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The spectrometer/telescope for imaging X-rays on board the ESA Solar Orbiter spacecraft

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ABSTRACT

Solar Orbiter is a Sun-observing mission led by the European Space Agency, addressing the interaction between the Sun and the heliosphere. It will carry ten instruments, among them the X-ray imaging spectrometer STIX. STIX will determine the intensity, spectrum, timing, and location of thermal and accelerated electrons near the Sun through their bremsstrahlung X-ray emission. This report gives a brief overview of the STIX scientific goals and covers in more detail the instrument design and challenges.
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1. Introduction

Solar Orbiter is a Sun-observing mission of the European Space Agency with NASA participation that addresses the interaction between the Sun and the heliosphere [1]. The launch is scheduled for 2017 with a primary mission duration of 4 years and a planned extension of 3 years. The spacecraft will carry ten instruments for remote sensing and in-situ measurements. It will approach the Sun to 0.28 astronomical units, inside the orbit of Mercury, thus allowing unprecedented high-resolution measurements.

The spacecraft mass is 1.8 t (payload 180 kg), power consumption 180 W and the telemetry rate 150 kbps when at a distance of 1 astronomical unit from Earth. The science orbit will be in 3:2 resonance with Venus, using gravity-assist maneuvers at every encounter to increase the orbit inclination. Towards the end of the mission, out of the ecliptic observations of the solar poles will be possible. The main science question that will be addressed by Solar Orbiter is “How does the Sun create and control the heliosphere?”. This comprises for example the study of energetic solar phenomena like flares, of solar transients and heliospheric variability, of the solar wind accelerating mechanisms and the solar dynamo working principle.

The X-ray imaging spectrometer on board Solar Orbiter is called STIX (Spectrometer/Telescope for Imaging X-rays). The STIX science goal is to study the acceleration mechanism of energetic electrons and to serve as the observational link between remote-sensing and in situ measurements [2]. It does so by determining the intensity, spectrum, timing, and location of those electrons near the Sun through their bremsstrahlung X-ray emission between 4 keV and 150 keV. This range includes both the thermal

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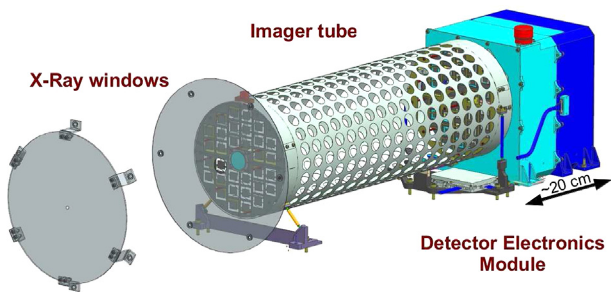

Fig. 1. Overview of the STIX instrument hardware.

Table 1
Main parameters of STIX.

Energy range	4–150 keV
Energy resolution	1 keV (FWHM at 5 keV)
Effective area	6 cm^2
Angular resolution	7 arcsec
Image placement accuracy	<4 arcsec
Field of view	2°
Time resolution	0.1 s (statistics limited)

part of the spectrum (typically from electrons at 10's of MK), and, above 15–20 keV, the non-thermal part from accelerated electrons.

Mechanically, STIX consists of three separate parts as shown in Fig. 1, mounted individually to the spacecraft. The X-ray entrance windows provide thermal protection against the intense solar flux close to the Sun. The Imager holds the grid assemblies required for Fourier imaging (see Section 2) and the aspect system. The X-ray detectors, front-end and digital electronics, power supplies and interface to the spacecraft are located in the Detector/Electronics Module.

The main instrument parameters are listed in Table 1. The significant contribution of STIX to Solar Orbiter results primarily from the synergy with the other instruments, sharing the same solar vantage point.

2. Imaging principle

The resource allocation for STIX on Solar Orbiter is 4 W power, 7 kg mass and 700 bits/s telemetry. For such limits only indirect Fourier imaging is feasible at X-ray energies.[1] The principle relies on measuring individual Fourier components of the source distribution with pairs of X-ray opaque grids separated by a large distance [3]. Such a grid pair selectively absorbs or transmits X-rays depending on the direction of incidence. By determining many such Fourier components, an image can be reconstructed.

In STIX, the grids of a pair have both slightly different pitches and angles to generate a Moire transmission pattern which encodes the incoming direction of the X-rays. Coarsely pixelized CdTe semiconductor sensors behind the grid pair detect the large-scale intensity distribution of the pattern through the count rate differences between the pixels, determining one Fourier component of the image. The fine structure of the Moire pattern does not need to be resolved. The grid pitch and the separation between the two grids determines the angular resolution of that pair, the grid angle the orientation of the Fourier component. The relative pitch and angle of the two grids determine the Moire pattern period and orientation and are designed to fit to the detector size and orientation. An example transmission pattern is shown in Fig. 2.

