Invited Paper

The SUMER instrument on SOHO: Design, performance predictions, and calibration aspects

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ABSTRACT

The solar EUV spectrometer SUMER will operate in the wavelength range 500 Å to 1600 Å on the SOHO spacecraft. It will allow measurements of profiles, Doppler shifts, and intensities of solar extreme ultraviolet lines. Various mechanisms for pointing and focussing of the optical components contribute to the versatility of the intrument. The normal incidence optical design of the telescope and the spectrometer puts very stringent constraints on the cleanliness of the instrument and the mechanical design. The calibration techniques used, including imaging tests in the EUV, wavelength, and radiometric calibrations will be outlined, and performance predictions will be given.

1. THE SUMER INSTRUMENT

The experiment Solar Ultraviolet Measurements of Emitted Radiation (SUMER) is a telescope/spectrometer operating in the wavelength range from 50 nm to 160 nm on the Solar and Heliospheric Observatory (SOHO) to study flow characteristics, densities, and temperatures of plasma in the chromosphere, transition region, and lower corona of the Sun[1].
The design is aimed at high spectral and spatial resolution images in the EUV of selected areas of the solar disk and beyond, out to two solar radii. The instrument capabilities include high sensitivity measurements of spectral line profiles, Doppler shifts, broadenings, and intensities with high temporal resolution for plasma diagnostic studies of small scale solar activities as well as full sun imaging. This is accomplished by a normal incidence telescope design, aimed at 1-arcsec resolution, and a spectrometer using an imaging detector. To cover the spatial and spectal range required by the scientific objectives, a number of mechanism devices had to be included to adjust the optical components, thereby increasing the instruments versatility while maintaining a very high resolution. This approach carries along a complex mechanical design, which makes it difficult to fulfil the cleanliness requirements of a solar optical instrument, and it increases the complexity of the calibration process.

2. THE OPTICAL DESIGN

The optical design is based upon two parabolic mirrors, one plane scan mirror, and a sherical concave grating, the mirror substrates being made from silicon carbide with a CVD SiC cladding for highest reflectivity at the extreme ultraviolet wavelengths, low scattering properties, and good attenuation of visible light.

The telescope is a single parabolic mirror design used at normal incidence. The mirror substrate is a parabolic section of 1300 mm focal length and an aperture size of 90x130 mm. The centre beam is 4.5° off the parabola axis (see Figure 1.). The spectrometer entrance slit cuts out a section of 1x300 arcsec from the solar image in the telescope focal plane when the nominal slit is used, and other slit sizes of 1x120 arcsec, 0.3x120 arcsec, 4x300 arcsec can be selected by moving the slit substrate. Light passing through the slit is collimated by a second parabolic mirror with 400 mm focal length, which is tilted by 2.5° away from the telescope axis. The parallel beam is then reflected by a plane scan mirror onto the spherical concave grating. By tilting the scan mirror the incidence angle on the grating is selected in such a way, that first and second order light is diffracted in the direction of the grating normal and, thus, the grating is used in the Wadsworth configuration. The range from 500 to 800Å is observed in the 2nd order spectrum, whilst 800 to 1600Å is scanned in the 1st order. The focal distance varies with wavelength from 1634.6 mm at 800Å to 1760.7 mm at 1600Å. Both, the scan mirror and the grating are moving on a platform along the direction of the grating normal to focus the monochromatic slit image in the plane of the imaging detector. The microchannelplate detector is using a Crossed Delay Line (XDL) read-out[2] to convert the two-dimensional image into an array of 1024x360 pixels. The detector simultaneously observes a spectral range of approximately 20Å in 2nd order and 40 Å in 1st order. The B-Detector is a back-up version of the A-Detector with slightly reduced optical performance because its mounting is not perfectly in the Wadsworth configuration. The pixel size of 25 μm corresponds to the nominal slit width of 1 arcsec in the

