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Performance of the Hard X-Ray Imaging Spectrometer

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The hard x-ray imaging spectrometer (HXIS) images the sun in hard x-rays. The instrument has the following characteristics: six energy bands in the range 3.5-30 keV; spatial resolution 8 arc sec × 8 arc sec. (FWHM) over a 2 arc min 40 arc sec, and 32 arc sec × 32 arc sec. (FWHM) over a 6 arc min 24 arc sec field of view; time resolution 0.5-7 s depending on the mode of operation. The instrument warns other instruments on board the Solar Maximum Mission (SMM) at the onset of a flare, and provides information on the flare location and intensity. Pre- and postlaunch technological experience is summarized. In general, the instrument performs surprisingly close to specification. A few anomalies in the performance are mentioned; they do not significantly affect the scientific yield of the instrument.

The Instrument in General

THE instrument consists of the following subsystems: 1) imaging collimator; 2) intermediate structure and thermal system; 3) position sensitive detector system; 4) interconnecting and analog electronics, high voltage power supplies; 5) data handling electronics and low voltage power supply.

Figure 1 depicts an open view of the imaging collimator and the detector system, and, in addition, the projection of the fields of view on the sun. The instrument is equipped with a Solar Limb Sensor (SLS) system, which is partly integrated with the collimator and partly with the analog electronics and the detector system.

For an explanation of the instrument's operation and for more technical details, see Ref. 1, for the collimator in particular, see Ref. 2.

Imaging Collimator

The collimator contains ten tungsten grid plates which are kept aligned relative to each other within an aluminum structure, this being a rectangular tube with stiffening frames.

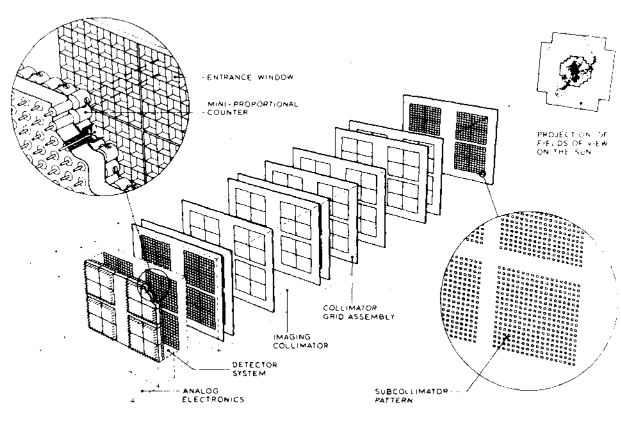
The requirements put on the structure are very severe. First of all it must keep its shape over the course of time. In addition it must return to its original shape after vibration and thermal tests, transportation, etc., within a few μm. To avoid effects of external forces introduced via the supporting rods, the structure must be stiff against bending and torsion. This instrument has proved that with lightweight construction techniques a mechanical stability on the order of 1 μm can be obtained. In order to achieve this, special attention was paid to the support of the collimator structure, realized by means of six rods designed according to a kinematic construction technique. In order to illustrate the distribution of tolerances within the grid plates and the structure, the plate characteristics are described below in some detail.

Each grid plate is equipped with more than a million holes, distributed over four grids, the smallest (in the first and last plate) being 46×46 μm². These holes take care of the fine field of view (8 arc sec × 8 arc sec FWHM). The smallest holes in the eight intermediate grid plates are 64×64 μm², thus allowing for a 9-μm tolerance in any direction without any decrease in *x*-ray transmission if the grid plates were perfect. However, the following deviations from nominal occur in the plates.

1) The positions of the holes vary relative to their nominal positions with a standard deviation of 2 μm. This is probably the result of the changed mechanical tension distribution in the plane of the grid after the holes have been etched.

2) The hole size varies with 2.5-μm standard deviation in either direction. As a result of the etching technique applied, the holes have no rounding whatever at the corners.

3) The grids are glued onto a plate frame in such a way that the positions of six critical points on a grid fit in the best (calculated) way to the nominal positions of these points, valid if the grids were perfect. This method has the advantage that the deviation from nominal of the hole positions for a complete grid plate is hardly more than that for a single grid. In addition to the grids, optical alignment components belonging to the built-in alignment system are glued to the



HARD X-RAY IMAGING SPECTROMETER

Fig. 1 Open view of the imaging collimator and the detector system. The collimator contains ten grid plates, each divided into 576 sections, as indicated on plates 1 and 10. The images formed are analyzed by the position sensitive detector system containing, in total, 990 miniproportional counters.

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frames. The error in the positions of the alignment components is minimal as a result of the best-fit method and is measured to be about 1 μm.

