

Radiometric Characterization of Space Instrumentation

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Year of Calibration	Wavelength Range/ nm	Instrument	Mission
1994	50 to 160	SUMER <i>Solar Ultraviolet Measurements of Emitted Radiation</i>	SOHO <i>Solar and Heliospheric Observatory</i>
1994	15 to 80	CDS <i>Coronal Diagnostic Spectrograph</i>	
1996	15 to 80	SERTS <i>Solar EUV Rocket Telescope and Spectrograph</i>	
1997	0.1 to 10	Chandra	
1998	0.1 to 10	EPIC <i>European Photon Imaging Camera</i>	XMM Newton X-ray Multi Mirror
1998	1 to 20	SEE XPS <i>Solar EUV Experiment XUV Photometer System</i>	TIMED <i>Thermosphere Ionosphere Mesosphere Energetics and Dynamics</i>
1998	1 to 20	XPS <i>XUV Photometer System</i>	SORCE <i>Solar Radiation and Climate Experiment</i>
2004	115 to 135	TWINS <i>Two Wide-Angle Imaging Neutral-Atom Spectrometers</i>	
2004	15 to 80	EIS <i>EUUV Imaging Spectrometer</i>	SOLAR-B
2005	15 to 80	MOSES <i>Multi-Order Solar EUV Spectrograph</i>	
2005	0.02 to 0.1	GBM <i>Gamma ray Burst Monitor</i>	Fermi <i>Gamma-Ray Space Telescope</i>
2007	17 to 37	EUNIS <i>Extreme Ultraviolet Normal Incidence Spectrometer</i>	
2005 2006 2007	1 to 240	LYRA <i>Lyman-alpha Radiometer</i> SWAP <i>Sun Watching using APS</i>	PROBA II <i>Project for On Board Autonomy</i>
2004 2006	10 to 240	SOL-ACES <i>Solar Auto-Calibrating EUV/UV Spectrophotometers</i>	SOLAR <i>Solar Monitoring Observatory / ISS</i>
2002 2007	10 to 240	SOL-SPEC <i>Solar Spectral Irradiance Measurement</i>	
2008	0.1 to 2.4	SphinX <i>Solar Photometer in X-Rays</i>	CORONAS
2009	0.1 to 12	eROSITA <i>extended Roentgen Survey with an Imaging Telescope Array</i>	Spektrum Röntgen Gamma
2011	0.1 to 2.5	MIXS <i>Mercury Imaging X-ray Spectrometer</i>	BepiColombo
2010 to 2016	10 to 240	EUI <i>Extreme Ultraviolet Imager</i>	SoI/O <i>Solar Orbiter</i>
2012 to 2015	70 to 105	SPICE <i>SPectral Imaging of the Coronal Environment</i>	

Figure 1: Overview of the calibrations of space instruments at PTB using synchrotron radiation. Source-based calibrations [1] are highlighted in yellow, whereas detector-based calibrations [2] are highlighted in blue.

Introduction

The Earth's atmosphere absorbs the short-wave fraction of the electromagnetic spectrum, starting with the ultraviolet (UV) spectral range up to the range of X-rays. This may be an important protection mechanism for life on the surface of the Earth, but it makes the exploration of space more difficult: measurements of the emission of stellar objects in this spectral range can only be carried out outside the Earth's atmosphere. Hereby, this fraction of the spectrum is of primary importance, not only for the observation and understanding of the astrophysical and solar processes, but also due to the intensive interaction with the Earth's outer atmosphere and the corresponding climatological and chemical significance of the atmosphere.

