# Monitor of All-sky X-ray Image (MAXI)

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**Abstract.** Monitor of All-sky X-ray Image (MAXI) is the first astrophysical payload which will be mounted on the Japanese Experiment Module (JEM) Exposed Facility in 2004. It is an X-ray all-sky monitor with unprecedented sensitivity to watch the activities of the X-ray sources in the whole sky in every 90 minutes. MAXI is boxshaped in 0.8 x 1.0 x 1.85 m with the weight of 500 kg. The mission life will be at least 2 years. MAXI has two fan-like field of views (FOV), 160 x 1.5 degree each. The X-ray instruments are Gas Slit Camera (GSC) and Solid-state Slit Camera (SSC). The GSC uses gas one-dimensional position sensitive proportional counters with 5340 $cm^2$ effective area in total and the SSC uses CCDs with 200 $cm^2$. Both are capable to detect one-dimensional image, which is used to obtain the locations of the X-ray sources in the FOV along the long direction. Together with the scan which determine the other direction, MAXI can scan almost all sky with a precision of better than 1 degree in the energy range of 0.5-30 keV. The CCD is electrically cooled to -60°C and the camera body is radiatively cooled to -20°C. The CCD chip itself and the radiators may suffer contamination problem. The continuous Ethernet down link will enable us to alert the astronomers in all over the world to the appearance of X-ray transients, novae, bursts, flares etc. We made a test counter and test chips in 1998. Those are being tested in RIKEN, NASDA and Osaka-university. In this paper the test results will be presented, as well as the general description of the MAXI mission.

## INTRODUCTION

A large majority of the X-ray sources are known to be variable on various time scales. The variations on short time scales (shorter than several days) of persistent sources can be studied with dedicated pointing observations with satellites. The variation on longer time scales (tens of days or longer), or the unpredictable outbursts of transient sources, however, is difficult to study unless a large part of the sky is constantly monitored. The all-sky monitors (ASMs) have been developed and have flown on generations of X-ray astronomy satellites. The Vela 5B satellite operated for ten years and collected a database of long-term variability of bright X-ray sources. Ariel V (Holt, 1976) and Ginga (Tsunemi et al., 1989) had ASMs, and discovered strong outbursts of binary sources such as black hole candidates and Be transient pulsars. The alerts by the ASMs enabled quick follow-up with higher sensitivity pointed observations. More recently, Watch on Granat (Brandt et al., 1990), and BATSE on CGRO (Fishman et al., 1989) have also detected outbursts from bright transient sources. The latest experiment is ASM on RXTE (Bradt et al., 1991), which is constantly monitoring about one hundred sources with higher sensitivity. A more sensitive monitor is also planned with MOXE on Spectrum X-gamma. We plan to extend the monitoring of the X-ray sky with MAXI on the International Space Station. In addition to the detection of bright or even faint transient sources, we plan to study the long-term variability of a large number of faint X-ray sources including binary sources and bright AGNs. In the previous year we described the design concept of MAXI (Matsuoka et al., 1999). In this paper we put weight on the detectors of MAXI.

## MONITOR OF ALL-SKY X-RAY IMAGE (MAXI)

MAXI (Matsuoka, 1997a, 1997b, 1999; Torii et al., 1999) is a highly sensitive X-ray all-sky monitor. It will be launched in 2004 by the Japanese HII-A rocket, and will be attached to Japanese Experiment Module (JEM) Exposed Facility (EF) on the International Space Station (ISS). The general description of JEM on the ISS, and its constraints as a platform for astrophysical experiments were presented in Matsuoka et al. (1997a). Considering the unstable attitude of the ISS and the synchronous rotation with the orbital revolution, a monitoring or a survey mission is suitable for ISS (Kawai et al., 1996, 1997). MAXI is box-shaped in 0.8 x 1.0 x 1.85 m with the weight of 500kg (Fig.1). JEM-EF has 10 ports for payloads. We have requested MAXI being mounted at port #1, the corner near JEM in the ram side, which has the best open field of view. The mission life time will be at least 2 years.

