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2010 Solar and Space Physics Decadal Survey White Paper: Next Steps in Solar Spectral Irradiance Studies

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Understanding the physical causes underlying solar spectral irradiance variations and the impact of these variations on terrestrial climate remain critical compelling challenges. On the solar side, the most fundamental unknown is the role of the "quiet-sun[7]," a question brought into focus by spectral irradiance observations during the recent deep minimum, which show opposing trends in the infrared and ultraviolet portions of the spectrum (Harder et al. 2009). On the terrestrial side, while it is clear that the Sun played only a small role in late twentieth century warming, the signature of solar cycle variations in climate are now quite well established (Gray et al. 2010). How this coupling occurs is not fully understood, suggesting something incomplete in our understanding of the climate system.

We suggest that in the coming decade, through the focused efforts outlined below, we can successfully address both of these scientific challenges and emerge with a new more complete understanding of the Sun and its influence on Earth. The essential ingredients in this effort are poised at the edge of our abilities, challenging but not risky, and take full advantage of current technological capabilities. These ingredients are:

- Radiometric imaging of the Sun to assess the absolute center-to-limb brightness of magnetic structures on full disk images at key wavelengths. This can be achieved via the coupling of an imager, capable of high relative precision, and a radiometer, to calibrate the absolute image intensity, into a single space-based instrument, a **Radiometric Solar Imager (RSI)**. Both of the necessary technologies have been demonstrated operationally, and can be readily combined into a single instrument with high return and low risk.

- High-resolution observations of the magnetic features identified in full disk images from the RSI. These are necessary to assess the variance underlying the full-disk pixels as a function of structure type, disk position, and solar cycle phase. Such observations can be achieved in the next decade by the judicious use of data from the Advance Technology Solar Telescope (ATST). The synergy between full disk radiometric imaging, achievable only from space, and ultra high resolution dynamical observations, achievable only with ground based apertures, will allow irradiance modeling to be extended beyond one-dimensional static atmospheres to include the statistical properties of underlying variations due to solar dynamics.

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[7] "Quiet-sun" in this white paper refers to internetwork regions, as is typical in irradiance studies. Internetwork regions are identified by low Ca II K emission, and are often assumed to be regions of low magnetic flux density. "Quiet-sun" as used here should not be confused with the broader non-coronal-hole-region usage found in other discussions of chromospheric, transition region, or coronal emission.

- High-resolution radiative magnetohydrodynamic modeling of the photosphere and chromosphere. These will enable a physical understanding of the connection between small-scale field dynamics and structure and the integrated spectral output. Many realizations of such models with varying flux density and geometry will be achievable on planned petascale computing platforms in the next decade. These will allow a statistical understanding of the physical causes of spectral variability and the construction of radiative diagnostics to disentangle thermodynamic changes from unresolved magnetic flux elements in the “quiet-sun”.

- Coupling of the measured or modeled solar spectral irradiance to comprehensive numerical models of the photochemical, radiative, physical and dynamical processes in the Earth’s atmosphere and ocean. Such multi-component models have reached a state of maturity that makes this coupling realizable and meaningful, with major ongoing efforts aimed at efficient implementation of these codes on next generation petascale computing platforms.

The coming decade thus promises a convergence of capabilities that if focused and supported can contribute significantly to our understanding of the radiative coupling between the Sun and the Earth. Through these efforts we will gain enhanced abilities to successfully model both the Earth’s regional climate variations and short and long term solar fluctuations.

Brief review of the scientific background

A critical component in understanding the causes of the Earth’s climate variability is a thorough description of the Sun’s role in this complex process (Lean 2000; Rind et al. 2008). Over the course of a solar cycle, as well as over centennial and millennial time scales, solar magnetic activity modulates its irradiance. Understanding the evolution and radiant output of solar magnetic features is thus at the heart of understanding the Sun-Earth connection, and radiometric imaging of the Sun is critical for both solar physics and Earth climate studies.

