# High Energy X-ray Spectrometer on Chandrayaan-1

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**Chandrayaan-1, India's first planetary exploration mission to Moon carries a suite of payloads including a High Energy X-ray spectrometer (HEX) designed to study low-energy (30–270 keV) natural gamma rays emitted from the lunar surface due to decay of uranium and thorium. The primary science objective of HEX is to study transport of volatiles on the lunar surface through the detection of the 46.5 keV line from $^{210}$Pb decay, which is a decay product of volatile $^{222}$Rn, both belonging to the $^{238}$U decay series. HEX is designed to have a spatial resolution of ~33 km at energies below 120 keV. The low signal strength of these emissions requires a large area detector with high sensitivity and energy resolution, and a new generation Cd–Zn–Te (CZT) solid state array detector is used in this experiment. Long time integration will be required to detect the emission because of the significant lunar continuum background and weak signal strength. The various sub-systems of the HEX flight payload and test results from ground calibration are described in this article. HEX will be the first experiment aimed at detecting low energy (<300 keV) gamma ray emission from a planetary surface.**

**Keywords:** Chandrayaan-1, gamma rays, lunar pole, moon, volatile transport.

## Introduction

THE primary scientific objective of the Chandrayaan-1 mission is to further our understanding of the Moon based on simultaneous mineralogical, chemical and photo-geological mapping of the lunar surface. Chemical composition of any planetary body provides important clues towards understanding its origin and evolution. *In-situ* measurements, remote sensing techniques and laboratory analysis of returned samples provide information on the elemental composition of planetary surfaces. High energy (>500 keV) gamma ray spectroscopy is a prime tool for remote sensing studies of chemical composition of planetary bodies and have been utilized to study composition of the Moon, Mars and Asteroids at various spatial resolutions. So far, detection of lower energy (<500 keV) gamma rays has not been attempted because of low signal strength and the anticipated high detector and planetary continuum background. With the development of new solid state array detectors it is now possible to explore this energy region. The High Energy X-ray (HEX) experiment on-board Chandrayaan-1 is designed primarily to study the emission of low-energy (30–270 keV) natural $\gamma$-rays from the lunar surface resulting from radioactive decay of the $^{238}$U and $^{232}$Th. In particular, HEX will address the question of volatile transport on lunar surface towards lunar polar regions using radon as a tracer. Significant loss of volatiles from the moon had occurred during its formation and the low surface gravity and the thermal environment also led to the loss of most volatiles from the lunar surface throughout its evolution. Nevertheless, radioactive decay, solar wind sputtering of lunar surface and natural degassing can lead to presence of volatiles in the lunar space. HEX is the first experiment designed to carry out spectral studies at hard X-ray energies (30–270 keV) using solid state detectors having good energy resolution.

## Volatile transport on Moon and expected fluxes

The extreme nature of thermal baking and cooling of the lunar surface leads to pole-ward transport of lunar volatiles (see Figure 1), implying their higher concentrations in permanently shadowed regions near the pole that can act as cold traps for such volatiles[1]. In fact, the possibility that there could be substantial reservoir of water ice embedded in lunar soil in such polar region of the moon is based on this concept. The HEX experiment on Chandrayaan-1 is designed to investigate the transport of volatiles on the lunar surface through the detection of the 46.5 keV $\gamma$-ray line from radioactive $^{210}$Pb (half-life ~22 years), a decay product of the volatile $^{222}$Rn (half-life ~4 days), both belonging to the $^{238}$U series. Transport of $^{222}$Rn to cold polar traps could manifest in a significant

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enhancement in the intensity of the 46.5 keV gamma ray line from these traps relative to the rest of the Moon. Other prominent emission lines from $^{234}$Th (63.3, 92.4 and 92.8 keV), $^{226}$Ra, $^{235}$U (186.2 and 185.7 keV) and $^{212,214}$Pb (238.6 and 214.9 keV) will also be studied to obtain low spatial resolution U and Th map of the polar and U–Th enriched (e.g. KREEP) regions. The possibility of inferring compositional characteristics of various lunar terrains, based on the shape of the continuum below 100 keV will also be attempted[2].