MAXI has two fan-like field of views (1.5° x 160°), i.e. horizon and zenith views. The slit camera can maximize the sensitivity without source confusion. Both views scan the entire sky in the course of one orbit of the ISS (~90 minutes). The two views are set almost perpendicular to each other to achieve complete sky coverage in spite of breaks in the observations when the ISS will pass through the South Atlantic Anomaly. The horizon view of GSC is slightly tilted upward by 6 degrees (in case of SSC, 20 degree) to avoid the earth occultation even when the Space Station faces down by 15 degree in the free-flying attitude. Thus MAXI can scan almost all sky with a precision of better than 1 degree and in X-ray energy range of 0.5-30 keV. The simulation showed that the sensitivity of MAXI is 1.7 mCrab in a day (Rubin et al., 1997). MAXI will be able to detect not only galactic objects but also extra galactic objects. It will achieve a non-biased long-term (day-year) monitoring of AGNs for the first time.

Detected X-ray photons are processed onboard and sent to the Tsukuba Space Center by the ICS antenna on JEM-EF through the DRTS satellites. The data rate is variable according to the intensity of X-ray, but it is about 40 kbps in average. Since it exceeds a limit of 1553B (15 kbps), Ethernet will be used to send the whole data. A subset of the data, which is the house keeping data and summary of the X-ray data, are sent by 1553B.

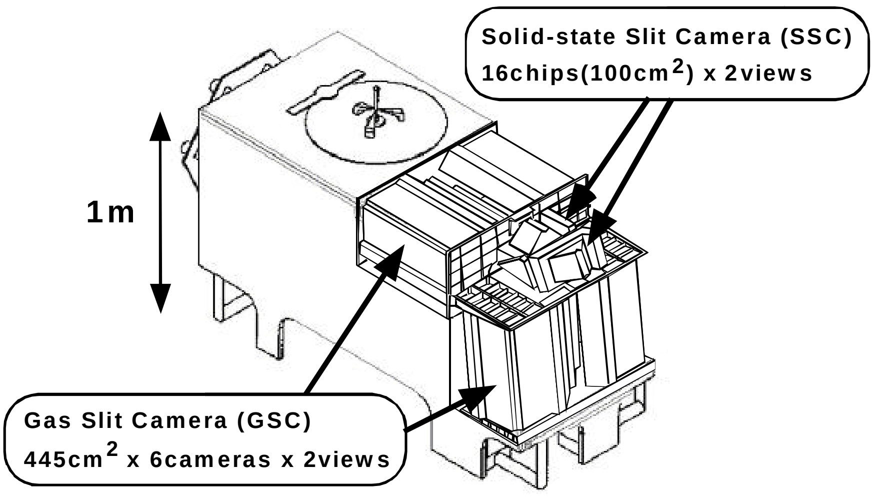


**FIGURE 1**. MAXI has two X-ray instruments; GSC and SSC. Each has two sets of cameras looking at the horizon and the zenith directions. Radiators and thermal shields are removed in this figure to show the cameras.

## GAS SLIT CAMERA (GSC)

GSC uses one-dimensional position sensitive proportional counters. The energy range is 2-30 keV. The merit of a gas counter is the large area. The window area of one GSC counter is 445 $cm^2$ (Fig.2 left). Since we will use 12 counters, the total area will be 5340 $cm^2$. Six of the 12 GSC are faced to horizon direction and the other six are to zenith direction (Fig.1). One camera covers 1.5° x 80° with a slat collimator and a slit on top. We use 3 cameras to cover 160°, each of which covers -80°~0°, -40°~40°, 0°~80°. We abandoned 10° in both sides, where the neighboring payload or some structure of ISS may block the FOV. Although two cameras can cover 160°, we put a center camera to increase the dwell time in the equatorial direction where the dwell time of one source is the shortest.

The gas of the counter consists of Xe (97%) + $CO_2$ (3%) with 1.4 atm at 0°C. We use this combination because Xe has a large stopping power and $CO_2$ is free from carbon deposition problem. The entrance window is made of one large foil of Be with 100 μm thickness. The anodes are 8 carbon fibers of 10 μm diameter with resistivity of 1.0 kΩ/cm. We use a thin wire, because a larger resistance is better to reduce the Johnson noise which is dominant in the position resolution in this relatively low resistance range.
Another reason is that we can use a lower voltage with less problem of sparks. The position along the wire is obtained by the charge division method for each X-ray photon. Using the left side readout L and the right side readout R, the position measure was defined as (R-L)/(R+L), which changes -1 to 1 as the X-ray position moves from left to right (Fig.2 right middle).

