Calibrating the aspect systems of the High Energy Solar Spectroscopic Imager HESSI

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ABSTRACT

HESSI will image Solar flares with spatial resolution ranging from 2 and 190 arcsec over the energy range from 3 keV to ≈100 keV and as low as 35 arcsec for energies up to 20 MeV, respectively. The system is based on Fourier-transform imaging in connection with high-resolution Ge-detectors. In order to achieve arcsec-quality images with an instrument having only arcmin alignment requirements one needs in addition two precise aspect systems: (1) The Solar Aspect System (SAS) will provide Sun aspect data with high precision ($<$ 0.2 arcsec relative and 1 arcsec absolute) and at high frequency (100 Hz). It consists of three identical lens/filter assemblies which focus Sun images on three 2048x$(13\mu\mathrm{m})^2$ linear CCDs at 1.55 m focal distance. Simultaneous exposures of three chords of the focused solar images are made and the pixels spanning each solar limb are recorded. (2) The Roll Angle System (RAS) will provide precise (arcmin) information on the roll angle of the rotating spacecraft. The RAS is a star scanner which points out radially and observes stars at 75 degrees from the Sun direction using a commercial lens and a fast CCD. The passage of a star image over the CCD will induce a signal in one or several pixels and the timing of this signal defines the roll angle, once the star has been identified by comparing its pixel position and amplitude with a star map. With a limiting magnitude of $m_V = 3$ we expect to observe at least 1 star per revolution (during direct Sun view) over 1 year; on the average we will detect about 10 stars/revolution. We report on the design, construction and calibration measurements of the SAS and RAS flight-model instruments.

Keywords: optical Sun sensor, interference filter, fused silica lens, optical star scanner, fast CCD, CFRP optical baffle, straylight calculations

1. INTRODUCTION

The High Energy Solar Spectroscopic Imager (HESSI) is a Small Explorer mission selected by NASA with a single instrument mounted on a spin-stabilized spacecraft on low earth orbit (600 km altitude, 38 degrees inclination).[1] The primary scientific aim of the mission is to investigate the physics of particle acceleration and energy release in solar flares. HESSI will observe the full Sun with an unprecedented combination of spatial resolution (between 2 and 36 arcsec) and energy resolution (1 keV at 3 keV, increasing to 5 keV at 20 MeV) in the energy range from 3 keV to 20 MeV. The HESSI instrument utilizes Fourier-transform[2] imaging with 9 bi-grid rotating modulation collimators[3] spaced at 1.55 m and 9 cooled germanium detectors.

The spatial resolution depends critically on a precise knowledge of the momentary pointing direction and roll angle. In order to have a spatial resolution of 2 arcsec (for the finest grids) and to precisely correlate with observations at other wavelengths two precise aspect systems are implemented: (1) the Solar Aspect System (SAS) which will yield sub-arcsec knowledge of the radial pointing with respect to the Sun center and (2) the Roll Angle System (RAS) which will provide precise knowledge on the roll angle of the rotating spacecraft (15 rpm). The combined SAS/RAS aspect system will provide a knowledge of the absolute pointing with an accuracy of 1 arcsec.

In the following, we describe the design, construction and pre-flight calibration measurements of the SAS and the RAS flight-model instruments.

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2. SYSTEM OVERVIEW

The aspect system consists of the two subsystems, the SAS and the RAS and the Aspect Data Processor (ADP). The SAS will provide quasi-continuous information on the pointing of the spacecraft with an accuracy of 0.4 arcsec (on a 1 σ level). The RAS is a star scanner that points out radially with respect to the imager axis and observes stars at 75 degrees from the Sun direction and provides roll angle information with an accuracy of 1 arcmin. The data stream from both aspect subsystems is collected by the Aspect Data Processor (ADP) which is part of the Instrument Data Processor Unit (IDPU).

2.1. Solar Aspect System SAS

The SAS is a set of three identical lens/sensor subsystems (spaced at 120 degrees). Each subsystem consists of a 4 cm diameter lens located on the front grid tray of the imager tube that focuses a solar optical image onto a 2048-element x $(13\mu\mathrm{m})^2$ linear CCD. In order to reduce chromatic aberration a two-stage bandpass filter (center wavelength at 670 nm, 12nm FWHM, peak transmission 1.5%) is implemented: the bandpass defining part is located on the lenses while a filter blocking the regions far away from the bandpass is located on a glass plate directly in front of the CCD. The latter ensures a safe reduction of the straylight which may pass through spurious leaks in the supposedly light-tight MLI cover (Multi-Layer Insulation) of the whole imager tube. The glass plates are turned by 6 degrees from parallel to the CCD plane in order to deflect the CCD reflected light away from the CCD.