While it is still an open question whether global structural changes in the Sun play a role in its variability[8], particularly over long time scales, the appearance and disappearance of small scale magnetic structures is known to account for most of the variation observed over the course of a solar cycle. Sunspots and pores have negative contrast against the background disk, while smaller scale magnetic fields generally contribute positively. Changes in the fractional areas covered by structures of different intensities modulate the solar irradiance. The magnitude and even the sign of the contribution of any given magnetic structure, however, depends not only on its size, as suggested above, but also critically on the wavelength being observed and the structure’s location on the solar disk. To understand solar irradiance variations three interlocking scientific activities are thus needed: 1) accurate and precise observations of the evolution of active regions (such as sunspots and bright facular regions) on the Sun through global solar imaging. This requirement for global imaging to determine the disk position of magnetic structures sets a limit on their resolution. 2) models and high resolution observations of solar magnetic structures that explain their radiant emission and the variance in this emission. This variance is caused by differences in the unresolved (sub-pixel) contributions underlying the global scale observations. 3) the

[8] The proposed effort will make a significant contribution to the resolution of this issue by measuring the radiometric contributions of magnetic structures and “quiet-sun” to solar spectral variability.

measurement of disk integrated solar spectral irradiance against which models can be tested. It is this disk integrated spectral irradiance, either observed (when available) or modeled (based on the level of solar activity), that is then used as radiative input to climate models to ultimately allow an understanding of the Sun's role in climate variability.

Harder et al. (2009) reported an important example of the effectiveness of this approach. They combined observations of solar spectral variability measured by SORCE SIM (Solar Radiation and Climate Experiment, Spectral Irradiance Monitor) and full disk images showing the evolution of solar active regions as observed by the HAO/NCAR Mauna Loa Solar Observatory's Precision Solar Photometric Telescope (MLSO PSPT; Rast et al. 2008) with theoretical interpretation using SRPM (Solar Radiation Physical Modeling; Fontenla et al. 2009) to show that both increasing and decreasing irradiance trends occurred as a function of wavelength during the descending phase of Solar Cycle 23. These offsetting trends summed to produce the observed decrease in total solar irradiance over the same period. Terrestrial climate modelers are now just starting to assess the ramifications of this result (Cahalan et al. 2010, Haigh et al. 2010).

To date all precision irradiance imaging of the Sun has been photometric, not radiometric, measuring the intensity of any pixel on the solar disk relative to some predefined background. By careful determination of the detector gain (flat-fielding) and the quiet-sun center-to-limb variation, the PSPT can achieve high precision (0.1%) relative photometry of the solar disk. *There are however no measurements of the absolute radiometric contributions of magnetic structures to the disk integrated irradiance*. This means that all observations and all modeling efforts must define a "quiet-sun" intensity, against which the contrast of the magnetic elements is determined. Since the "quiet-sun" intensity of the Sun varies from disk center to the limb, and this profile is wavelength dependent, all contrast measurements and magnetic structure identifications are made relative to some arbitrary definition of the "quiet-sun" center-to-limb profile. Moreover, the "quiet-sun" is indeed not completely quiet, and over the solar cycle the number of unresolved magnetic flux elements contributing to pixel-integrated intensities likely varies. Put starkly, we as yet have no idea whether the trends discussed above (or other variations observed) are due to changes in magnetic structure number densities, structure intensities, the "quiet-sun" reference state, or more likely, some combination of these; the possibilities cannot be unambiguously untangled without absolute radiometric imaging.

We suggest that this shortcoming can be readily overcome via a PSPT-like instrument with radiometric capabilities (the RSI). The effort would combine extant expertise in radiometry and imaging, to design an instrument capable of producing absolutely calibrated solar images at specific critical wavelengths (Table 1 summarizes possible filter bands of interest). Such an instrument would provide absolutely calibrated center-to-limb profiles of magnetic structures, and contribute the next critical step along a path that will ultimately yield a radiometric imaging spectrometer for full spatial and spectral monitoring of solar variability.