Apart from the errors in the grid plates, there is a small error in the initial alignment of each intermediate grid with respect to the first and last plate. This error is about 1 μm.

Reviewing the various tolerances, the first conclusion is that the 9-μm play mentioned before is to a large extent eaten up by the hole size and position variation (1 and 2). The application of larger hole sizes for the intermediate plates is certainly a must if a triangular transmission profile (i.e., the transmission as a function of the angle of incidence) is required. In order to achieve this the transmission profile must be determined by the first and last grid hole sizes only.

The second conclusion is that the structure should indeed keep the grid plates well aligned within a few μm for optimal performance. However, even if 10- or 20-μm misalignment were to occur, the instrument would still yield useful scientific results. During the integration and test phase of the instrument the collimator structure was found to be extremely stable, the structure being manufactured at the beginning of 1979 and aligned in March 1979; no deviation in alignment could be observed in November 1979 after a vibration test, thermal vacuum test, and several transportations between institutions. The vibration test input level was 6 g. Notching was applied to limit the acceleration at resonance frequency to 51 g. During the static test the input level was 18 g.

The alignment check was based on measurements made with the alignment system, which provides for each intermediate grid plate an individual measurement of the plate position with an accuracy of about 1 μm.

During flight quite a good estimate of the alignment can be derived from transmission measurements of the fine field of view relative to those of the coarse field of view (184 $\times$ 184-μm^2 hole size). For this, x-radiation from solar flares seen by both fine and coarse fields of view is used. The coarse field of view is, of course, much less sensitive to misalignments. Although no in-depth study has been carried out so far, no obvious decrease in fine field of view transmission has been determined. Given the surprisingly good stability observed preflight and the specific characteristics of the construction technique followed, a small change is in fact very unlikely to occur.

Rather, one is afraid of an alignment "accident" resulting in a serious misalignment of a grid in an arbitrary direction, resulting in excess transmission at an arbitrary location on a grid plate. This obviously has not happened.

If one can conclude that the transmission of the collimator is close to the value of a perfectly well-aligned collimator, the transmission profile (i.e., the transmission as a function of the angle of incidence) has remained close to nominal as well. Any effect on the profile goes hand in hand with a transmission decrease.

Intermediate Structure and Thermal System

The intermediate structure is an optical bench carrying the collimator, the detector system and the analog electronics, and the thermal system. It provides a three-point mount of the instrument to the spacecraft. The lightweight construction technique applied is the same as used for the collimator.

The same principles are used for the support of the collimator on the intermediate structure, for the support of the intermediate structure on the spacecraft instrument support plate, and for the support of the grid plates within the collimator structure. The mechanical stability of the system from spacecraft instrument support plate (simulated by the vibration table) to collimator structure was tested through vibration test with the help of a mirror mounted on the vibration table and a mirror on the collimator structure. The angles between the mirrors were the same before and after the vibration tests, within the measuring accuracy of a few arc seconds.

The thermal system surrounds the collimator on all sides. At the front and rear ends, the X-rays penetrate through thin foils which are part of the thermal system. Temperature gradients over the collimator structure are minimized by insulation at all planes parallel to the optical axis and an aluminum tube outside of this insulation. Heat exchange between the tube and the intermediate structure through radiation has been stimulated by appropriate paints; heat exchange through conduction via the supporting rods has been diminished as much as possible. The radial temperature differential over the collimator structure should be below 0.4°C.

The thermal behavior of the instrument is in accordance with the predictions insofar as absolute temperatures and gradients are concerned. However, during flight on two occasions (May 20 and July 22) some damage to the thermal foils at the front of the collimator has occurred. As a result, the temperature inside the foil package has risen by 40°C. This has not affected the collimator performance. It has caused changes in the yaw pointing direction, as measured with respect to the spacecraft Fine Pointing Sensor, of -14 and -9 arc sec, respectively, in total -23 arc sec. Before these events the yaw remained stable to within arc seconds. The pitch has been stable since launch. From the available thermal models used during instrument design, a qualitative explanation of the change in yaw can be made as being a consequence of the change in heat input at the front end resulting in a temperature difference between the collimator structure and intermediate structure. The size of the effect is much more than can be expected from the thermal model. The shift in pointing direction has been partially compensated for by adjusting the spacecraft pointing.

The pointing direction can be determined by means of the two Solar Limb Sensors (SLS's). The fact that these two SLS's yield the same pointing within 1 arc sec means that the additional heat input has not resulted in an expansion of the first plate relative to the last plate of more than 6 μm (3 μm in both the positive and negative sense).

Position-Sensitive Detector System and Analog Electronics

The detector system consists of two detectors, each containing 450 miniproportional counters (mpc's). 16 mpc's of each detector are irradiated continuously by radioactive sources ^{55}Fe and ^{109}Cd.