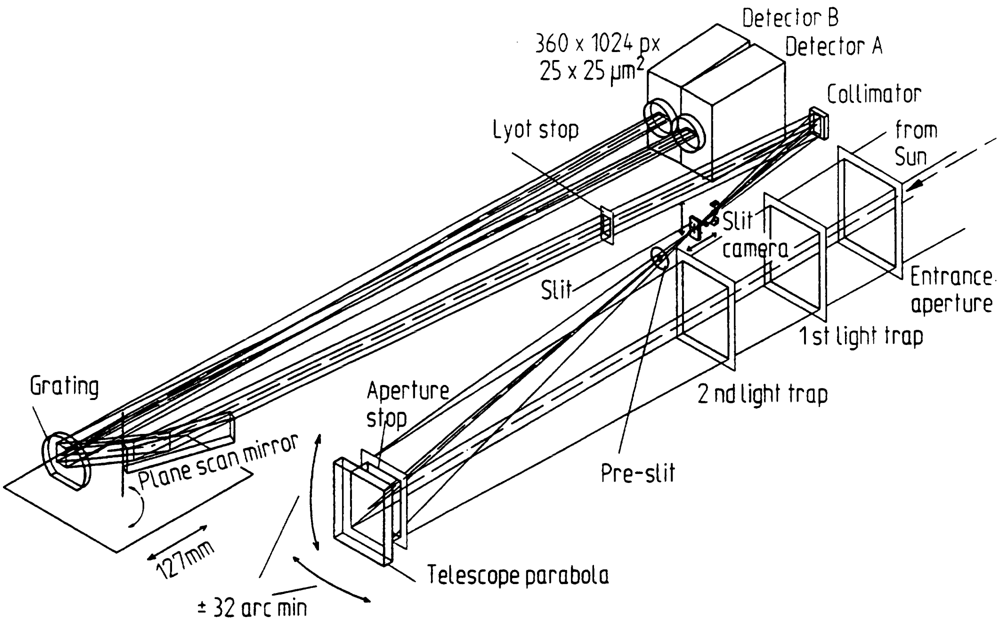

Figure 1: Schematic view of the optical design of the SUMER instrument

telescope focal plane, and the spectral resolution can be characterized by spectral elements of 40 mÅ per pixel in 1st order and 20 mÅ per pixel in 2nd order. The resolving power $\lambda/\delta\lambda$ varies between 1.9×10^4 and 4.0×10^4 as a function of the observing wavelength, where $\delta\lambda$ corresponds to the pixel size.
The characteristic values of the optical design are summarized in Table 1.

Table 1 Characteristics of the optical design of the SUMER telescope/spectrometer

The Telescope	**Equivalent f-number**	**10.66**
	Focal length	**1302.47 mm**
	Plate scale in slit plane	**6.315 µm /arcsec**
	Full aperture size	**117 mm²**
	Total dynamic field-of-view	**64 x 64 arcmin²**
	Pointing step sizes:	**0.38 arcsec per half step**
The Spectrometer	**Collimator focal length**	**399.60 mm**
	Wavelength range	**400 - 800 Å (2nd order)**
		800 - 1600Å (1st order)
	Selectable entrance slits	**1x300, 1x120, 0.3x120, 4x300 arcsec²**
	Grating ruling	**3600 lines/mm**
	Radius of curvature	**3200.78 mm**
	Plate scale	**0.588 mm/Å(at 800Å)**
		0.643 mm/Å (at 1600Å)
The Detectors	**Array size**	**360 spatial x 1024 spectral pixels**
	Pixel size	**25 x 25 µm²**

3. MECHANICAL DESIGN ASPECTS

All optical components are housed inside two boxes at the two extremes of the 2.4-m long structure, which are connected by a light-weight but rigid spacer section. The aperture of the closed optical housing can be opened by a motorized door mechanism. Several motor driven moving devices are needed inside the structure for the precise displacement of optical components during operation:

- Telescope pointing: The telescope parabola is mounted inside a system of two nested frames, each one approximating a motion of the mirror on a spherical surface around the focal point in horizontal and vertical direction, respectively. While SOHO is directed to the Sun centre, the range of pointing the SUMER telescope is +- 32 arcmin in both dimensions with a resolution of 0.38 arcsec per half-step. This makes possible to scan the full solar disk (and beyond, out to nominally 2 solar radii in all directions) and acquire full Sun images by collecting aproximately 18500 exposures (using the nominal slit size) by operating the instrument in an automatic mode.
- Slit selection : Depending upon expected line intensities from different spectral or spatial regions of the solar spectrum, different slit sizes can be selected to accommodate acceptable integration times and the detector count rate limitations. Four slits are available (see Table 1) by moving the slit substrate in a vertical direction. The slit selected can be positioned in the optical plane by a stepper motor drive with an accuracy of 6.25-μm step size. This corresponds to one arcsec or one pixel on the detector. Two holes of sizes 6.3 μm and 2 mm can be selected in addition for ground testing and calibration of the instrument.
- Slit focussing: The position of the slit along the telescope axis is adjustable to provide best image quality. This can be used to compensate for any focal length variations or structural separation changes due to thermal or non-thermal reasons. It should be noted that this is possible, because a separation between the slit and the collimator can to some extend be compensated by refocussing the grating.
- Wavelength scanning: The wavelength range imaged on the detector is selected by a rotation of the scan mirror. This is a plane mirror used at grazing incidence. A rotational motion around the side next to the grating is induced by a stepper motor drive making possible a wavelength change from one extreme to the other within about 21 seconds.
- Grating focussing: The variable angle of incidence on the grating makes it necessary that the focal length of the spherical, concave grating is adjusted with the wavelength scan. For the full wavelength range, the grating and the scan mirror are moving on a platform along the grating normal with a scanning capability of 127 mm.

All mechanisms use the same type of stepper motor, which have been specially modified to comply with extreme cleanliness requirements (see below), and ball lead screws or satellite roller spindles for gearing. Rotational parts are moving in dry lubricated ball bearings or flexural pivots.

4. THE CLEANLINESS PROGRAMME

The design and purpose of the SUMER instrument constitute a special challenge in regard to the cleanliness of the system. The normal-incidence optical scheme and the aim to observe weak spectral lines in the presence of the full solar radiation, impart special demands on the requirements specifications for sensitivity and stray light. This renders the instrument very sensitive to contamination of molecular and particulate nature, as particles and molecular deposits increase the scattering and reduce drastically the throughput of the EUV system. Moreover, the combined effects of organic species and high flux of solar radiation is known to produce irreversible deposition of contaminants on mirror surfaces by photochemical activation and subsequent polymerization[3]. Prevention and control of contamination has thus been a major effort and is carried through the entire programme[4] from the design phase to the end of the mission.

To establish quantitative measures of tollerable contamination, several experimetal and theoretical studies have been carried out which assess the effects on the optical performance of different contamination modes: Self contamination by dust particles, outgassing of organic condensables, effects of EUV and solar wind radiation, and, most impoitant, combined effects of the above. From these, special preventive measures in the design of the instrument and stringent contamination control activities have been defined. The requirements for molecular deposits on the surfaces of the optical compartment was set at $0.1\mu g/cm^2$, and for particulate matter a Level 200 per MIL-STD-1246B was considered adequate. Since these requirements are not easily fulfilled, significant measures to reduce contamination have been implemented, most important are special design features and the selection of proper materials. Briefly, among the special design features are:

A clean optical compartment: The design includes a closed optical housing which can be purged with clean gas.

- Materials were selected so as to avoid organic material wherever possible, otherwise high temperature materials have been chosen and kept outside the optical compartment. All components containing organic material have been tested for outgassing by a specially develloped test method and conditioned until they comply with the cleanliness requirements.
- An aperture door keeps the instrument closed, exept when EUV measurements are undertaken.
- A UV blind window in the aperture door serves to heat the primary mirror passively by the solar infrared radiation, keeping the mirror temperature higher than all other surfaces.
- A solar wind deflection plate is installed inside the entrance baffle, held at a potential of -2 kV, to prevent protons and alpha particles with energies up to 5 keV and 10 keV, respectively, from impacting the telescope mirror.
- Ultra-high vacuum stepper motors have been specially designed and extensively conditioned and verified for low outgassing before integration.
- Mechanisms use dry lubrication on MoS_2 basis or use lubrication free devices like flexural pivots.