Radiometric Solar Imager (RSI)

The essential new instrumental component of solar irradiance studies over the next decade is an instrument that images the Sun at carefully chosen wavelengths while simultaneously measuring the integrated output along the same light path to produce *absolutely calibrated radiometric images*.

Table 1. Possible filter bands for the RSI instrument

Wavelength (nm)	FWHM (nm)	Use with F-P filter	Purpose/Function
CaIIK 393.4	0.02	Yes	Ca II K core and wing intensity (tunability requirements) Determination of faculae and plage regions Scattering polarization source characterization
607.1	0.5	No	Standard red PSPT continuum (instrument continuity) Determination of sunspot umbra and penumbra
409.4	0.02	Yes	Standard PSPT blue continuum (instrument continuity) Brightness temperature, relative photometry
HeI 587.6, 1083 NaID 589.0,589.6	0.2	No	Scattering polarization source characterization Chromospheric contributions
Ha 656.3	0.02	Yes	Prominence analysis Scattering polarization source characterization
CaII triplet 855	0.02	Yes	Scattering polarization source characterization
~600, ~700, 862, ~900 , ~1000, 1650	0.5	No	Photospheric temperature structure (relative photometry) Opacity minimum

What design features/requirements are needed for a compelling Radiometric Solar Imager?

- Diffraction limited images of the full solar disk.
  - This requirement sets the size of solar image to be ~0.6°, or ~0.5 arc seconds per detector pixel. The solar image must under fill the detector for scattered light determination.
- The detector relative pixel-to-pixel precision of 1 part in 10^3 is needed and must be maintained over the course of a solar cycle.
  - This requirement translates into being able to determine the brightness temperature of a 1 arc-second scene on the Sun with about 1-2 degrees Kelvin accuracy. This level of relative precision is currently achieve in the best PSPT images, and should be attainable using similar techniques from space.
- The instrument requires scientifically optimized broad wavelength band-pass filters to isolate different layers in the solar atmosphere.
  - The current PSPT instrument uses 5 filters (two Ca II K core and one wing, 607nm red continuum, 409nm blue quasi-continuum). Additional filters in the near infrared, in the neighborhood of the H^- opacity maximum, would be able to determine changes in the photospheric thermal structure.
  - Augmentation in specific chromospheric lines would enable radiometric calibration of the illumination source in the presence of magnetic homogeneities for scattering polarization measurements.
- Narrower and more uniform filter functions than can be achieved with band-pass filters are needed, leading to consideration of a tunable Fabry-Perot filter (F-P in Table 1).
  - Wavelength tuning through the Ca II K feature would allow scanning with height and careful understanding of core to wing ratio proxies.
  - Similarly, the anisotropy of the radiation will change significantly across both the Ca II K the Hα line profiles, and scanning would contribute to better understanding of the chromospheric polarization signal with implications for field measurements.
- Design must provide calibrated radiometric measurement of the light following the same light path as the beam through the optical elements.

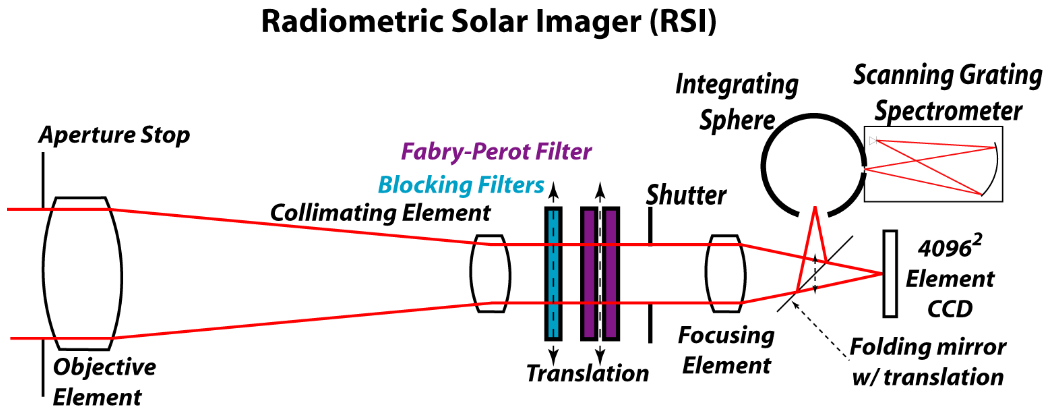

Figure 1: A concept drawing for this instrument, detailed optical design, component specification, and calibration methodology are required for a phase A instrument design.