To ensure reliable and comparable measurements of space-based instruments, these have to be carefully characterized and traced to radiometric standards. For more than 20 years now, PTB has, within the scope of numerous joint research projects with external partners, established itself as the world leader in characterizing space instrumentation by means of synchrotron radiation in the spectral ranges from UV radiation to X-rays. Various technologies were used for the radiometric support of a series of missions – most of them dedicated to solar radiometry. Another important point is, especially in the X-ray range, the characterization of imaging X-ray-optical elements; for this task, the European Space Agency (ESA) ordered its own beamline section. Figure 1 shows a selection of instruments that were characterized or calibrated by PTB using synchrotron radiation. The different colors serve to differentiate instruments where the method is source-based (yellow) [1] from those where it is detector-based (blue) [2]. Starting with the supply and calibration of transfer standards for the *Solar and Heliospheric Observatory* (SOHO) in 1994 [3], methods and

instrumentation have constantly been developed. Since 2013, a dedicated vacuum tank for the calibration of flight instrumentation of up to 1.20 m in length and a mass of up to 100 kg has been available at the *Metrology Light Source* (MLS) (see Fig. 2). It was used for the first time to calibrate the spectrometers for the *Solar Orbiter* (SolO) mission starting in 2018 – which is the direct successor of the SOHO mission.

Source-based calibration of spectrographs for solar radiometry

The source-based calibration of spectrographs can be carried out either directly with the calculable primary radiation of the electron storage ring, or with the aid of transfer radiation sources whose calibration is, in turn, traced to the electron storage ring as a primary source standard. Calibration using the first method must be categorically carried out at the electron storage ring, so that the required infrastructure (e.g. an adequate vacuum chamber, cleanroom environment, etc.) must therefore be available. With its flexible operation modes, the MLS is an ideal source for this task. It allows variation of the spectral radiant intensity over a wide range by adapting the electron current correspondingly. This allows, for example, the linearity and the saturation behavior in the responsivity of the spectrometer to be investigated. The spectral slope of the radiation can be changed by adapting the electron energy. At the MLS, the electron energy can be reduced from the nominal value of 630 MeV down to 105 MeV, so that shorter wavelengths, which could possibly lead to higher diffraction orders in the spectrographs under calibration, are considerably suppressed. One of the advantages of direct calibration is that transfer sources can be dispensed with, thus allowing smaller uncertainties. Also, calibration is possible at all wavelengths, since synchrotron radiation supplies a continuous "white" spectrum. Last but not least, large inlet apertures of the instruments can be illuminated as a whole. Attention must, however, be paid to the fact that synchrotron radiation is highly polarized, which may require two calibrations to be carried out at two orientations differing from each other by 90°, vertically from the incident radiation. Due to the white spectrum caused by the use of grating spectrographs, higher diffraction orders may occur; they must be suppressed by appropriate means. An example of this is the calibration of the SPICE (*SPECTral Imaging of Coronal Environment*) [4] spectrograph for the Solar Orbiter Mission. This spectrograph operates in diverse wavelength sections in the spectral range from approx. 45 nm to 110 nm. Using synchrotron radiation, it is possible to illuminate the whole inlet aperture of

43.5 mm x 43.5 mm – which would not be the case with the transfer sources available. For the calibration of the wavelength section around 100 nm, calibration can be carried out at a reduced electron energy of approx. 150 MeV. This allows the intensity ratio of 50 nm photons to 100 nm photons to be reduced by approximately two orders of magnitude compared with the MLS operated at nominal energy, so that the intensity of any possible higher diffraction orders is considerably reduced.

The calibrations of the spectrographs *Coronal Diagnostic Spectrometer* (CDS)[5] and SUMER (*Solar Ultraviolet Measurement of Emitted Radiation*) [6] of the SOHO mission are excellent examples of calibrations carried out using transfer sources provided by PTB. These spectrographs were calibrated at the respective institute of the instruments' developers (at the *Max Planck Institute for Solar System Research* (MPS) for SUMER and at the *Rutherford Appleton Laboratory* (RAL) for CDS). The calibration of the SOHO spectrographs was later validated several times by means of NASA's sounding rocket SERTS (*Solar EUV Rocket Telescope and Spectrograph*) whose calibration, in turn, took place at RAL, in cooperation with PTB, through the use of the CDS source. Numerous other examples of source-based calibration of spectrometers are shown in Figure 1. Hereby, the SUMER source, the CDS source or calibrated deuterium lamps were used as transfer radiators.

