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Spectroradiometry for Solar Physics in Space

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Realistic physical and chemical descriptions of the Sun require observations that have been made with spectroradiometrically calibrated telescopes and spectrometers, i.e., with instruments that have a known spectral responsivity. Such calibrations assure that a measured spectral radiance or irradiance is determined on a scale that is defined by the radiometric standards realised and used in laboratories.

For ground-based observations of the Sun in the visible or near-infrared spectral regions, comparisons with laboratory standards of radiance or irradiance are relatively straightforward. However, measurements at shorter or longer wavelengths, or measurements of the total solar irradiance with a radiometric accuracy to within one part in 1000 that is indispensable for climatology today, require observations outside the atmosphere. For these the spectral responsivity of the instrumentation must be known.

Calibrating telescope-spectrometer combinations for the wide wavelength range of space observations is a complex and problematic task, particularly for extended space missions. Satellite telescope-spectrometer combinations can be calibrated before launch in the laboratory by use of appropriate primary or secondary radiance or detector standards. We review such standards and their use in the context of the SOHO instrument calibrations and we note limitations in accuracy and coverage of parameter space.

Environmental influences, such as contamination on the ground and the influence of radiation in space may, however, cause the spectral responsivity of satellite instruments to change between laboratory calibration and initial operation in space and during the subsequent long period of orbital operations. In-orbit monitoring and validation of the responsivity of a satellite instrument is, therefore, necessary. This has been achieved for SOHO by intercomparisons of the responses of the various Instruments when a common source is viewed, by observations of stars, and by under-flights.

In the past, solar physics has often been a trailblazer for new astronomical techniques. The efforts to calibrate solar observations as they are reported in this book should therefore be of interest for astronomy as a whole.

2.1 Introduction

The advent of spectroscopy in solar physics led, about 100 years ago, to the development of astrophysics. Today, our knowledge of the Universe is, in part, based on spectroradiometric[1] observations, i.e., on the determination of the spectral irradiance or spectral radiance[2] of a variety of objects and over a wide range of wavelengths. Such measurements require determination of the number, the spectral and, in case of the radiance, also the spatial distribution of photons from an object that arrive in the focal plane of an observer's telescope. When combined with atomic and molecular data, spectroradiometrically accurate observations provide evidence for deriving temperatures, densities, elemental abundances, ionisation stages, and flow and turbulent velocities in objects that are in the gaseous or plasma state. In this way, we elucidate the physical structure and chemical composition of astronomical objects, as well as the processes that cause them to emit and evolve. Such observations also provide similar insight into properties of plasma, gas, and dust in interplanetary, interstellar, and intergalactic space.

Because rigorous science requires accurate data, solar physicists should insist that their spectroradiometric observations are traceable to laboratory standards through sufficiently frequent and thorough spectroradiometric calibration. This implies determination of the spectral responsivity, i.e., the effective area of a telescope-spectrometer combination as a function of energy or wavelength.[3]

In Section 2.2, we consider the laboratory basis for radiometric calibration, and discuss, with explicit attention to solar physics, the transfer of the calibration to satellite instruments. In Section 2.3, we discuss specific cases of solar satellite instrument calibrations and introduce the calibration of telescope-spectrometer combinations on the Solar and Heliospheric Observatory (SOHO).

The radiometric inter-calibration of SOHO is an example of an effort to reconcile the responsivities of all the spectroradiometric instruments on a spacecraft under real-time operations and without recourse to stellar atmosphere modelling, such as that used for the radiometric calibration of the Hubble Space Telescope [*Colina and Bohlin*, 1994].

The effort described in this book originally had a purely scientific aim, namely to assure a correct physical interpretation of the SOHO observations. In the meantime, this effort has also attained a practical use: irradiance measurements by SOHO instruments are today directly flowing into data sets that are made available for operational purposes (cf. [*McMullin et al.*, 2002b]).

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[1] In astronomy, the term *photometry* is often used when dealing with broadband intensity measurements; those with higher spectral resolution are called *spectrophotometry*. However, in the terminology of physics, photometry refers to intensity determinations that are relevant to human vision. Therefore, we have chosen to use the terms *radiometry* or *spectroradiometry* in this paper.