Apart from the six primary energy bands referred to in the abstract, there are a few narrow bands to measure the peak position in the pulse-height distribution from the mpc's concerned. On the basis of observed peak positions, the microprocessor system updates the values of the high voltages on the detectors so as to compensate for possible shifts in the position. The adjustment takes place in steps of 0.4%. The detectors show a very satisfactory behavior, taking all detector characteristics into consideration. Only a very small output decrease is observed; detector 1 shows a linear decrease of 1.2% per month, detector 2 exhibits an exponential decay: 2.8% decrease after 3 months and 3.6% decrease after 5 months. It is unknown where these decreases come from. It could be less efficient electron or charge collection, decreased amplification, aging of electronic components, etc. The energy resolution can be affected in the worst case as the square root of the output change, which in this case does not lead to diminished scientific yield of the instrument.

The stepwise position sensitivity and the detector drift field position can also be checked during flight, because half of the inflight calibration sources shine on the intersections of four mpc's. Countrate distribution over a set of four mpc's can be observed both during quiet conditions and during solar flares.

The detectors are protected during passes of the spacecraft through the radiation belt (South Atlantic anomaly). The high voltages are lowered during that time on the basis of the flux of particles passing through the detectors. After each passage the high voltages are restored to their previous values as stored in the instrument memory. This system turns out to work perfectly.

The precise determination of the detector outputs takes quite some time (10 min). This does not cause any problem, because the previously calculated values are always available. Therefore the inflight calibration sources can be relatively weak. The reaction time if the particle flux enhances is short, as is the time needed to initiate the normal mode of operation again.

The analog electronics consist of a number of subsystems for pulse height analysis, photon event location, pile-up rejection, dc restoration, etc. The performance of each of these systems can be checked during flight, although this has not been done in detail so far.

All systems seem to work according to their specifications, as do the high voltage supplies.

Data Handling Electronics

The data-handling electronics of HXIS is a very versatile processing system based on a pair of microprocessors in a master/slave configuration. The master/slave roles are interchangeable by ground command.

The system evolved as two virtually independent microprocessors in order to make the experiment as free as possible of single-point failures. This configuration also optimizes the overall data collection and transmission function. With a spacecraft telemetry allocation of 5-Kilobits/s^{-1} approximately 7 s is required to transmit six complete images, corresponding to the six energy bands, together with count rate and housekeeping data. However, scientific considerations require a degree of flexibility such that time resolutions of imaged data up to the order of 1 s are attainable. Such high time resolution necessitates a high degree of data selection and compression, which in turn requires that the microprocessor involved be dedicated almost exclusively to this task. This would greatly reduce the data collection efficiency, if a single microprocessor were used, by introducing "dead time." Using two microprocessors, we have been able to separate the functions of data collection and of data selection/compression/transmission. In the normal configuration one microprocessor accumulates data while the other is processing accumulated data and passing it to the telemetry system. After a preset time, controlled by the master, these functions are interchanged.

The microprocessors have several additional important functions, namely, to regulate the high voltage to the proportional counters, to perform periodic in-flight calibrations, and to provide a flare alert, complete with spatial position and intensity information, to the spacecraft for use by other experimenters.

The data handling electronics are described in Ref. 3. Therefore only sufficient detail to support the aims of this paper (to describe technical experiences arising from the mission) will be given here. The electronics are all complementary metal-oxide semiconductor (CMOS), each half consisting of a central processing unit (CPU), an Intersil IM6100A, which interacts with a series of peripherals and memory via a 12-line unibus, using the same architecture and instruction set as the PDP-8E. Each microprocessor operates in three 4096 ("4K") word memory fields. The default instruction field contains the basic program in 2K of read-only memory (ROM), with a further 1K of random-access memory (RAM). The remaining 1K of addresses are not used. There is also a pair of 4K fields of RAM, one of which is normally used for data accumulation, the field selected being under software control.

The decision to include such a large ROM program was taken to permit the flying of a highly sophisticated "default mission" with the minimum of ground-based commands. The ROM therefore embodies a considerable degree of "intelligence" for the examination of, and reaction to, the data stream in real time. A penalty of this decision is the need to finalize a complex program well before any experience is gained from integration and test, or operation, of the instrument. Having used this approach, we suggest that for future missions it is sufficient to develop a shorter and less sophisticated ROM designed principally to permit ready loading of special purpose programs into RAM. For situations where the loading of programs postlaunch is expected to be difficult, however, we feel that the choice made for HXIS is appropriate.