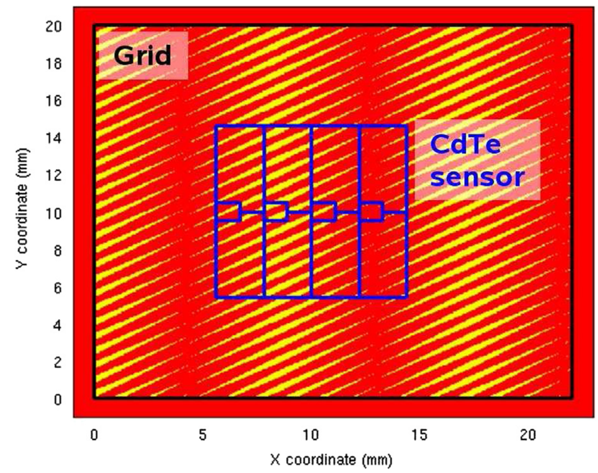

Fig. 2. Moire pattern generated by vertically impinging photons on two grids with pitches 666 μm/690 μm and angles 60°/64°. The black rectangle indicates the grid size, the blue lines the pixel structure of the detectors. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

The Fourier imaging technique combines a large 2° field of view (full Sun at perihelion) with a fine angular resolution of 7 arcsec. A restriction is that only sources of limited complexity can be reconstructed, as the number of independent image elements (in Fourier space, not on an image plane) is given by the number of grid pairs. Knowledge of the structure of flaring regions from Yohkoh HXT and RHESSI supports the adequacy of this imaging concept.

30 Fourier components in three directions are determined by STIX. One detector is used for continuously monitoring the background, and one for coarse location of intensive flares.

3. Instrument hardware description

3.1. X-ray windows

The solar flux at 0.28 astronomical units distance from the Sun is 17 kW/m^2. This high flux must be prevented from entering the spacecraft. To address this, STIX uses two Beryllium windows, 1 and 2 mm thick.[2] The windows are designed such that complete failure of one window, for example by a micrometeorite, does not critically harm Solar Orbiter (avoidance of a single-point failure).

An important requirement for the X-ray transparency is homogeneity of the transmission to better than 4% root-mean-square at all positions, as a non-homogeneity would directly degrade the imaging performance. The absorption at 4 keV of 3 mm Beryllium is about 99%. Such a high value is indeed desirable to attenuate the very high flux of low-energy X-rays, which would otherwise impede the detection of higher energies.

With a coating of Al-SiOx, the Sun-facing window will attain about 300 °C at closest approach, the rear window 180 °C. Flexible mounting braces on the front window allow for thermal expansion. They also limit, due to their small cross-section, the heat flow from the windows into the spacecraft feed-through to which they are attached.

The small central holes in the windows are part of the aspect system, described below.

3.2. Imager

The Imager consists of a lightweight tube holding the Tungsten grid assemblies for Fourier imaging at both ends at a separation of

[1] In contrast to direct imaging with grazing incidence mirror optics.

[2] The windows are designed by Almatech, Lausanne, Switzerland.

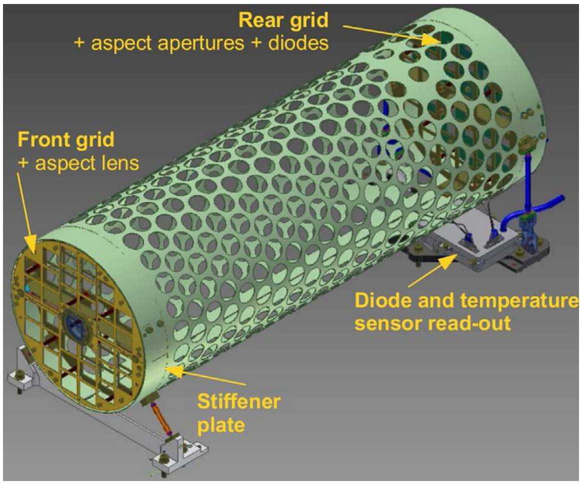

Fig. 3. Design of the Imager.

55 cm (see Fig. 3). The tube provides stiffness against relative twist of the front with respect to the rear grid assembly, which is the most important stability requirement for imaging.[3] The grids are 400 μm thick and have pitches ranging between 38 μm and 1 mm. Such a large ratio between pitch and thickness (deep, narrow trenches) cannot be produced from a single sheet. Instead, thin Tungsten foils are first etched with the required grid patterns, and then up to 16 such layers are precisely stacked and glued together.[4]

The Fourier imaging principle allows very high resolution down to 7 arcsec in X-rays. Obtaining the highest scientific return through comparative studies with other instruments requires in addition to place the images with a comparable resolution onto the solar disk. The pointing accuracy of the spacecraft is specified as several arcminutes only. Thus STIX needs a separate aspect system, implemented as a solar limb detector.