- *It is this part of the design that sets this instrument apart from other systems that image the Sun.* The RSI will provide absolutely calibrated solar images by coupling high precision relative photometry across the CCD to a radiometric measurement of the integrated light through the same pass-band.
- In-flight radiometric calibrations to correct for sensitivity degradations are thus essential. Both detector-based corrections (such as the SORCE SIM, Harder et al. 2005) and light source-based calibrations (Thuillier et al. 2009) need to be considered in the design.

- The absolute preflight radiometric calibration of the instrument must be traceable NIST standards, as in the calibration plan for the upcoming SIM instrument for the NOAA TSIS mission using the NIST SIRCUS (Brown et al. 2006).
- Because of the broad wavelength coverage needed for this experiment, reflective designs are favored, but refractive equivalent designs have not been ruled out.
- This instrument could stand-alone and be flown on a mission of opportunity, or it could be flown in conjunction with other instruments on a larger mission or Small Explore Mission (SMEX). Moreover, the RSI instrument capabilities could be combined with other imager or magnetogram needs.

Importance of both global and high resolution observations

Advancing our understanding of solar spectral irradiance will require, over the next decade, the integration of global-scale relatively low- and small-scale high-resolution observations. Global imagery is required for solar spectral irradiance modeling and reconstruction because the intensity of magnetic features on the disk depends on their disk position, and so a measurement of their position is required to assess their contribution to the integrated disk irradiance. High-resolution observations are required to assess the unresolved structure and dynamics underlying the global scale observations.

Observations to date do not agree about the center-to-limb brightness of magnetic structures at global image resolution. This is not only because of wavelength dependencies and resolution differences between them, but more fundamentally because only contrast measurements at 0.1% precision have been possible to date (no radiometric imagery of that accuracy has been achieved), and there is no universal definition of the background “quiet-sun” intensity against which the contrast is to be measured. As a consequence, observations of magnetic structure center-to-limb profiles vary widely (Ermolli et al. 2007), and models attempting to reproduce those profiles have no accepted measurement against which to assess their accuracy. The RSI will for the first time provide the absolute center-to-limb intensity of any disk pixel at critical wavelengths.

Moreover, the underlying magnetic structures are poorly constrained at full disk resolution. Pixels of the same magnetic flux density can have very different intensities depending on their underlying unresolved flux distribution (Criscuoli and Rast 2009). To understand the variance in absolute intensity observed for any one magnetic structure type, low-resolution global observations must be accompanied by high-resolution images of the same locations. These do not need to be radiometric, but they must be numerous, a collection of highly resolved tiles for each global structure type, to build up, as a function of disk position the statistics of the underlying intensity and dynamics. This is the only way that global modeling of the integrated solar spectral irradiance can move beyond one-dimensional static atmospheric models and begin to incorporate unresolved complexities.

Radiative MHD modeling underpinning

That in turn will require high-resolution radiative magnetohydrodynamic modeling of the photosphere and chromosphere that can be used to assess the fidelity of the irradiance models. Such high resolution modeling efforts will be increasingly possible with increasingly powerful computing resources in the coming decade. These should be used in conjunction with the high-resolution observations to inform the spectral irradiance modeling efforts (Domingo et al. 2009). In particular one wants to ask, what is the range and distribution of pixel intensities at the global image resolution that can be expected for a given wavelength and disk position. Many realizations of the dynamics in these simulations and the integrated output as a function of wavelength could be used to reconstruct the underlying variance of the lower resolution pixels. Global vector magnetic field observations from the Helioseismic Magnetic Imager (HMI) on the Solar Dynamics Observatory (SDO) should be used in close conjunction with the modeling to constrain the field topologies.