The above-mentioned SUMER and CDS transfer sources are based on a hollow-cathode discharge. Maintenance of the hollow cathode must take place after approximately 10 hours in operation, i.e. the cathode is replaced and the anode is

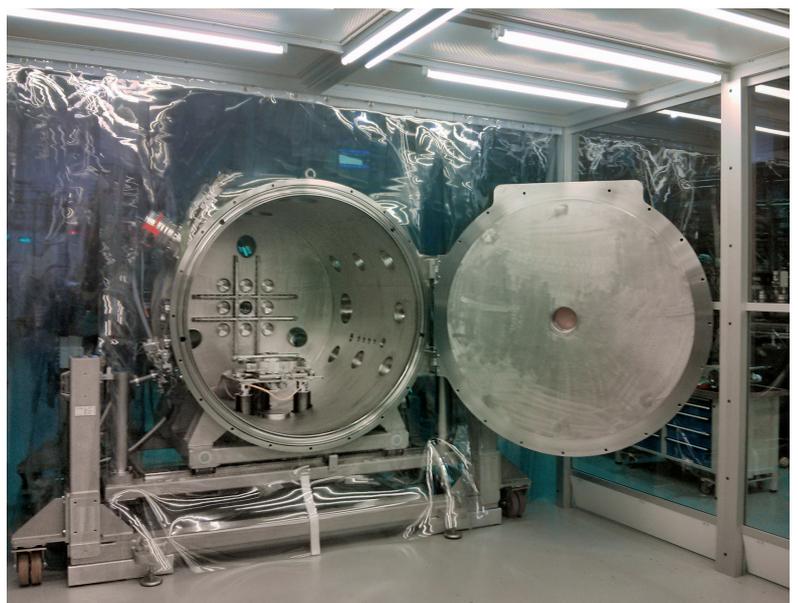


Figure 2: Large vacuum tank for the calibration of space instrumentation at the MLS. For loading and unloading, the tank is located in a cleanroom environment.



Figure 3:
View into the area of the MLS measuring hall that is used for the source-based calibration of space instruments. In the background (top right), one can see the large tank (Figure 2). The tank is flanged at the end of the beamline to utilize the direct, calculable radiation of the MLS. As an alternative, another source such as the SUMER transfer source (bottom right) can be positioned in the beam path. This source can be calibrated at the neighboring measuring station (top left) and traced to the MLS [1].

cleaned. Calibration by means of transfer sources taking place at PTB's lab instead of the home lab of the instruments' developer offers the possibility of re-calibrating the transfer source soon after maintenance, so that the calibration uncertainties which can be achieved with transfer sources are substantially improved. Figure 3 provides an overview of the laboratory area at the MLS which is used for source-based radiometry, with the beamlines and the measuring stations M2a and M2b [7].

Detector-based radiometric characterization of space instrumentation

Besides source-based radiometry [1], for which the electron storage ring is used as a calculable primary source standard, also detector-based radiometry with synchrotron radiation [2] is used to characterize and calibrate instruments with components for outer-space missions at the diverse corresponding beamlines at BESSY II and at the MLS [7]. Radiometric quantities are hereby traced to electrically calibrated cryogenic radiometers as primary detector standards for the measurement of absolute radiation power of monochromatized synchrotron radiation. Similar to the optical spectral range, semiconductor photodiodes have meanwhile established themselves as the respective transfer detector standards also in the range of UV and VUV radiation as well as for X-rays. Existing commercially available semiconductor photodiodes, however, do not live up to all the requirements of the actual detection systems in these short-waved spectral ranges. In general, high

requirements are placed on the spectral sensitivity of radiation detectors, especially with regard to radiation resistance. When used for space instrumentation, this not only includes resistance to the intensity of the radiation to be detected, but especially to particle radiation (e.g. protons) which they are exposed to in their operational environment [8]. In addition, particular requirements result from the fact that the detectors must be "solar blind", i.e. insensitive to visible and infrared radiation [9]. For this purpose, semiconducting wide-band-gap materials (such as aluminum gallium nitride) are used instead of silicon, so that the energy of the photons in the visible spectral range is not sufficient to generate a photocurrent. For spectrographs and imaging telescope systems, imaging detectors are developed which require spatially resolved characterization. Besides line-based detectors (*Charged Coupled Device, CCD*), components in which each pixel can be read out separately via a downstream on-chip electronic unit (*Active Pixel Sensor, APS*) [10] are increasingly being used.