[2] If an object is not spatially resolved, irradiance, I, the power detected per unit area (i.e., W m^{-2}; often, loosely, called flux) is measured. *Spectral* irradiance refers to the irradiance per energy (or wavelength) interval at a given energy (or wavelength), i.e., W m^{-2} eV^{-1} (or W m^{-2} nm^{-1}). Radiance, R, is the power emitted per unit area per unit solid angle, i.e., W m^{-2} sr^{-1} [*Grum and Becherer*, 1979]. *Spectral* radiance refers to the radiance per energy (or wavelength) interval at a given energy (or wavelength), i.e., W m^{-2} sr^{-1} eV^{-1} (or W m^{-2} sr^{-1} nm^{-1}). If the distance, d, to a uniformly emitting object of area, S, is known, then the irradiance is related to the radiance by $I = R(S/d^2)$.

[3] The effective area of an instrument is the equivalent collecting area of an ideal instrument, i.e., of an instrument that detects incident radiant energy with a responsivity of 100 %.

2.2 The Laboratory Basis for Spectroradiometry and its Transfer to Orbit

Any spectroradiometric measurements that are performed on the Sun or other astronomical object with the aim of deriving physical properties must be traceable to, i.e., ultimately based on a comparison with, primary laboratory standards, i.e., on absolute radiation sources or detectors that can be realised in the laboratory [*Cook*, 1994].[4] In this Section we discuss the primary standards for laboratory radiometry and general ways of applying them to the spectroradiometric calibration of solar spectrometric space telescopes. We also consider calibration changes during an instrument's orbital lifetime and how one can determine changes from the laboratory calibration once an instrument is in orbit.

2.2.1 Primary Radiometric Standards

Ideally, there would be one primary standard for absolute spectroradiometry. However, because of the large range of radiance and irradiance as well as energy (or wavelength) of electromagnetic radiation studied in science and its applications, practical considerations and current technology have resulted in four. There are two emission, or source, standards – black bodies and electron (or positron) storage rings – and two detector standards – double-ionisation chambers and cryogenic electric substitution radiometers (ESRs).

Black bodies [cf., *Kaase et al.*, 1984] are emission standards based on thermodynamics: the radiation from a black body is related to its temperature by the Planck law. To optimise the accuracy of these standards, they are normally operated at the melting temperature of an appropriate metal.

Electron or positron storage rings [cf., *Madden et al.*, 1992] are standards based on electrodynamics. Here, the *Schwinger* [1949] formula is used to calculate the synchrotron radiation emitted by accelerated charged particles. Inputs required for the calculation are the energy and current of the stored beam, as well as the magnetic induction at the point where the radiation is emitted; small corrections are required to account for the finite vertical extent and divergence of the particle beam.

Rare-gas double-ionisation chambers are detector standards based on the fact that the photo-ionisation yield of various rare gases, present in an optically thick column, is unity from 22.8 nm, the second ionisation threshold for He, to 101.2 nm, the first ionisation threshold for Xe [*Samson*, 1964; *West*, 1998].

Cryogenic ESRs [cf., *Möstl*, 1991] are detector standards that are based on accurate current and voltage measurements. The temperature increase of an irradiated cavity cooled to liquid helium temperature is compared by a null method with the temperature increase caused by deposition of accurately measured electrical power into an equivalent cavity. Although corrections for reflections, scattering, and diffraction must be made, cryogenic ESRs are accepted as the most accurate radiometric standards [*Fox and Martin*, 1990].

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[4] The criterion for a primary standard is that it can give a result directly without the need for any calibration relative to the quantity being measured. One must be able to write down its operating equation in full without any unknown (or empirically determined) constants or functions that are a function of the quantity being measured [*Quinn*, 2001]. By international convention, namely through the International Committee for Weights and Measures (CIPM), standards are given in terms of the units defined by the Système International (SI).

The Accuracy with which the radiometric scales are realised by synchrotron radiation, black bodies (at $\lambda > 650$ nm) and cryogenic substitution radiometers has been evaluated by *Stock et al.* [1993]. Their uncertainty analysis, carried out for visible radiation, indicated that synchrotron radiation, black bodies and cryogenic ESRs produced and detected spectral radiant intensity[5] with uncertainties of 0.1 %, 0.07 % and 0.007 %, respectively.[6] *Thornagel et al.* [1996] measured emission from an electron storage ring with a cryogenic radiometer and found agreement between the two primary standards within 0.3 % at a photon energy of 15 keV and 0.08 % for visible radiation; in the latter case confirming the analysis by *Stock et al.* [1993].

