sponsored by the Atmospheric Radiation Measurement (ARM) Program, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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