The imaging axis in STIX is given naturally by the alignment of the front and rear grids, and is not directly related to the detector placement behind. A lens rigidly mounted to the front grid assembly images the Sun seen through the small central holes in the Beryllium X-ray windows onto the center of the rear grid. A precisely machined array of fine apertures in a cross-shape passes the light onto four linear, non-pixelized photodiodes behind. When the solar limb crosses one of the apertures, a stepwise change in the current in the corresponding photodiode is observed. The image size will change continuously but slowly due to the varying distance of Solar Orbiter to the Sun. During satellite slewing the image will move faster. Once a number of such limb crossings have been determined in at least three directions, the solar disk location on the rear grid at a particular point in time can be determined by interpolating the aperture crossing times. This location and the center of the lens determine the imaging axis. An image placement accuracy of better than 4 arcsec is expected to be achievable this way.

3.3. Detector/electronics module (DEM)

The DEM consists of two subunits, the Detector Box containing the front-end electronics [4] and the attenuator, see Fig. 4, and the Instrument Data Processing Unit behind it.

[3] Other misalignments, like transverse shifts or differential thermal expansion, can be corrected to a certain degree by redundant information in the count rates. Relative twist needs to be controlled to better than 3 arcmin.

[4] The grids are produced by Mikro Systems Inc, Charlottesville, USA.

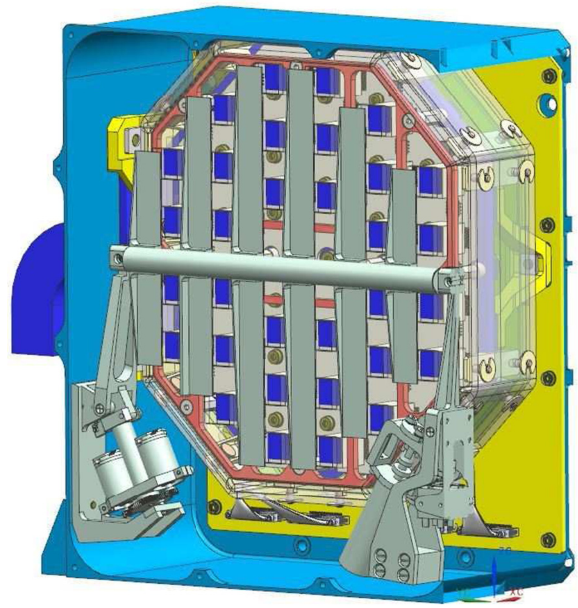

Fig. 4. Design of the Detector Box, showing the 32 Caliste-SO hybrids (dark blue), towards the left the spacecraft cold element, above the mechanical attenuator (grey), behind the warm front-end board (yellow) with the cable connections to the cold front-end at the bottom, and the multi-layer insulation of the cold unit with its support grid (red). Structural support of the cold unit uses Vetronite elements (bright yellow). The right side of the enclosure is not shown for clarity. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

A mechanical attenuator is used to reduce the count rates during high intensity flares.[5] It consists of 1 mm thick Aluminium blades that can be moved via two redundant electric motors into and out of the X-ray path. A high-output paraffin actuator is implemented in addition, forcing the attenuator open in a one-shot manner in case one or both of the motors get stuck.

X-ray detection occurs in 1 mm thick CdTe semiconductor sensors of $10 \times 10\ \mathrm{mm}^2$ area. This thickness absorbs 63% of all photons at 100 keV. The cathode is a monolithic layer of Platinum, the anode is subdivided into 8 large and 4 small pixels, as indicated in Fig. 2. The anode is realized as a Schottky contact, reverse biased at 200 V to 300 V.[6] The arrangement of the pixels in four stripes is required for the detection of the large-scale Moire structure. The additional use of two large and one small pixel per stripe allows to adjust the effective area depending on the incoming count rate to limit pulse pile-up and deadtime by disabling pixels. Smaller pixels also have less capacitance, lowering the electronic noise of the amplifier.

The CdTe crystals are bonded to hybrid circuits called Caliste-SO [5], containing as the principal component the low-noise, low-power ASIC IDeF-X HD [6], plus voltage filtering and bias routing. 13 input channels of the ASIC are routed to pads on top of the package, interfacing with the 12 pixels and the guard ring[7] of the CdTe sensor. The remaining 19 channels of the ASIC are unused and are powered off. Fig. 5 demonstrates with one of the first Caliste-SO samples that the required energy resolutions and low counting threshold are achievable.