While the global run of temperature with height in the solar photosphere can be accurately determined from the center-to-limb variation of intensity at a given wavelength, the local thermal structure, which is needed to disentangle the irradiance contributions from different magnetic structures within a pixel, is much harder to determine and involves combining intensity measurements at different wavelengths to determine the temperature gradient. Such relative photometry (Foukal and Duvall 1985) is extremely difficult using ground based observations because of seeing induced misalignment and lack of an absolute photometric reference. RSI solves these problems. In principle, the temperature at any height can be determined from measurement of absolute intensity at a single wavelength, but multi-wavelength determination would be much preferred for accuracy. Unfortunately, even in the continuum, different wavelengths sample different atmospheric heights because of the wavelength dependence of the main opacity source in the photosphere, the H^{-} ion, making multi-wavelength measurement of intensity coming from a single height difficult. However, since H^{-} opacity increases with wavelength in the blue, reaches a maximum at 862 nm, decreases to a minimum near 1.6 μm, and then increases again towards longer wavelengths, careful selection of pass-bands at different wavelengths corresponding to equal opacity values on either side of the maximum allows a two-wavelength measurement of temperature at specific heights in the atmosphere. This procedure would ensure an accurate determination of the thermal gradient with good height resolution, and thus potentially untangle thermal from magnetic contributions to each pixel. It would lead directly to an assessment of the role and cause of the "quiet-sun" variability.

Coupling to terrestrial climate modeling

The variability of the terrestrial climate and space environment are closely related to the variability of the solar irradiance. The extreme ultraviolet (EUV) and X-ray, which are absorbed by the thermosphere and ionosphere, can vary by tens to 100s%, while the visible bands vary by ~0.1% or less. As a result, the thermosphere and ionosphere vary significantly over a solar cycle, with the neutral temperature increasing by ~60% from solar minimum to solar maximum conditions (Schunk and Nagy 2009). Moreover, the stratosphere (van Loon and Labitzke 2000) and even the troposphere display 11-year variability on both global scales and regional scales (Haigh 1996, van Loon et al. 2007). The change, particularly in the troposphere, is stronger than expected from a linear response to the solar total irradiance change. Numerical studies have suggested that the stratosphere ozone heating and ocean-atmosphere interactions may both act to enhance the tropospheric climate response to solar signal (Kodera and Kuroda 2002, van Loon et al. 2007, Haigh et al 2005). Therefore, to correctly quantify the response of different atmospheric regions to solar variability, and to understand the mechanisms responsible for coupling these responses, it is critical to have both an accurate description of the solar spectral irradiance and a comprehensive atmospheric model that accounts for coupled photochemical, radiative, and dynamical processes in the upper and lower atmosphere and the ocean.

One example of such a model, pushing the capabilities as we enter the petascale-computing decade, is NCAR's Community Earth System Model with the Whole Atmosphere Community Climate Model (WACCM) as its atmosphere component. The CESM consists of five components for the atmosphere, ocean, sea ice, land surface, and land ice linked through a coupler that exchanges fluxes and state information among these components. Details of CESM can be found from the NCAR CESM website. WACCM is a climate-chemistry general circulation model spanning from the Earth's surface to the thermosphere. Of particular interest for the solar variability, WACCM provides the infrastructure to incorporate solar spectral irradiance information. It is written to take advantage of modern machine architectures, with hybrid parallelization using shared memory techniques (OpenMP) within a node and a distributed memory approach (MPI) across nodes. NCAR is actively engaged in transitioning these models to machine architectures composed of hundreds of thousands of processors, and it is models like these, using accurate solar irradiance inputs, that will in the next decade untangle the link between solar and climate variability.

Synergistic science

While the primary aim of the Radiometric Solar Telescope is irradiance and climate coupling science, if appropriately designed the instrument could have significant impact on other important outstanding problems:

- Inversion of scattering spectropolarimetric data requires characterization of the illuminating source at the observation wavelength. Radiometric observations of the solar disk intensity in the presence of magnetic inhomogeneities would provide this.