For the vacuum ultraviolet (VUV) spectral domain, which is of prime interest in this paper, black bodies are not suitable, since their VUV spectral radiance is very low (cf. Figure 1 of *Hollandt et al.* [1996b; 2002]). Similarly, for practical reasons, rare-gas double-ionisation chambers are infrequently used in laboratory calibrations.[7] Thus, the primary standards used in laboratory calibrations of the VUV radiometric responsivity of spectrometric space telescopes are storage rings and cryogenic radiometers.

2.2.2 Secondary Standards

Storage rings are large, complex, and expensive; cryogenic radiometers are less so, but still inconvenient for routine laboratory applications. Therefore, it is often more practical to use simpler, stable sources or detectors, known as transfer standards, that are themselves calibrated by comparison with a primary standard. Examples include D_2 lamps [*Saunders et al.*, 1978], tungsten-filament incandescent lamps [*Bass*, 1995], hollow-cathode [*Hollandt et al.*, 1994] and Penning [*Heise et al.*, 1994] discharges, as well as silicon photodiodes [*Canfield et al.*, 1998a; *Gullikson et al.*, 1996], trap detectors [*Fox*, 1991], and metal photo-emissive diodes [*Bass*, 1995; *Canfield*, 1998b].

2.2.3 Radiometric Calibration of Spectral Irradiance Detectors and Telescope-Spectrometer Combinations for Use in Space

In modern solar astronomy from space, an assortment of four methods is used to calibrate irradiance detectors as well as telescope-spectrometer combinations:

- Calibration by use of a primary or secondary standard that is operated in orbit as part of the scientific payload. Standards carried into orbit can seldom be used to assure a calibration "end-to-end", i.e., from entrance aperture to detector output, of a telescope-spectrometer system. However, they have been employed for monitoring the stability of irradiance detectors.
- Pre-flight calibration in the laboratory by end-to-end, component, and/or subsystem level tests, with radiometric standards being employed where required.
- Calibration of an orbiting telescope-spectrometer combination by comparing simultaneous observations of the same source made by both the telescope-spectrometer

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[5] *radiant intensity* is a radiometric quantity whose SI unit is W sr^{-1}.

[6] Unless otherwise indicated, all uncertainties in this paper are given in terms of one relative standard uncertainty, i.e., with a 68 % confidence limit.

[7] See, however, *Wienhold et al.* [2002], for an application as an in-orbit standard.

combination to be calibrated and a similar instrument flown on a sub-orbital rocket or the Space Shuttle. The latter measurement, sometimes referred to as an "underflight", uses instruments that are calibrated with a radiometric standard in the laboratory before and after use in space.

- Calibration in orbit by what are called "celestial standards", i.e., by stars or other astronomical objects whose spectral irradiances are stable and have been determined earlier.

Use has also been made of the physical principles underlying the optical characteristics of given components in predicting the performance of instruments [*Rosa*, 1997]. Given a few benchmark measurements, such predictions can be used to interpolate from responsivity measurements at a few values of instrument parameters into a continuous calibration space.

2.2.4 Monitoring the Stability of Spectral Responsivity

Unless extreme care is exercised, the consequences of contamination of optical surfaces can be dramatic for a solar telescope in space. Surface layers that originate from exposure to pre-launch environments or from "outgassing" from the spacecraft bus and payload itself cause changes in performance when exposed to the harsh electromagnetic and particle emission from the Sun.[8] The variability of the VUV radiation of the Sun [*Solanki*, 2002] compounds the problem: disentangling solar variations from changes in calibration is often not trivial. Underflights are, therefore, usually required.

Unless on-board radiometric standards that calibrate the overall system from end to end, or reliable celestial standards that are confirmed to be stable and can be compared easily with solar radiation, are available, it is particularly difficult to detect whether a change in the spectroradiometric responsivity has occurred between laboratory calibrations and measurements in orbit.

2.3 Absolute Calibration of Solar Instruments onboard Spacecraft

2.3.1 Solar Total Irradiance Monitors

In order to demonstrate connections between laboratory primary standards and radiometrically accurate observations of the Sun, we start with a discussion of total solar irradiance monitors. A number of these are directly traceable to primary laboratory standards.