Besides characterizing and calibrating radiation detectors, PTB also characterizes individual optical components (mirrors, filters, diffraction gratings) for space instruments with regard to their spectral reflection, transmission or diffraction efficiency, using the reflectometers available at PTB's laboratories [11]. Similarly to radiation detectors, hardness to all kinds of radiation is an important aspect for use also for optical components. Since it is possible to measure spectral properties with small relative uncertainties (1 % or better), the radiation hardness of different reflecting coatings or thin-film filters can be investigated by carrying out measurements before and after irradiation.

Complete spectrometer systems can also be calibrated by means of detector-based radiometry (Figure 1) by using monochromatized radiation. Whether an instrument is more suitable for source-based or for detector-based calibration cannot be answered categorically; in each individual case, it depends on the properties of the respective spectrometer (e.g. inlet aperture, angular acceptance, wavelength range, etc.).

X-ray astronomy

In the universe, usual matter is, for the major part, available in the form of hot gas. At temperatures of more than 10^7 K, the gas emissions are particularly intensive in the X-ray range. Since this type of radiation cannot penetrate the Earth's atmosphere, such investigations must be carried out in space using an X-ray observatory with high sensitivity, good spectral resolution and a large field of view. Observing the emission lines of different chemical elements provides information about the creation

and the development of black holes and of faraway galaxies under the influence of dark matter and dark energy.

At its former lab at BESSY I, PTB had already contributed to the calibration of the instruments for the two existing X-ray satellites XMM-Newton of ESA and Chandra of NASA [12, 13]. At PTB's lab at BESSY II, components for future X-ray missions of ESA are currently being investigated. One of the next large-scale missions, which will probably start in 2028, is dedicated to "The hot and energetic universe". For this purpose, the *Advanced Telescope for High-Energy Astrophysics* (ATHENA) has already been developed as the concept of the mission [14]; it is based on the concepts of the missions IXO (*International X-ray Observatory*) and XEUS (*X-ray Evolving Universe Spectroscopy*) which were, however, never implemented. The envisaged effective mirror surface of approx. 2 m² corresponds, at grazing incidence for, e.g., 1 keV radiation, to a real mirror surface of 600 m² which must be realized with small form errors and high rigidity whilst keeping it as lightweighted as possible. The solution consists in stacking many small mirror surfaces. With Si wafers with ribs on their reverse side, *silicon pore optics* (SPO) with a large number of mirror channels can be realized; their inlet aperture is typically 1 mm², and their length 70 mm (Figure 4, top) [15].

The quality of each of the mirror channels can only be investigated with a pencil beam at grazing incidence onto the reflecting surface. For this purpose, the *X-ray Pencil Beam Facility* (XPBF) has been set up at PTB's lab at BESSY II [7, 15]. Since 2005, the lab has been equipped with a collimated X-ray beam (diameter: 100 μm, divergence: < 5 μrad) with a fixed photon energy of 2.8 keV. For special investigations, it is, however, possible to set the energy to 1 keV or 7.6 keV. The mirror element to be investigated can be positioned with reproducibilities of 2 μm and < 5 μrad with the aid of a hexapod which is under vacuum (Figure 4, bottom) and whose displacement is checked by two optical autocollimators. An X-ray-sensitive CCD camera is located at a distance of 5 m from the optics; it can detect both the direct and the reflected beam. From the position and the shape of the reflected beam, statements concerning the local quality of the reflecting surface can be made, especially with regard to form errors.