Contamination control has also been implemented in the assembly area and the calibration facility. Precision cleaning and vacuum baking has been made mandatory for every piece of flight hardware before entering the cleanroom. The cleanroom, which contains the assembly area, the optical alignment bench, and the calibration vacuum system, is certified to Class 100 cleanliness, and it contains an active charcoal filter panel in the air circulation system to clean the air from condensable organic materials. The calibration vacuum system is using oil-free pumps only, and the instrument can be inserted from the cleanroom side, while the vacuum support side is outside the cleanroom.

5. THE CALIBRATION PLAN

5.1 Light sources

A full pre-flight calibration of the SUMER system will take place in the Test- and Calibration System which has been built adjacent to the SUMER cleanroom. This vacuum system consists of a 1-m diameter by 3-m long vessel with a beamline of 4 m length attached on one side, which is outside the cleanroom, and a loading port on the cleanroom side. Different light sources, covering the full wavelength range of SUMER, can be mounted at the end of the beamline with a collimating mirror, such that the instrument is illuminated by a collimated beam filling the full aperture of the telescope. The light sources to be used are a Kr line source with high intensity emission at 1236Å , a Kr continuum lamp extending the emission to the long wavelength end with a maximum at 1450Å, a Pt-Ne hollow cathode lamp with a rich spectrum of lines above 1200Å for wavelength calibration. In addition, for full wavelength tests, an open DC discharge source is mounted, which can be operated with several noble gases to produce spectral line emissions between 537Å and 1470Å. The radiometric calibration will be performed with another but similar light source[5]: An open hollow cathode discharge source (HCS) with its own collimating mirror will replace the former light sources. The HCS-system has been calibrated against the electron storage ring BESSY as a primary radiometric source standard. Operating it with noble gas, a list of 32 lines, distributed across the wavelength range, is produced with photon fluxes ranging from 10^7 to 10^9 photons/sec inside a collimated beam of 10 mm diameter. Given a theoretical instrumental throughput between 1×10^{-3} and 1×10^{-4}, this intensity is just right to stay inside the dynamic range of the detectors.

5.2 Calibration strategy

Although the fabrication processes of subsystems are accompanied by calibration tests at the individual component level, which comprises imaging and efficiency tests of mirrors at full wavelength range and full spectral characterization of detectors, the end-to-end calibration of the system requires a strategy which streamlines the various tasks to be performed for a complete calibration of the instrument. The calibration plan, which has therefore been established, can be devided into several phases: First, alignment and imaging tests have to be made using visible light sources. Second, in-vacuum testing using light sources above 1200Å will be performed to establish the performance and imaging quality in the VUV, and, third, full wavelength range tests and calibration will complete the calibration process. The tasks to be performed during in-vacuum calibration are, among others:

- Final optical end-to-end alignment, since the grating and detectors only function at EUV wavelengths.
- Calibration of mechanism transfer functions.
- Verification of telescope image quality.
- Measurement of spectrometer resolution and contrast.

- Stray light tests at all wavelengths and out-of-band supression.
- Wavelength calibration.
- Radiometric calibration.

All these tests have to be carefully timelined with the environmental test programme of the flight model, the radiometric calibration, in particular, shall be the last activity, as the KBr photocathode coating of the detectors shall not be exposed to ambient air after the final calibration. The light sources will be exchanged as necessary while the instrument is under vacuum or purged with dry nitrogen when recovered from vacuum.

5.3 Results from the calibration rehearsal

A short rehearsal of the calibration has been performed with the Qualification Model of SUMER and, using the hollow cathode source (HCS), first images give us an idea of what we can expect from SUMER. In Figure 2 we show a spectrum of the lamp, operated with Krypton. Specifically, it is the column sum of one image taken with an integration time of 4 sec and using the 1x300 arcsec slit size. It is seen that besides the Krypton resonance line at 1236Å, the Hydrogen Lyman Alpha line is also prominent in this spectrum, and many other, weaker lines which are as yet unidentified, are present. The small number of counts between the lines also gives a good indication of the very low noise level, as no background correction has been applied. Although this light source is not forseen for optical performance verification, the spectral resolving power is shown to be very good, however, here the line width of 190 mÅ is mainly limited by line width and the high f-number of the source beam, which is filling only a very small fraction of the aperture.