The most accurate radiometric instruments operated in space are electric substitution radiometers (ESRs), such as the Active Cavity Irradiance Monitors (ACRIM) [*Willson*, 1999] on the Solar Maximum Mission (SMM) [*Bohlin et al.*, 1980; *Chipman*, 1981] and the Upper Atmosphere Research Satellite (UARS) [*Reber et al.*, 1993], and the Differential Absolute Radiometers (DIARAD) and PMO6-V instruments that are part of the Variability of Solar Irradiance and Gravity Oscillations (VIRGO) [*Fröhlich et al.*, 1995] package on SOHO. These ESRs operate at about 300 K and, in principle, have measurement uncertainties at the 0.2 % level [*Fröhlich and Lean*, 1998]. Nevertheless, significant adjustments of

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[8] How such contamination has been minimised for SOHO is summarised in this volume by *Thomas* [2002].

the data from given instruments – adjustments that are justified by apparent degradations and changes in observing parameters – have been required [*Fröhlich*, 2002]. Moreover, in order to make a plausible time series out of data sets that cover different periods and were obtained by different instruments, the absolute scale of some measurements had to be shifted by up to 0.5 % to make them fit onto the Space Absolute Radiometric Reference Scale [*Crommelynck et al.*, 1995]. The need for such data reconciliation, which exceeds the expected instrument uncertainties, demonstrates the problematic nature of absolute radiometry from space platforms and the need for improvements in instrumentation.

The variations in the total solar irradiance – variations that are relevant to understanding the influence of the Sun on the climate of the Earth – are thought to be at the 0.1 % level. *Quinn and Fröhlich* [1999] suggest that the next generation of instruments for such measurements should employ a primary standard, namely a cryogenic ESR whose measurement uncertainty is 0.05 % or better.

2.3.2 A Solar EUV Broadband Radiometer

The SOHO spacecraft carried a Solar Extreme-ultraviolet Monitor (SEM) that was described as “highly stable” [*Hovestadt et al.*, 1995]. SEM comprised a freestanding 5000 l/mm transmission grating, aluminium-coated silicon photodiodes, and aluminium filters that defined the bandpass. SEM was designed to measure the He II 30.4 nm irradiance from the Sun as well as the integrated flux between 17 nm and 70 nm.

Although originally assumed to be insensitive to in-flight degradation in radiometric performance, the responsivity of SEM is now believed to have decreased by about 15 % over a period of 400 d at 30.4 nm [*McMullin et al.*, 2002a]. This change in performance was discovered as a result of a series of pre-planned, dedicated underflights – an experience that points to the need for such measurements for all space experiments that require radiometric accuracy.

2.3.3 Solar Spectral Irradiance Measurements

The only satellite spectrometers with true, on-board, *spectral* irradiance calibration capabilities that permit efficiency changes to be tracked from the time of laboratory calibration through integration, launch, and years of use in orbit are the Solar Ultraviolet Spectral Irradiance Monitors (SUSIM) [*VanHoosier et al.*, 1988; *Brueckner et al.*, 1993]. These have modest spectral resolving power and no telescope, but monitor the full-disk VUV and UV solar spectral irradiance in the wavelength band that drives the photochemistry of the Earth’s ozone layer. The SUSIMs, which have observed the Sun several times from the Space Shuttle and from the UARS, comprise several spectrometers and four D_2-lamp transfer standards, which have significantly different duty cycles. The initial spectrometer calibrations were established in the laboratory by direct comparison with synchrotron radiation. During orbital operations, one of the spectrometers is not used to view the Sun, since this could contribute to degradation in performance, but only to monitor relative changes in the output of the D_2 lamps.

The Solar Stellar Irradiance Comparison Experiment (SOLSTICE) [*Rottman and Woods*, 1994] is also part of the UARS instrument complement and monitors the full-disk solar spectral irradiance with approximately the same resolution and spectral range as SUSIM. SOLSTICE was calibrated using synchrotron radiation before launch, but has no on-board calibration lamp per se. Instead, SOLSTICE tracks changes in its responsivity by comparing solar irradiances to those of hot stars that are thought to have negligible variability. The set of stars is large enough that changes in the instrument can be disentangled from unexpected stellar variability by comparing each star to the ensemble average. Moreover, excessive variability was not expected, since the stars in question had earlier been observed by IUE and HST. Two potential difficulties with SOLSTICE measurements are: (i) possible undetected change in the instrument responsivity between pre-launch calibration and in-orbit observations, and (ii) the large dynamic range, about 10^{8}, over which accurate radiometry is required. Different exposure times and a wide range of spectrometer entrance and exit apertures accommodate this range. However, the aperture differences mean that the solar and stellar observations use different fractions of the spectrometer optics, which may be non-uniform in performance. Careful instrument design and weekly monitoring of relevant non-uniformities indicated that their influence remained within a few percent over the ten-year UARS mission.