## Estimation of emission flux

Both line and continuum emissions are expected in the 30–270 keV energy range in a lunar environment. Estimation of continuum flux requires modelling of the galactic cosmic ray (GCR) interactions with the lunar regolith material. We have used a Monte Carlo code written using Geant4 package[3] and estimated the lunar gamma continuum flux for <300 keV energy considering appropriate GCR flux and compositions of various types of lunar terrain. The gamma continuum flux peaks at ~100 keV, and decreases as a function of energy in the region 100–300 keV, and shows dependence on lunar composition, particularly in the <100 keV region[2]. The maximum continuum flux occurs at ~100 keV and is 0.0025 photons $cm^{-2}$ $s^{-1}$ $keV^{-1}$ (for ferroan anorthositic (FAN) composition and average solar activity), and it decreases to ~0.0008 photons $cm^{-2}$ $s^{-1}$ $keV^{-1}$ at 300 keV, since most of the high energy gamma rays will repeatedly lose energy by Compton scattering before escaping the lunar surface (see Figure 2). Estimates of the continuum fluxes (1–300 keV) for various level of solar activities show that the maximum gamma continuum flux (for FAN composition) is 0.0027, 0.0025, and 0.0021 photons $s^{-1}$ $cm^{-2}$ $keV^{-1}$ at ~100 keV for solar minimum (modulation parameter $M = 300$), average solar ($M = 600$), and solar maximum ($M = 900$) conditions respectively[2,4].

Although data for expected detector (cadmium–zinc–telluride (CZT)) background at the energy range (30–270 keV) and space (lunar) environment are not available, background measurements with CZT detector flown in high altitude balloon flight suggest a value of ~0.0006 $s^{-1}$ $cm^{-2}$ $keV^{-1}$ when active anticoincidence shield is employed, while a value of 0.0001 $s^{-1}$ $cm^{-2}$ $keV^{-1}$ was inferred for a 2 mm thick CZT detector surrounded by a thick BGO active shield in a satellite placed at ~1.5 million km from the earth in L2 orbit[5,6].

For emission from the U, Th enriched (KREEP) regions of the Moon, conservative estimates suggest required exposure times ranging from 10 min ($^{212}$Pb, 238.6 keV) to 14 h ($^{228}$Ac, 209.2 keV) for detection of signals at 3 sigma level above background[4]. Nominal exposure time required for the 46.5 keV line from $^{210}$Pb will be several hours. However, if volatile transport to colder polar region is operating on the moon, the signal of the prime line (46.5 keV) of interest from $^{210}$Pb in the polar region is expected to be significantly enhanced and the total exposure time requirement will be correspondingly reduced. The polar orbiting Chandrayaan-1 will facilitate accumulation of signal over the polar region for long

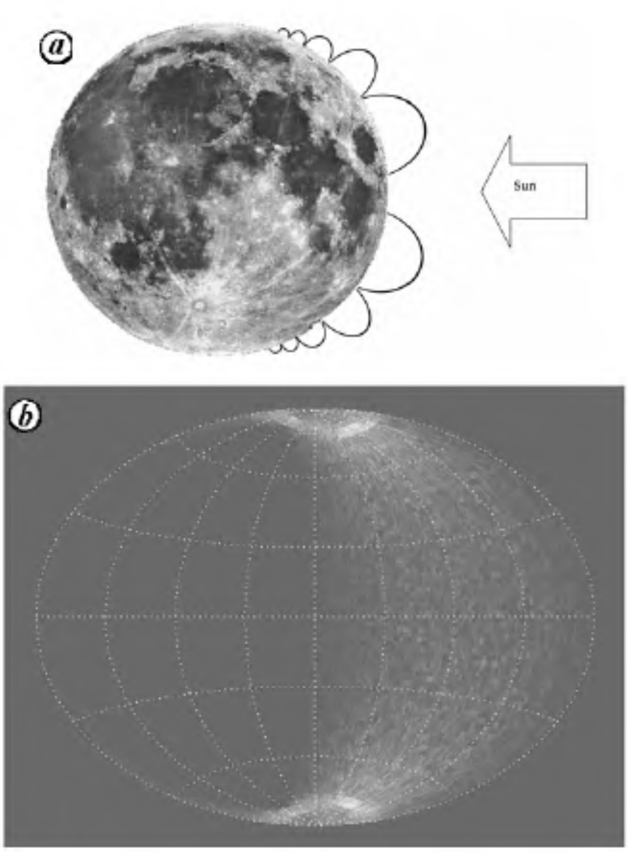


**Figure 1.** ***a***, Schematic showing pole-ward migration of volatiles. ***b***, Results from simulations indicating the pole-ward migration of volatiles driven by the thermal cycling.