The CCD (Loral 145 EDC) is glued directly to an Al stand in the SAS sensor box which is bolted to the rear grid tray. This CCD mounting structure guarantees stable positioning on a micron level. Using a constant cadency (128 Hz), each pixel of the CCD video signal is sampled twice, at the offset level and at the signal level. The two samples are converted using a 12 bit ADC with a resolution of 0.5 mV/ch. By subtracting the two values from each other, the reset noise cancels out and a signal with a dark level of $<$ 1 mV and a noise of about 0.5 mV is obtained. In normal mode[4] bit 1 to 10 of the subtracted signal are sent to the ADP using a synchronous serial link with a speed of 1 μs/pixel.

In order to adjust the response to fit best into the 10 bit dynamical range, the integration time can be programmed for values between 0.016 ms and 2 ms with a nominal value of 0.5 ms. All digital data handling and control logic is programmed into an onboard FPGA (Field Programmable Gate Array, Actel RH1020).

2.2. Roll Angle System RAS

The RAS points out radially and observes stars at 75 degrees from the Sun direction. Stars within a field-of-view of 30 degrees (in plane) and 1.2 degrees (orthogonal to the satellite spin axis) are focussed by a lens (Leica Summilux, f/1.4, 50 mm) onto a 2048 x 96 pixels x $(13\mu\mathrm{m})^2$ TDI CCD (Dalsa IL-E1).[5] (The originally selected CCD, Dalsa IL-C6, showed a rather low charge transfer efficiency from the photo site to the CCD shifter for small signals and had to be replaced.) After every integration time the charge of all 96 pixels of each column is moved to the CCD shifter and then shifted out to get a video signal of 2048 pixels. Similar to the SAS sensor, the video signal is sampled twice, at the offset level and at the signal level. After conversion using a 12 bit ADC and subtraction (see above), a 10 bit signal with a resolution of 0.5 mV/ch is then transmitted through a synchronous serial link to the ADP with a speed of 1 μs/pixel. For a nominal operational temperature of -20 °C, a signal with a dark level of about 30 mV and a noise of $<$0.4 mV has been measured.

The optical system is protected from direct Sun illumination by the satellite instrument deck and from Earth-reflected light by an optical baffle for a viewing angle of $\pm$15 degrees from the RAS optical axis. Nevertheless, the Earth shine will reach the lens for many spacecraft revolutions. Since the CCD has no feature to drain the charge which is produced from deep saturated signals (i.e. anti-blooming) a special mechanism had to be introduced to handle the Earth shine. If more than 64 pixels reach the Earth shine threshold an Earth shine signal is produced on the front-end (or first-level) RAS FPGA (Actel RH1020). This causes the ADP to switch to the fast reading mode, the highest possible cadency with a cycle time of $\approx$2.2 ms. When the Earth shine signal switches off, an additional, programmable number of fast readouts (reasonable numbers are between 100 and 200) will be done before switching back to the normal readout cadency. During the fast readings, no data are written to the ADP FIFO memory. This Earth shine procedure shows a dead time for the RAS sensor of $\approx$0.8 sec after rotating out of the Earth shine. Taking into account that the baffle reduces the straylight enough for angles $>$20 degrees from the RAS optical axis, the additional dead time is expected to be $<$0.6 sec.