The UARS SUSIM and SOLSTICE instruments have monitored the VUV solar irradiance regularly and simultaneously since 1992. *Woods et al.* [1996] compared the results and those of several other VUV solar irradiance monitors. The difficulties in making spectral irradiance measurements are demonstrated, in part, by the delay between the launch of UARS and the publishing of this comparison: despite the emphasis on careful pre-flight calibrations, protection of the instruments from contamination, and onboard calibration (SUSIM) and efficiency tracking (SOLSTICE), early results did not agree. Extended observations gave the observing teams additional insight into their instruments, especially scattered light properties, and now there is confidence that the two instruments agree and both provide regular, accurate measurements of the VUV solar spectral irradiance within the uncertainty limits.

The next generation of solar spectral irradiance instruments is represented by the Solar EUV Experiment (SEE) on the TIMED spacecraft [*Woods et al.*, 1998] and the Spectral Irradiance Monitor (SIM) [*Rottman et al.*, 1998; *Lawrence et al.*, 1998]. The latter is particularly interesting because it incorporates a very sensitive ESR as a detector in its focal plane and a dual spectrometer arrangement that allows degradation in orbit to be tracked.

2.3.4 Telescope-Spectrometer Combinations for Solar Spectral Radiometry

Solar physicists have attempted spectroradiometric measurements of the solar radiance from space since the 1960s. The telescope mirrors and spectrometers on the Orbiting Solar Observatories OSO-4 and OSO-6 were separately calibrated before launch with transfer standard photodiodes [*Reeves and Parkinson*, 1970; *Huber et al.*, 1973]. However, it was shown during these calibrations that spatial non-uniformities in the diffraction efficiency of a concave grating, which was used in the calibration facility to produce a monochromatic test beam, introduced an inherent uncertainty of at least 10 % [*Huber et al.*, 1973] into the radiometric pre-launch calibration. Such optical non-uniformities have also affected the responsivity of the CDS [*Lang et al.*, 2000] and UVCS [*Gardner et al.*, 2000] instruments on SOHO. The calibration of the S-055 spectrometer on Skylab [*Reeves et al.*, 1977a] was similar to that of the OSO-6 instrument [*Reeves et al.*, 1977b] and performance was monitored during the mission by means of underflights [*Timothy et al.*, 1975]. Nevertheless, the ultimate S-055 radiometric accuracy was insufficient to disentangle possible changes in the instrument sensitivity from variations in the VUV output of the Sun.

The radiometric calibration of the spectroheliometer flown on OSO-8 was also established in the laboratory [*Arztner et al.*, 1977; *Bonnet et al.*, 1978]. This instrument had a Cassegrain telescope and suffered a large loss of responsivity in orbit. A similar instrument, also first flown on OSO-8 [*Bruner*, 1977], was part of the payload of the Solar Maximum Mission (SMM). This instrument, in its second version, had a Gregorian telescope and featured a polarimetric capability. Data on the responsivity of the SMM-spectroheliometer were published [*Woodgate et al.*, 1980], albeit without an assessment of uncertainties.

2.3.5 Solar Spectroradiometric Telescopes on SOHO

This book reports on spectroradiometric calibrations for the SOHO mission [*Fleck et al.*, 1995] and covers the most comprehensive effort to date to achieve accurate solar spectroradiometric measurements from space. The SOHO mission required extreme cleanliness in construction, integration, and launch operations so that changes in performance in orbit would be minimised [*Thomas*, 2002].The spacecraft builders worked with a cleanliness requirement of a few hundred nanogram of condensable and particulate contamination per square centimetre, while the instrument teams aimed for even less. The minimal deterioration in the responsivity of these instruments over the course of the SOHO mission [*Pauluhn et al.*, 1999; 2001; *Schühle et al.*, 2002; *Gardner et al.*, 2002] is attributable to the cleanliness achieved.[9]

UVCS

The spectroradiometric efficiency of the Ultraviolet Coronagraph Spectrometer on SOHO (UVCS) [*Kohl et al.*, 1995] was determined before launch at selected wavelengths by use of transfer-standard photodiodes that had been calibrated at the U.S. National Institute of Standards and Technology (NIST). A one-meter spectrometer selected a narrow wavelength band from an external light source and a large collimating mirror produced a simulated solar beam [*Gardner et al.*, 1996]. The results, which had an estimated uncertainty of 16 %, have been confirmed [cf., *Gardner et al.*, 2002] by underflights with the Spartan 201 Shuttle-deployed coronal spectrometer.