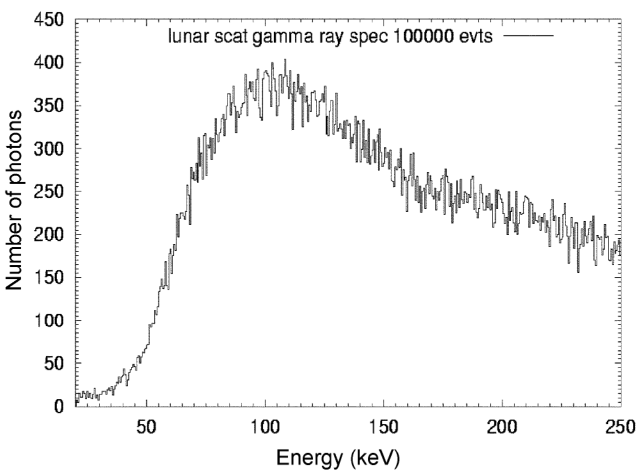


**Figure 2.** Simulated lunar X-ray spectrum (see refs 2 and 4).

durations and it should be possible to detect the enhanced signal of $^{210}Pb$ and quantify the magnitude of volatile transport on the lunar surface.

## Instrument configuration

The detector system and the control electronics are two physically separate units which when connected together forms the full HEX payload hardware. A block diagram of HEX is shown in Figure 3.

### *Detector system*

Solid-state pixilated CZT arrays are used in HEX payload for the detection of low energy photons in the energy range 30–270 keV from the lunar surface. In order to keep the background events to a minimum, an anticoincidence system (ACS) consisting of CsI(Tl) scintillator coupled with two photomultiplier tubes (PMTs) is positioned below the CZT detector arrays. A stainless steel collimator is mounted above the CZT arrays to limit the FOV to a 33 km × 33 km spot on the lunar surface from the 100 km orbit of Chandrayaan-1.

The detector area of 144 cm$^2$ is realized by cascading nine CZT arrays, each 4 cm × 4 cm and 0.2 cm thick and composed of 256 (16 × 16) pixels (size: 2.4 mm × 2.4 mm). Each CZT module (256 pixels) is coupled with two Application Specific Integrated Circuits (ASICs) XAIM3.2 (made by IDEAS, Norway), each containing 128 amplifiers, shaper circuits and associated control circuits. The ASICs are connected in a daisy chain and each ASIC provides output signals on a common shared bus. It is a low noise, low power multi-channel integrated circuit, which is self-triggered and data-driven.

The ASIC outputs are in the form of currents for 1 μs duration and are suitably processed by the Front-End Electronic (FEE) circuits. The FEE design involves processing the signals from ASIC to get the energy and position (pixel) information of the event triggered by an energetic photon incident on the pixilated CZT detector

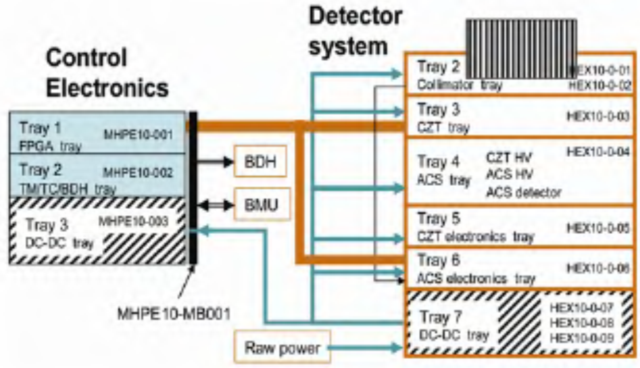


**Figure 3.** Block schematic of the HEX hardware.

array. Depending upon the energy of the incoming radiation, this energy loss is dominated either by the photoelectric effect or Compton scattering. Suitable bias voltage (~600 V) is applied to the CZT detector to facilitate the collection of electron/hole produced by each photon interaction resulting in a charge pulse at the output. Energy information (pulse height) is digitized by a 10-bit ADC and sent to control electronics for transmission of the data.