The magnetic diagnostics of the chromosphere relies on the modeling of the resonance scattering polarization in many lines (some listed in Table 1). This requires the proper characterization of the illuminating source at the various wavelengths involved in the excitation of the corresponding atomic systems. In particular, the center-to-limb variation at those wavelengths is a critical quantity for the determination of the degree of radiation anisotropy. Along with the ambient magnetic field, this anisotropy is ultimately responsible for the observed polarization signature of the scattered radiation. For this reason, radiometric observations of the solar disk intensity in the presence of magnetic inhomogeneities are essential for the modeling of polarized radiation transport in the chromosphere and thus for deducing the magnetic field properties there (see McIntosh et al. White Papers).

- Large-scale flows within the solar convection zone, either associated with global scale motions or active regions should induce thermal fluctuations (Spruit 2003, Rempel 2005). Latitudinal variations in intensity have been reported in PSPT data (Rast et al. 2008) at the very limit of what can be achieved via ground-based observations. With RSI these could be tightly constrained as a function of wavelength, with implications for global dynamics and dynamo modeling efforts.

- Careful measurement of Doppler and intensity fluctuations as a function of wavelength can be used to characterize the source of the solar p-modes (Severino et al. 2008). The RSI could do this at multiple wavelengths to quantify the source properties, with implications for understanding global mode line-shapes and local helioseismic kernels.

REFERENCES:
(NOTE: These references are representative of recent work, they are not complete.)

Brown, S.W., Eppeldauer, G.P., and Lykke, K.R. (2006) Appl. Opt. **45**, 8218
Cahalan, R.F., Wen, G.Y., Harder, J.W., and Pilewskie, P. (2010) GRL **37**, L07705
Criscuoli, S. and Rast, M.P. (2009) A&A **495**, 621
Domingo, V., et al. (2009) SSRv **145**, 337
Ermolli, I., Criscuoli, S., Centrone, M., Giorgi, F., and Penza, V. (2007) A&A **465**, 305
Fontenla, J., Curdt, W., Haberreiter, M., Harder, J., and Tian, H. (2009) ApJ **707**, 482
Foukal, P. and Duvall, T., Jr. (1985) ApJ **296**, 739
Gray, L.J., et al. (2010) Rev. Geophys. **48**, RG4001
Haigh, J.D. (1996) Science **272**, 981
Haigh, J.D., Blackburn, M., and Day, R. (2005) J. Climate **18**, 3672– 3685.
Haigh, J.D., Winning, A.R., Toumi, R., and Harder, J.W. (2010) Nature **467**, 696.
Harder, J.W., Fontenla, J., Lawrence, G., Woods, T., and Rottman, G. (2005) Sol. Phys. **203**, 169
Harder J.W., Fontenla, J., Pilewskie, P., Richard E., and Woods T. (2009) GRL **36**, L07801
Kodera, K. and Kuroda, Y. (2002) JGR **107**, 4749
Lean, J. (2000) GRL **27**, 2425
Rast, M.P., Ortiz, A., and Meisner, R.W. (2008) ApJ **673**, 1209
Rempel, M. (2005) ApJ **622**, 1320.
Rind, D., Lean, J., Lerner, J., Lonergan, P., and Leboissitier, A. (2008) GRL **113**, D24103
Spruit, H.C. (2003) Sol. Phys. **213**, 1
Severino, G, Straus, T., and Steffen, M. (2008) Sol. Phys. **251**, 549
Schunk, R.W. and Nagy, A.F. (2009) Ionospheres, Cambridge University Press
Thuillier, G., Foujols, T., Bolsée, D., Gillotay, D., Hersé, M., Peetermans, W., et al. (2009) Sol. Phys. **257**, 185
van Loon, H. and Labitzke, K. (2000) GRL **27,** 2965
van Loon, H., Meehl, G.A., and Shea, D.J. (2007) JGR **112,** D02108