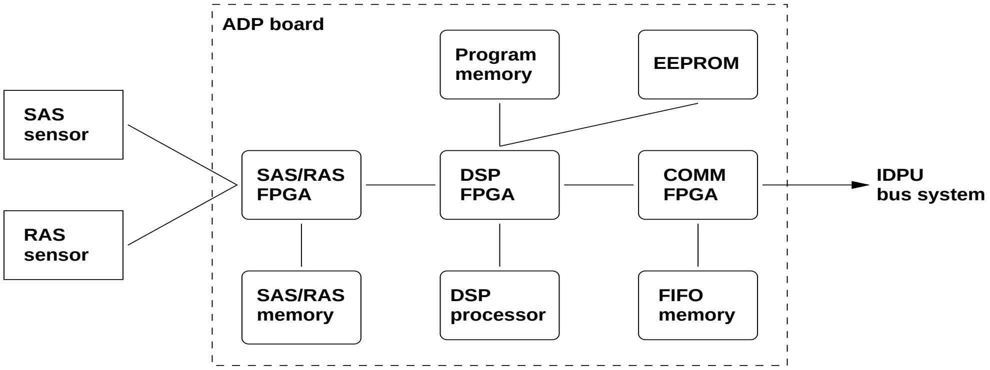

Figure 1. Simplified logical scheme of the Aspect Data Processor (ADP). For description and abbreviations see paragraph 2.3 in the text.

The integration time (corresponding to RAS cadency) is programmable with a minimum of 8 ms (for having the data written to the FIFO) and no relevant maximum. Taking into account a star passage time of 16 ms, an integration time of 8 ms provides the sampling of a star passage by three consecutive time bins which will allow a roll angle determination with an accuracy of 1 arcmin.

2.3. Aspect Data Processor ADP

The Aspect Data Processor Board is connected to the VME-like bus system in the IDPU. It receives the signals from the aspect sensors, i.e. the three SAS sensors and the RAS sensor. On the ADP, the SAS/RAS signals reach the second-level SAS/RAS FPGA (Actel A14100) which stores all pixels in the SAS/RAS memory. Also, this FPGA processes the solar limbs and the star events and stores adequate information in the SAS/RAS memory. The DSP processor (Data Signal Processor, SMG320C50, 50MHz) of the ADP reads this data and after software processing and formatting telemetry packets are written to the FIFO memory where the data is ready to be read by the IDPU data controller board through the VME bus system (see Fig. 1).

For the SAS, solar profiles (1d images) can be commanded with either 10bit or 8bit (MSB) resolution. In the SAS/RAS FPGA the pixels of every image are compared to a programmable threshold value to detect the solar limbs. The limb addresses are read from the SAS/RAS memory by the DSP program and limb telemetry packets are written to the FIFO. In order to reduce the telemetry, the ADP can optionally divide the initial cadency of 128Hz by factors of 2 (128, 64, 32, 16 or 8 Hz).

For the RAS, every pixel of each image is compared with the corresponding value of the programmable threshold table by the SAS/RAS FPGA and the addresses for pixel values above threshold are written to the SAS/RAS memory. Since a star event can be spread over several pixels due to the point spread function of the lens system and to increase the signal to noise ratio, the pixel values for 2 to 4 adjacent pixels and two consecutive time bins can be added and then compared to the threshold value. The number of pixels to sum over can be programmed for five different regions of an image. The data in the SAS/RAS memory is then read by the DSP program and image and/or star event telemetry packets (always 10bit resolution) are written to the FIFO.

3. MEASUREMENTS AND RESULTS

3.1. SAS measurements

For calibration, the imager with the integrated SAS subsystems (lenses on the front tray and the SAS electronic box on the rear tray) was pointed at the Sun. Setting an initial pointing ahead of the Sun image motion, the drift of the Sun over the field- of-view (≈ 1 degree) gives a well defined trajectory in the SAS image plane. Aquiring images for every integration cycle, Sun profiles were obtained (see Fig. 2). Since the width of the solar limb, i.e. the angle over which the intensity raises from zero to about 50% of the maximum intensity (for images taken at 670 nm), is in the order of 1/100 arcsec, the measured width is a function of diffraction, chromatic aberration, environmental and instrumental influences. Approaching the limbs, the background is increasing gradually due to diffuse reflections

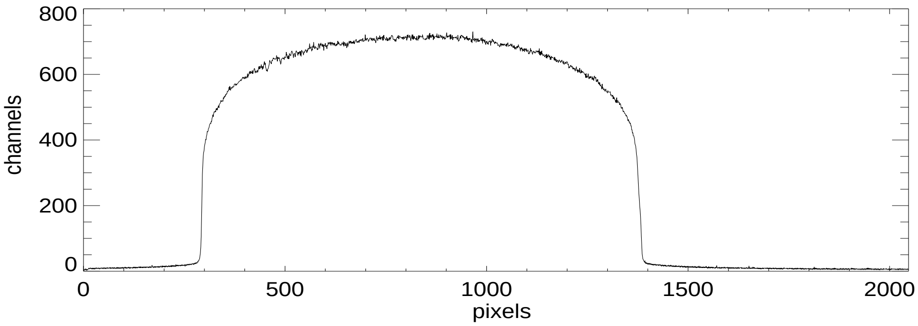

Figure 2. Measured Sun profile, integration time ≈ 500 μs. One pixel corresponds to 1.73 arcsec.