Even though X-rays in the 30–100 keV range have a high probability for interaction in the detector via photoelectric process, the incident X-ray photons can also result in partial deposition of its energy due to Compton scattering. This partial deposition of energy in the CZT detector could result in poorer energy resolution and increased background. HEX employs another X-ray detector to identify and reject partial energy deposit events using an anticoincidence technique. A CsI(Tl) scintillator crystal coupled to photomultiplier tubes, is used as the ACS. CsI(Tl) is less hygroscopic and also less fragile compared to other scintillators. The ACS is configured as a single piece CsI(TI) system (14 cm × 14 cm × 1 cm). Light produced in the crystal due to interaction of high energy X-ray photons is detected by two side mounted PMTs. The PMTs are biased to 800 V by a HV unit. The two PMT outputs are summed at the input of a charge sensitive amplifier which converts charge to voltage and the pulse height amplitude will be proportional to incident photon energy. HEX identifies the scattered event using the principle of coincidence of signals from the two detectors (CZT and CsI(Tl)) within a short time window of ~3.5 microsec. Events which trigger both detectors are tagged and can be rejected during ground processing

### *Control and processing electronics*

The Control (processing) electronics on command collects the pixel position, energy and Event Tagged Time (ETT), generated from within the HEX electronics, and formats the data into 2048 byte packets and stores in memory. It has its interfaces with telemetry for various health information's and telecommand systems. This is also used to configure the CZT detector ASICs for various information. For every event detected, the ASIC will send out the trigger, energy and position information of the hit channel in a format shown in Table 2.

**Table 1.** High Energy X-ray Spectrometer specifications

| Parameter | Specifications |
|---|---|
| Energy range | 30–270 keV |
| Energy resolution | 12% at 60 keV |
| ACS threshold | ~50 keV |
| Spatial resolution | 33 km × 33 km FOV |

**Table 2.** Event data format

| | |
|---|---|
| Energy information (ADC o/p) | 10 bits |
| Pixel position | 7 bits |
| CZT sub-array address | 5 bits |
| Event Trigger Time (ETT) | 17 bits |
| ACS presence | 1 bit |
| Total event data | 40 bits |

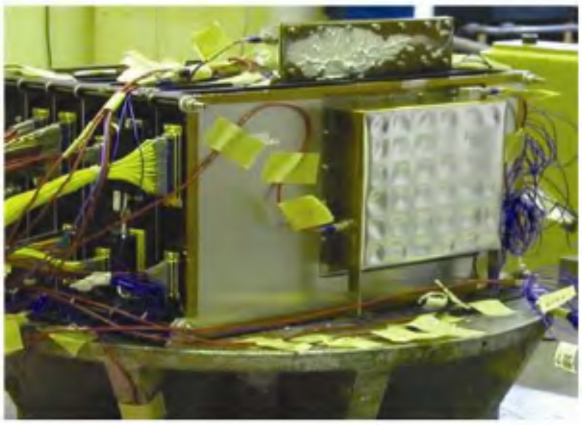

**Figure 4.** High Energy X-ray Spectrometer on vibration test table.

The acquired data are stored into the FIFO, which generates a request flag and waits for Data Handling/Solid State Recorder system of the spacecraft to receive data from the FIFO. Appropriate interface with telemetry and telecommand system ensures transmission of all data to the ground station. Figure 3 is a schematic of the HEX hardware configuration.

## Instrument calibration and results

HEX was successfully subjected to space qualification tests that included thermal cycling in a vacuum chamber (thermovac) and vibration tests simulating launch conditions. Mechanical integrity and consistency in electrical performance were checked before and after vibration. Subsequently, the payload was placed inside a thermovacuum chamber where the electrical performance of the system was tested at a few microtorr for extremes of temperatures (–20°C to +50°C) expected in lunar orbit. During stand-alone tests and tests after integration onto the spacecraft, HEX was operated for various input voltages ranging from +37 V to +42 V to largely simulate the changing on-board power condition for various solar illumination scenarios. All HEX parameters were monitored and found to be nominal. The operating temperatures for the CZT detectors on HEX are designed to be below +10°C. Due to the large sensitive area of CZT (144 $cm^2$), active cooling of these detectors was not considered and instead a passive cooling configuration is implemented using a heat-pipe and radiator. The heat-pipe connects the CZT heat dissipation board to the cold radiator plate and is designed to provide the required operating conditions in the lunar orbit envisaged for Chandrayaan-1. This cooling requirement of CZT implies that a formal calibration of the detectors is best carried out in thermovacuum chambers where the absence of convective cooling and cold temperature of space can be simulated simultaneously.