Annual observations of stars that pass through the field of regard of UVCS have shown changes in responsivity that are functions of aperture, i.e., of the position of the UVCS internal occulter. At the standard aperture width[10] of 11 mm, the decrease in responsivity appears to be 7.5 % per year [*Gardner et al.*, 2002]. This decrease has been confirmed by *Valcu et al.* [2002], who compared spectra of ζ Tau obtained with the two UV channels of UVCS in the 117 nm to 125 nm region with spectra obtained by IUE.

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[9] However, it is worth mentioning that some of the detectors flown on SOHO were not those originally foreseen. The replacements required a gain that was too high for solar applications and, as a consequence, lost gain prematurely in regions of the detector where the total number of detected counts was large. The high voltage on the replacement detectors therefore had (and still has) to be increased periodically, so that their responsivity could be maintained over the mission.

[10] UVCS is a coronagraph with external and internal occulters. Adjustment of the latter, which is done to reduce the level of scattered light, changes the aperture.

Because of limited resources and instrument constraints, it was not possible to calibrate UVCS before launch over the full range of instrument apertures used in science observations. In-orbit studies and laboratory tests using replicas of the flight gratings have shown that, because the diffraction efficiency of the gratings is not uniform across their surface, the effective area of the UVCS O VI and Ly-α channels are slightly non-linear functions of the width of the apertures [*Gardner et al.*, 2000; 2002].

The performance of the UVCS gratings and detectors is instructive to those who attempt to model the performance of complex instruments from first principles [*Rosa*, 1997; *Ballester and Rosa*, 1997]: it is often difficult to predict the behaviour of state-of-the-art optical components, including detectors, and coatings – and the inevitable contaminants – over the complete range of physical dimensions, optical angles, wavelengths, and accumulated signal expected in use. Thus, performance models should be verified with benchmark measurements over as much parameter space as possible.

SUMER

The spectroradiometric efficiency of SUMER, the Solar Ultraviolet Measurements of Emitted Radiation instrument on SOHO [*Wilhelm et al.*, 1995], was measured prior to launch [*Hollandt et al.*, 1996a] by using a source standard that was calibrated by comparing it with synchrotron radiation [*Hollandt et al.*, 1996b]. [11] The source standard consisted of a hollow cathode, which emitted a line spectrum, and a spherical normal-incidence collimating mirror. The collimated beam had a diameter and divergence of (10 ± 1) mm and $\pm 1'$, respectively. In the laboratory calibration of SUMER, the image of the flux-limiting aperture of the hollow cathode underfilled the aperture in the focal plane of the telescope, which is, at the same time, the entrance slit plane of the spectrometer. An unobstructed observation of the entire source radiation was thus achieved and spectroradiometric responsivities that included the reflectivities of all optical surfaces, the grating efficiencies, as well as the detector performance could be established. Indeed, appropriate combined articulations of the source and telescope mirror also permitted mapping of the responsivity of the instrument as a function of the light beam's position within the the entrance pupil. The pre-launch calibrations have subsequently been further refined under operational conditions [*Wilhelm et al.*, 1997; *Schühle et al.*, 2000].

CDS

The spectroradiometric responsivity of CDS, the Coronal Diagnostic Spectrometer [*Harrison et al.*, 1995], was measured prior to launch in a manner similar to that used for SUMER, i.e., by using a source standard that had been calibrated by comparing it to synchrotron radiation. But, in this instance, a Wolter type-II telescope served as the collimator [*Hollandt et al.*, 1996b] and the collimated beam was limited to 5 mm diameter when it left the telescope. The nominal divergence was $\pm 30''$. Inside its vacuum tank, the CDS

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[11] The calibration of the transfer source standard was performed by the Physikalisch-Technische Bundesanstalt (PTB) Berlin by use of the BESSY (Berlin Electron Storage Synchrotron) storage ring. It was verified in the course of this calibration that the radiometric scale of the source standard agreed with that of a NIST photodiode: a NIST photodiode generated the signal expected from the photon flux in the helium lines, when it was illuminated by the collimated beam of the source standard, run with helium gas (cf. [*Hollandt et al.*, 2002]). Although this was not a high-quality metrological comparison of the NIST and PTB scales, the test provided an important reassurance within the aimed-for accuracy.

instrument could be moved perpendicular to the beam while the optical axis was maintained, so that the instrument apertures that illuminated the grazing- and normal-incidence gratings could be mapped. The laboratory calibration of CDS [*Lang et al.*, 2000] turned out to be a much more complex undertaking than that of SUMER. Several reasons contributed to this, for example, the collimated beam was not uniform, i.e., showed structure in its cross section, and exhibited an angular divergence exceeding its nominal value by nearly a factor of four.