from the CCD chip surface and subsequent back-reflection from the CCD window. Therefore, the limbs have been fitted with an error function adding a linear background. This fit provides a well defined width and position of the measured limb. Subtracting quadratically all known components of the point spread function, an additional limb broadening of 1 to 2 arcsec is obtained which is a realistic upper limit for seeing.

For ideal circumstances and with positions (lens optical center, CCD pixel location) known exactly, the mid-perpendicular of the 3 chords, the straight line between the two limbs on each CCD, would intersect in one point, the momentary Sun center position. Given the accuracy of our dimensional measurements and given thermal and mechanical instabilities, the mid-perpendiculars usually do not intersect in one point but form a residual triangle. The size and shape of the triangle depend sensitively on the position of lenses and CCDs. The best guess for the Sun center is then the center of gravity of the three intersects of the mid-perpendiculars. The six measured radii and the residual triangle form a set of not self-consistent parameters which can be used for calibration of the SAS pointing. The following calibration algorithm has been used:

1. Assume that lens/CCD no. 1 is in correct position.
2. Minimize the variance of the size of the residual triangle by varying the two undefined angles.
3. Minimize the size of the residual triangle by varying the two shifts along the CCDs.
4. Minimize the variability of the radii by varying the two shifts perpendicular to the CCDs.

As shown in Fig. 3, these three 2-dimensional minimization algorithms lead to a set of calibration parameters which is self-consistent. Using the ground based measurements, the geometry of the SAS could be easily calibrated to an accuracy of 5 arcsec for the angles between the CCDs and 1.5 μm for the components of the CCD positions. Therefore, the relative pointing is expected to be better than 0.2 arcsec. The offset to the grid axis and thereby the absolute pointing will be drawn from our dimensional measurements of all features of the imager.

3.2. RAS measurements

For calibration, the RAS has been taken to Jungfraujoch, Switzerland, at an altitude of 3500 m above sea level. Unfortunately, the measuring nights were not very cold and a CCD temperatur of -5 to 0 °C has been measured. However, the dark level and noise measurements show no relevant decrease of the performance comparing to the operation at an ideal temperature at about -20 °C. A rotating mirror has been installed in front of the RAS lens to project the star onto the RAS optics. The rotational speed has been adjusted for 16 ms star passage time over the CCD, corresponding to the spacecraft spinning at 15 rpm. Adjusting the azimuth of the RAS for a star to measure, the image of a star moves parallel to the 96 pixels in a column over the CCD and no additional image blur is produced.

Several stars with magnitude $m_V \approx 0$ have been measured with various focal length. Using an integration time of ≈9 ms, star events with three consecutive time bins have been taken only. After subtracting the previously measured