## CZT detector calibration

Ground calibration efforts focused on deriving the conversion of ADC channels to photon energies for each of the 2304 pixels of CZT. The setup consisted of placing radioactive sources, Co-57 (122 keV), Am-241 (59.5 keV) and Ba-133 (30, 80 and 256 keV) in front of the collimator, covering the 30–270 keV energy range. The primary CZT calibration tests involved generation of spectra from these sources across all pixels and at various temperatures to derive the energy resolution, gain and offset determination (to convert ADC channels to energy units), all as a function of a few discrete temperatures. This database is then used to derive values of the above pixel parameters for any energy and detector temperature. Relative calibration carried out on ground meets the required specification (Figure 5); absolute calibration will be done through observations of standard astrophysical sources such as the Crab Nebula from the lunar orbit.

## Anticoincidence system (ACS)

The ACS ensures Compton suppression of events in the CZT detector, and rejection of background events due to the space environment in lunar orbit. The ACS has four pre-defined windows or channels covering the energy range: 26–114 keV (Win 0); 114–201 keV (Win 1); 201–306 keV (Win 2) and (306–879 keV (Win 3). ACS calibration addressed the conversion of these four windows in CsI(Tl) to energy ranges. Since the light output of the scintillator is sensitive to temperature, these conversions are also derived for various temperature settings. Two radioactive sources were used for ACS calibration, $^{133}$Ba (30.97 keV, 81 keV, 356 keV) and $^{57}$Co (122.1 keV, 136.5 keV). Figure 6 shows four ACS spectra measured with an external multichannel analyser at four different temperatures of the detector housing. The temperature dependence for the 356 keV peak channel fitted using a quadratic function is shown in Figure 7. The relative behaviour of the peak channels with temperature matches that from earlier works[7]. The corresponding variation of low-energy threshold of ACS with temperature can be derived from these results. A direct consequence of the shifting of the low-energy threshold (LET) is that even for a constant input spectrum, the total counts in each of the ACS windows will vary with temperature.

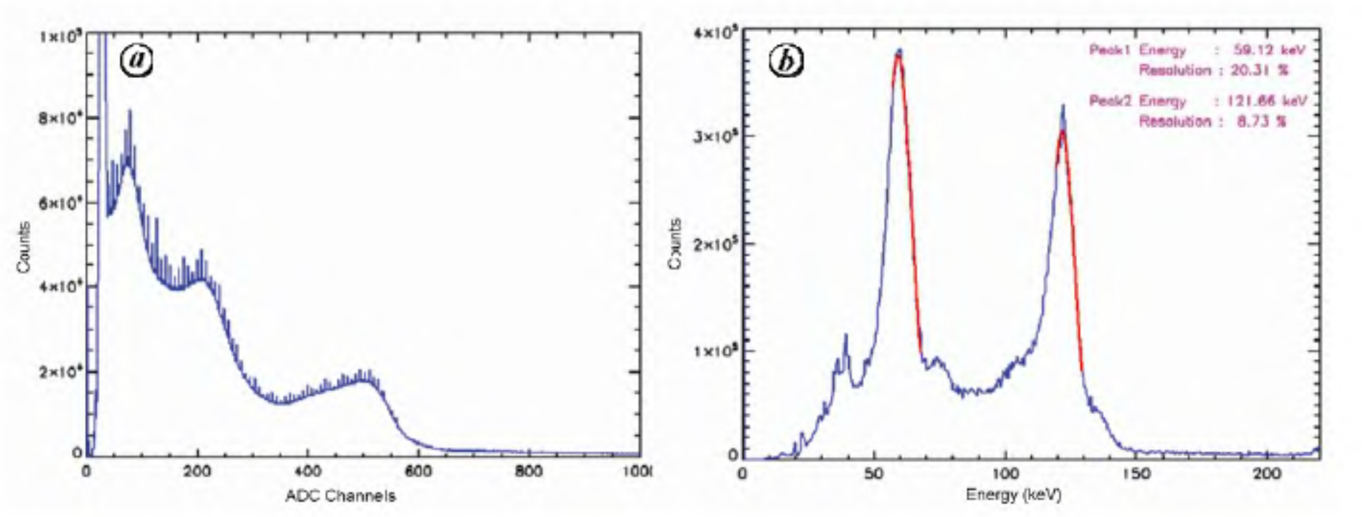


**Figure 5.** Sample spectra from the calibration of CZT. ***a***, Raw spectrum from all CZT pixels with no corrections on individual pixel gain and offsets. ***b***, Summed spectrum after applying pixel gain and offset corrections.