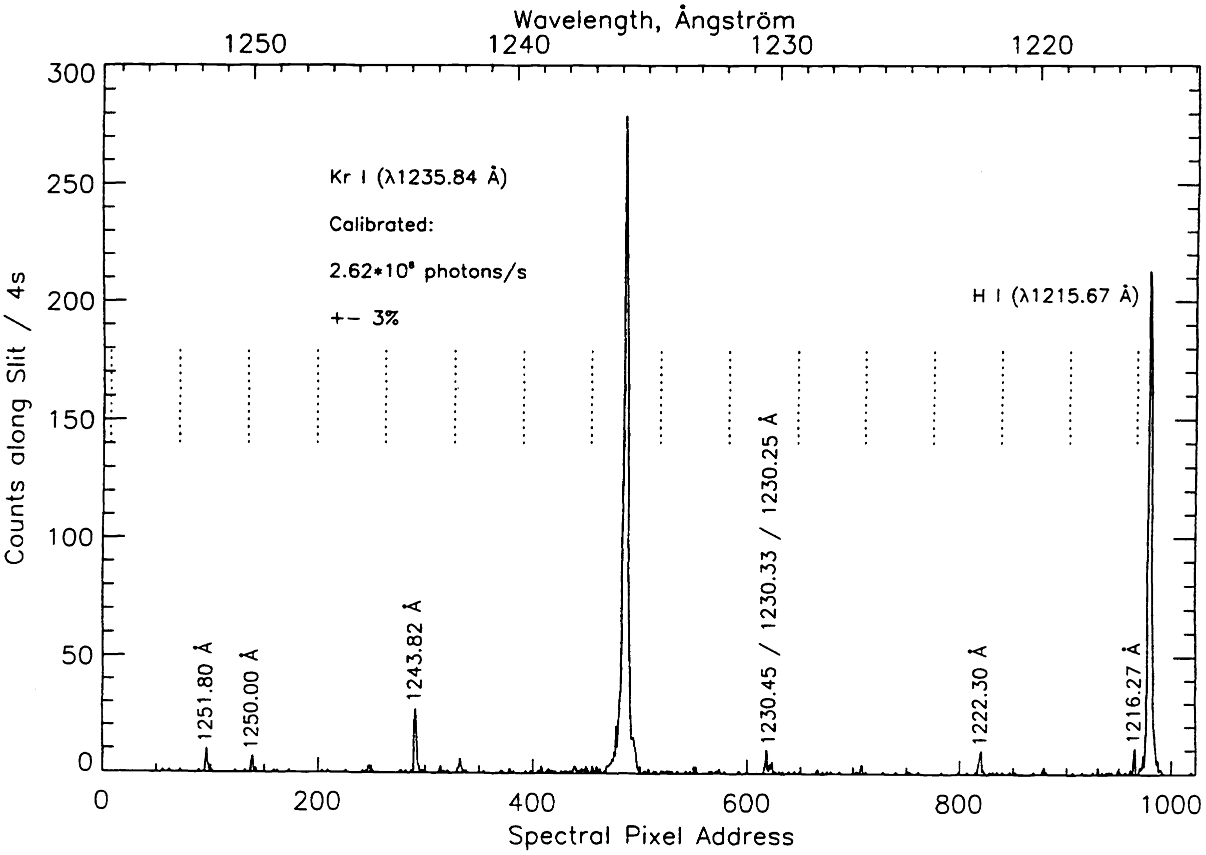

Figure 2: Column sum spectrum of an image taken from the radiometric calibration source in the region of the Krypton resonance line at 1236Å.

6. ACKNOWLEDGEMENTS

I would like to thank all persons who have contributed so far to the calibration of the SUMER instrument, in particular W.Curdt, C. Diesch, D. Hassler, J.Hollandt, M. Huber, M. Kühne, P.Lemaire, A. Poland, G. Timothy, K. Wilhelm, and the technical staff of the SUMER team. Financial support of the Deutsche Agentur für Raumfahrtangelegenheiten (DARA) and the Max-Planck-Gesellschaft (MPG) is greatfully acknowledged.

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