[5] The attenuator is designed by Almatech, Lausanne, Switzerland.

[6] At the beginning of the mission. Due to irradiation damage, the required bias voltage will increase over the mission. Up to 800 V are available from the high-voltage converters.

[7] The guard ring is connected to guarantee the same electrical potential as the pixels for optimum protection against edge-related leakage current.

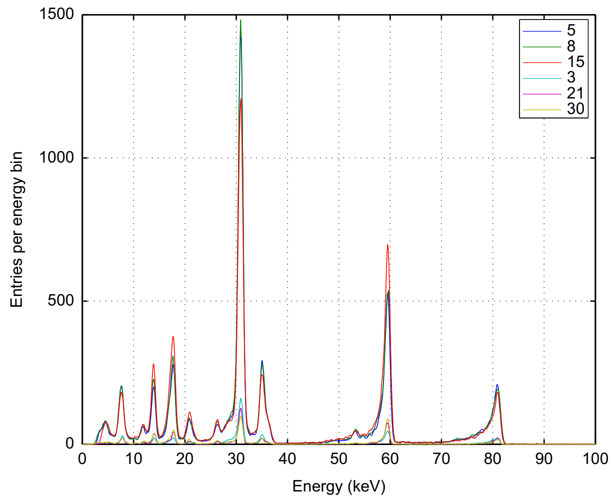

Fig. 5. Spectrum obtained with Caliste-SO at −20 °C and bias 200 V, using simultaneously a Barium-133 and an Americium-241 source. Three large (channels 5,8,15) and three small (3,21,30) pixels are shown. The resolution at 31 keV is for the small pixels 0.9–1.0 keV full-width-half-maximum, for the large pixels 1.1 keV. The trigger threshold is 3 keV.

To achieve low electronic noise with the ASIC, the leakage current per pixel needs to be below 60 pA, which is obtainable by passively cooling the sensors to −20 °C or below. The inside of the spacecraft and the DEM case are close to +50 °C during the most interesting observation times near perihelion, therefore excellent thermal insulation of the sensors is needed. The circuit board with the Caliste-SO hybrids is mounted on an Aluminium-Beryllium alloy cold plate, which in turn is thermally connected to a spacecraft-provided cold element. The cold unit is insulated by Vetronite mounting elements and multi-layer insulation against the warm environment. Except the Caliste-SO, only buffer amplifiers, signal conditioning circuitry, voltage filtering, temperature sensors and part of the test pulse generator are located on the cold front-end.

Analog-to-digital converters, voltage regulators, the digital-to-analog converters of the test pulse generator, and further support circuitry are mounted on a warm front-end board where power dissipation and heat load are less restricted. The electrical connections between the two parts consist of 204 wires of thin (AWG36) and long (50 cm) cable. About 150 mW of heat is transported over these cables, an acceptable fraction of the 1 W electrical power of the cold front end.

The warm front-end is in turn connected to the IDPU that controls the whole instrument [7]. All digital control is contained in a field-programmable gate array and in the processor that runs the flight software. The 32 detectors will independently sample with a rate of about 20,000 counts per second during intensive flares which requires clocks to run in the range of 20 MHz. Differential transmission is used for all fast signals over the long cables to the cold front-end. The IDPU allows autonomous operation over extended periods of time (up to 80 days, when no contact to Earth is possible) and provides the spacecraft interfaces. Several months of science data can be stored on board and selectively retrieved by telecommand to allow flexibility within the tight telemetry budget.

Also for telemetry bandwidth reasons, count values will be accumulated and transmitted to Earth in 32 approximately logarithmically spaced energy bins. The bin energy limits need to be known to 100 eV root-mean-square to preserve the spectral information. Radioactive Barium-133 sources are integrated into the Detector Box, and high resolution spectra will be accumulated during non-flaring intervals and transmitted occasionally to Earth. Ground analysis will then determine updated calibration constants that are uploaded to STIX.

Data handling uses rate-based flare detection and on board optimization of time/energy intervals within each flare. One of several data compression algorithms then converts the data to a set of visibilities which can be transmitted in fewer than 100 bytes. This enables more than 1000 statistically significant flare images to be transmitted per hour within the telemetry budget.

For redundancy, both the cold and the warm front-end are divided into four identical quarters. The arrangement of grid-pair/detector units is chosen such that a failure of one quarter, e.g. by a short circuit, results only in reduced, but not totally compromised imaging performance. The IDPU is arranged as two identical units in cold redundancy, each one being able to control all of STIX.

4. Outlook

The ESA critical design review for STIX is planned for 2013. The flight instrument will be delivered to ESA in January 2015, for the planned launch in January 2017.

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