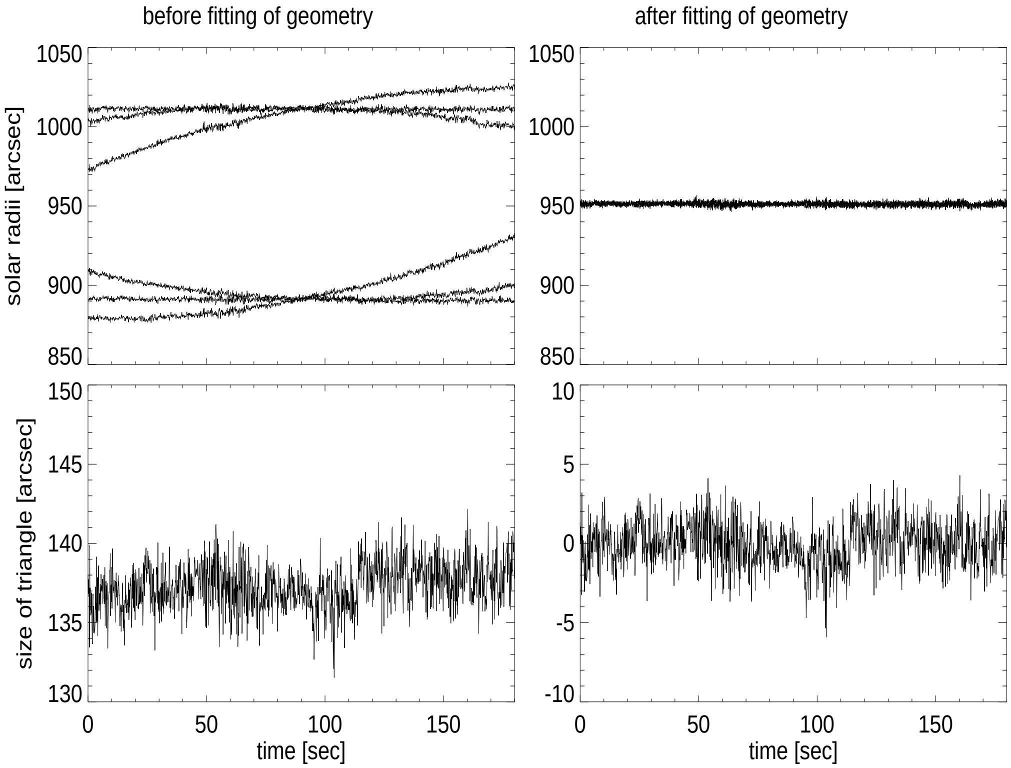

Figure 3. The left column of two plots show the 6 measured solar radii (upper plot) and the size of the residual triangle (lower plot), i.e. the square root of the area of the triangle, for the nominal geometry of the SAS lenses and CCDs. The plots in the right column show the same variables after fitting of the geometrical parameters of the SAS subsystems.

background the dependency of the width of the star event on the focal length has been calculated (see Fig. 4). In order to have comparable results, each data point has been corrected for the appropriate off-axis angle using a guess for the dependency of the point spread on the yaw angle, the angle which corresponds to the position of a star event on the CCD. However, the fit for the best focal length shows very little dependency on this guess of the point spread. Optimizing the focal length, a point spread of $\approx$0.5 arcmin has been measured for an on-axis star event.

By calculating a theoretical response of the CCD, taking into acount the spectral transmission of the optical system, the spectral response of the CCD and the spectral type and magnitude of the measured star, a response of star events up to 75% has been observed.

In order to determine the absolute roll angle of the spacecraft, the optical axis of the RAS has been aligned to the imager with an accuracy of 1 arcmin, corresponding to 1 arcsec positioning error of an event at the solar limb. Therefore, the position of the CCD in the RAS sensor box has been measured with respect to the RAS tooling balls on a 3d coordinate measuring machine and after integration the RAS tooling balls have been measured with respect to the imager tooling balls. The yaw angle, i.e. the position of a star event on the CCD, is rather uncritical since it will be used for star identification only.

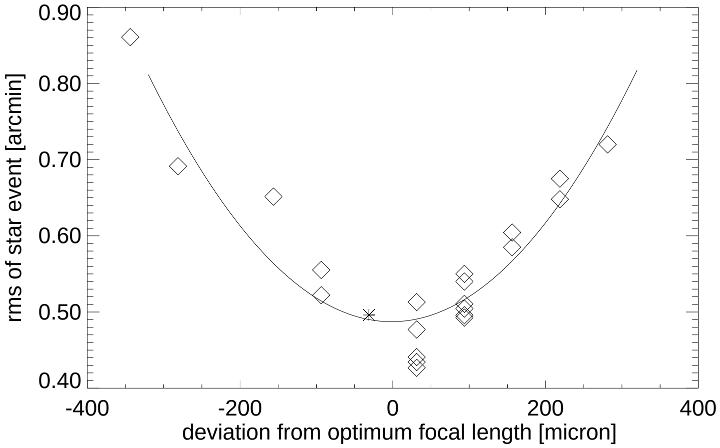

Figure 4. Fit for best focal length. The width of a star event has been measured for various focal length. The quadratical fit of the data leads to the optimum focal length, at zero on the abscissa. The data point marked with an asterisk is a weighted mean for many data points which has been taken to estimate the dependency of the point spread on the off-axis angle.

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