Since a focal length of 20 m was planned for the IXO Mission, another positioning possibility of the CCD camera at exactly this distance was realized in 2010. For mirror systems that are designed as a Wolter telescope and contain two reflections, this distance presupposes, at an angle of incidence of up to 1.4°, a vertical translation of the camera of 2 m at a simultaneous inclination of approx. 5.6°.

Even though it was shown from the measurements carried out at a short distance of 5 m that it is possible, under certain conditions, to extrapolate to larger distances [16], a further beamline with a camera distance of approx. 13 m is planned for the ATHENA Mission.

Besides these measurements at the XPBF, mirrors as well as mirror coatings are also investigated in the X-ray range [17]. On the other hand, also detectors (such as DEPFET detectors for the Mercury Mission MIXS [18], pnCCDs for eROSITA [19] or scintillation detectors for the Fermi Gamma telescope [20]) are calibrated.

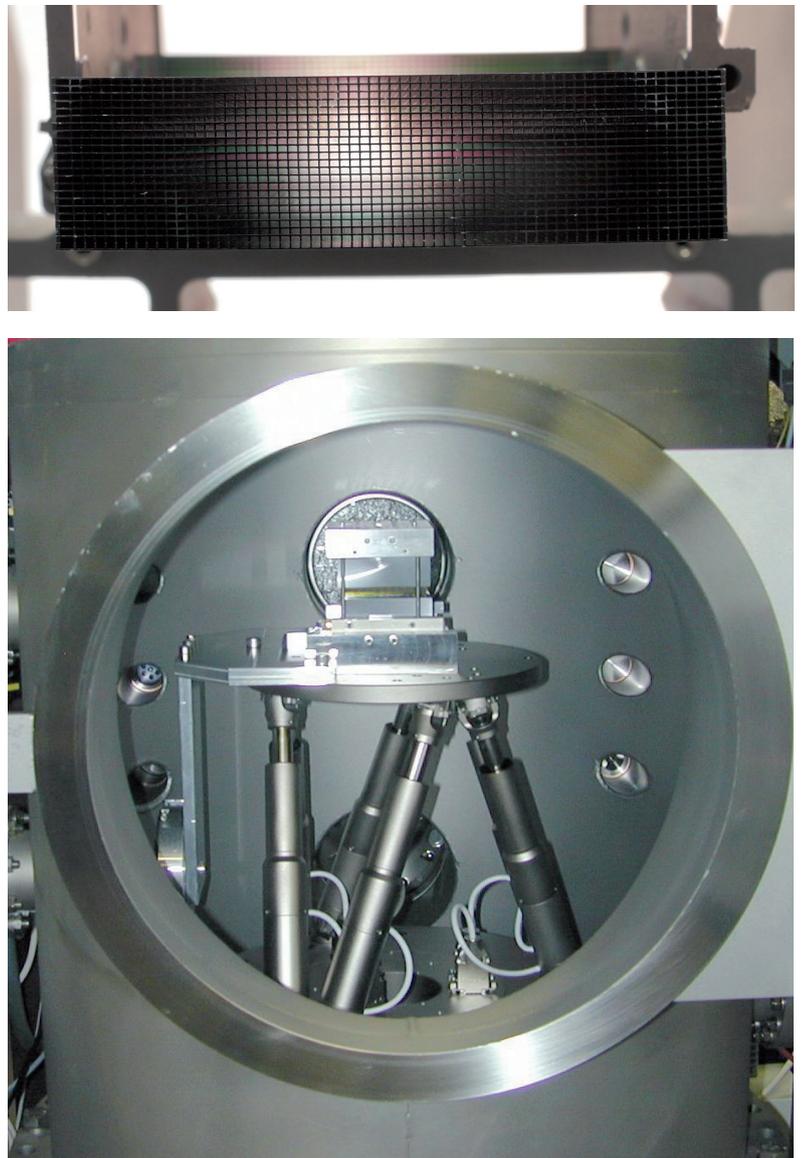


Figure 4.

Top: Silicon pore optics (SPO) consisting of stacked wafers with ribs on their reverse side.

Bottom: SPO on the hexapod of the *X-ray Pencil Beam Facility* (XPBF).

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