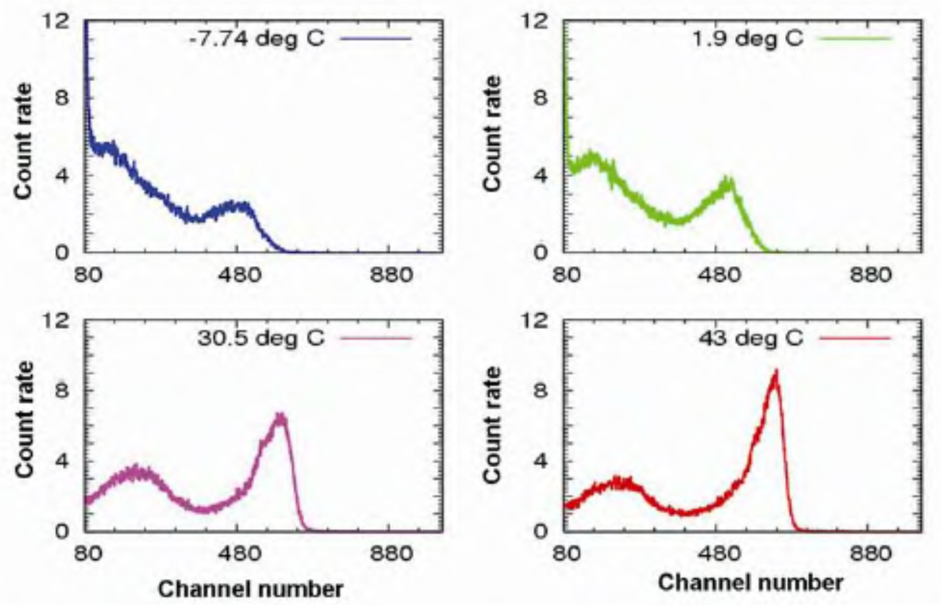


**Figure 6.** CsI(Tl) scintillator spectrum for $^{133}$Ba radioactive source at various temperature; quoted values refer to ACS housing.

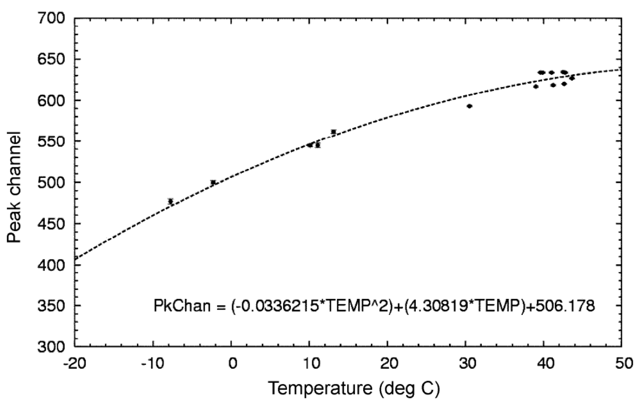


**Figure 7.** Temperature dependence of CsI(Tl) scintillator gain (at 356 keV).

This characteristic of the ACS spectrum demands careful monitoring of the crystal temperatures and application of suitable corrections in the data reduction process.

Each X-ray event in HEX is tagged with an ADC channel, event time and a flag that indicates if a simultaneous event occurred in CZT and ACS within the ~3 microsec. HEX data system outputs a frame of data (2048 bytes) whenever the FIFO gets full. This condition is satisfied when 405 CZT events are registered. Hence the time interval covered by each frame is variable and is driven by the event rate. As a frame is written out, the cumulative ACS counts (reset after each readout) in each of the four windows, is written into the frame header. These window counts are used to derive a time profile of ACS counts in the four broadband windows covering from ~30 to 900 keV. The flagging of individual events which registers a hit in the specified ACS window, enables generation of vetoed/cleaned CZT spectrum.

## Summary and conclusions

The HEX payload was commissioned on 5 December 2008. It is important to understand the in-orbit temperatures experienced at the CZT detector as the solar phase angle evolves with time. When the CZT detector temperature exceeds +10°C, HEX will be switched off due to anticipated increase in noisy pixels. HEX thermal model shows such a condition could occur for a short period (~1 month) in the lunar orbit around the noon-midnight condition when the solar phase angle is 10 degrees or less. During the dawn–dusk orbit of Chandrayaan-1 (solar phase angle close to 90 degrees), power constraints could also reduce the duty cycle of HEX. Nevertheless, with the payload operating during all other times, complete lunar surface coverage can be achieved during the 2-year nominal mission and with repeated coverage of the lunar poles. As the first spectroscopic experiment in this energy band, we look forward to interesting results from the Chandrayaan-1 mission.

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