Whatever the balance adopted, we cannot stress too highly the need for reprogrammability. It is quite impossible, in an instrument designed to operate in a hostile, varying environment with data arising from previously unobserved phenomena (in this case high time resolution X-ray pictures) to define optimal instrument operation and data handling. The HXIS microprocessors and software were therefore designed to be reprogrammable at three levels: 1) The values of certain constants routinely used by the default ROM were made adjustable by ground command, internal checks being included to prevent inadvertent loading of false values. Using this facility it has been possible to adjust characteristics of the data stream (temporal resolution, areal coverage during flare response, and flare alert and belt safety response trigger levels) to optimize use of the default ROM. 2) Patches can be made to RAM segments of the ROM field to replace subroutines, interrupt service routines and, in some circumstances, segments of ROM by transferring control to these new patches at appropriate ROM decision points. 3) One 4-K RAM field is available for loading complex extensive stand-alone programs should these prove necessary.

The third option has not, at the time of writing, proven necessary, but the second option has been used to extremely

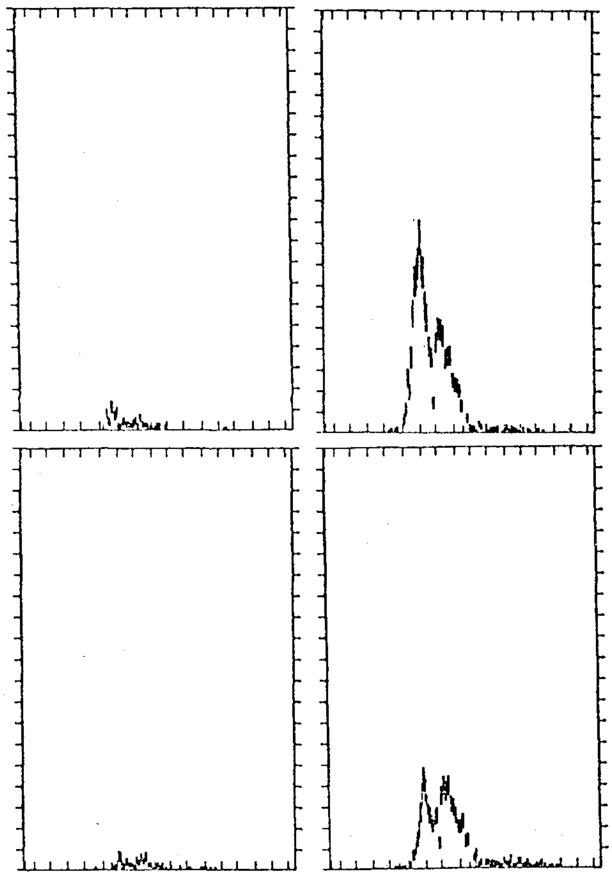

Fig. 2 Event of May 9, 1980, 07:12 universal time (UT) as registered by four adjacent mpc's in the fine field of view. The energy range of the source data is 16-30 keV. On each plot the vertical scale is 0-50 counts/s, the horizontal scale has ticks at 1-min intervals.

good effect in, to a large extent, neutralizing a potentially serious hardware failure. On May 7, 1979, after three months of operation, one microprocessor ceased to give any signs of life and has failed to respond to any commands since that date. As a result half of the data (every other set of images) was lost and the telemetry stream only 50% utilized. One of the peripherals attached to each microprocessor is an accumulator bank (ACB), a subsystem which samples certain key countrates, instrument parameters, and high energy X-ray monitors at an adjustable time resolution which is currently 0.125 s. Patches have been devised for the ROM field which fill the gaps in the telemetry stream with continuous high time resolution ACB data, data which was not included in the default data stream.

No sorting or compression is applied to the ACB data, so that counting efficiency is almost unaffected. Even so there is sufficient time to include all the ACB data in the telemetry stream. This reprogramming has enabled us to maintain full use of the available telemetry channel even in the event of a major change in the data handling system. Alternative patches could be envisaged later in the mission.

It is not possible to locate with any certainty the source of the failure which has caused the loss of one microprocessor. A number of components could result in the symptoms observed. In the remaining microprocessor the only symptoms of malfunction noted have been apparent failures in two small segments of RAM memory. Once again a number of chips could be responsible. It is not even possible to demonstrate the times of these failures as post launch. Both memory segments are in little used areas and were discovered during the course of patch development for in-flight software modifications. Prior to these discoveries the last time that memories were tested was during prelaunch integration and test.

Sample Result

To illustrate the resolution of the instrument, Fig. 2 presents intensity/time profiles of a small event as registered by four adjacent mpc's in the fine field of view. No correction has been applied for overlap between adjacent field of view elements. Knowledge of the characteristics of the collimator will allow the effects of such overlap as exists largely to be removed from fully processed images.

Acknowledgments

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