In-orbit Comparisons with Stellar Spectra

It is of interest to compare the calibrations of instruments designed for observations of the Sun, such as those on SOHO, with those designed for observing night-sky objects. Such a comparison informs us about whether the realised radiometric scales for solar and stellar ultraviolet observations agree with each other within the expected uncertainty limits. The comparison is more than a check on the correct application and transfer of the laboratory standards, because in a pragmatic but debatable course of action, observers using some of the space telescopes for night-sky objects, such as IUE, Voyager, and, most importantly, the Hubble Space Telescope, made use of stellar models rather than laboratory standards to establish the ultraviolet responsivity.[12] Other space telescopes, the Hopkins Ultraviolet Telescope (HUT) [*Kruk et al.*, 1999], for example, are traceable to primary standards and have pre- and post-flight calibration or are validated by underflights.

UVCS observations early in the SOHO mission show that its radiometric scale agreed with that of IUE to within measurement uncertainties [*Valcu et al.*, 2002; *Gardner et al.*, 2002]. Other intercomparisons with stellar observations are in progress [*Lemaire*, 2002; *Wilhelm et al.*, 2002].

2.4 Conclusions and Outlook

The ISSI Team Workshop on the Radiometric Inter-Calibration of SOHO and this volume are testimony to the fact that the calibration of SOHO was performed with foresight, care, and regard for an approach that involved traceability to primary radiometric standards. Such laboratory standards provide a basis for obtaining accurate physical information from radiometric observations.

The Team Workshop dealt with radiometric calibration only. However, the overall calibration of a telescope-spectrometer combination requires that a number of additional quantities be determined: the pointing accuracy and stability, plate-scale, on- and off-axis point-spread functions, the spacecraft reference frame, flat-field maps, straylight and the occurrence of ghost images, counting non-linearities, dark counts, and lengths of observation intervals. We enumerate these measurement parameters here for the sake of completeness, and note that some of them must be known for a proper spectroradiometric calibration as well.

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[12] The accuracy of 3 % claimed for the responsivity of HST in the ultraviolet, which is better than our knowledge of the solar ultraviolet radiometric spectrum, may, in fact, be correct, and an intercomparison with solar radiometric scales may seem superfluous. Yet, the reader is reminded that exquisite accuracy for the mirror shape of HST was claimed before the presence of spherical aberration was discovered. Unexpected discrepancies are always possible before an experimental check has been made.

The SOHO concern for all aspects of calibration has not been common for satellite missions. In the past, many astronomical findings have been made in spite of what may be considered a cavalier attitude toward spectroradiometric instrument calibration. Given time pressures in a competitive environment, some might argue that timely launch of many astronomical missions was achieved as a result of such neglect and that suppression of in-orbit calibration runs gained more, albeit uncalibrated, observing time. However, we note that it is the data quality and not the data quantity that enables scientific discovery: long observations that result in a statistical accuracy significantly greater than the radiometric accuracy are often unnecessary.

A growing tendency towards more accuracy in astronomy will make reliable calibration of observing instruments more and more of a necessity. As many calibrated quantities are susceptible to change during orbital operations, or as consequence of particular events such as spacecraft eclipses or large solar flares, frequent in-orbit monitoring of the various parameters is also necessary.

As pointed out in the Foreword, in many astronomical projects involving spectroradiometric measurements from space, there often occurs a conflict between calibration and other program goals during assembly, integration, and verification phases. When resources are constrained, calibration activities, especially end-to-end spectroradiometric measurements, are frequently the first to be sacrificed. Moreover, it is not uncommon today, for effort to be spent on in-orbit calibration observations intended to recover parts of a missed laboratory calibration. Fortunately, the SOHO observers had benefited from a comprehensive understanding of the instruments and their calibration that had been achieved in the laboratory before launch.

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A broader view of radiometric calibration of space instruments by the authors is in preparation.

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