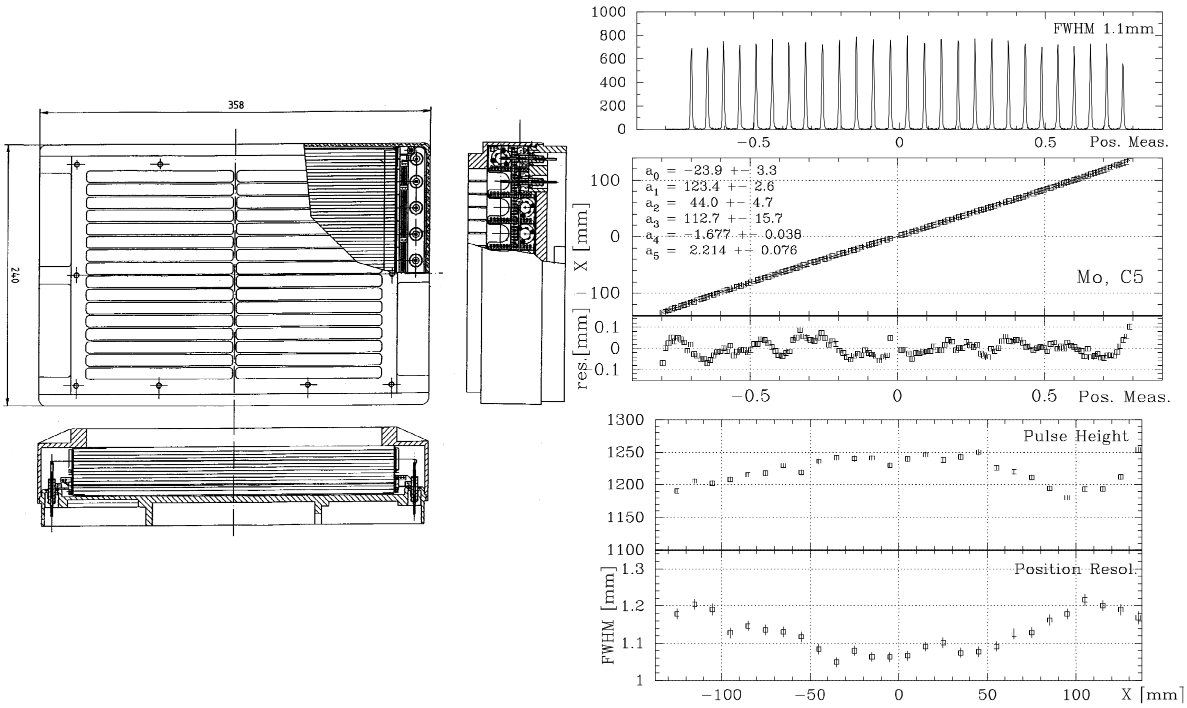


**FIGURE 2**. Left: GSC counter. The outer size is 36 x 24 x 9 cm. It is made of Ti and the weight is 5 kg.
Right top: GSC position measure histogram in 10 mm step along the anode. Mo-K(17.45keV) beam of 0.2 $mm^{\phi}$ was illuminated. The bias voltage was 1600V. The window is from -137 to 137 mm. Right middle: The relation of the real position and the position measure in 2 mm step. The residuals from the empirical equation (see text) are within ±0.1 mm. Right bottom: Pulse height and position resolution along the anode. The position resolution is anti-correlated to the pulse height. It also becomes lower at lower energies (eg. 2mm for Cu-K 8.0keV), which can be retrieved by using a higher voltage (eg. 1700V) (Fig.3 right).

The engineering model was made by Metorex in 1998 and tested in RIKEN (Kawai et al., 1999). The obtained histogram of the position measure is in Fig.2 right top. The relation of the real position and the position measure is almost linear, but has some edge effect (Fig.2 right middle). We use empirical equation as

$$X = a_0 + a_1 \times PM - \frac{a_2}{(PM - a_4)} - \frac{a_3}{(PM - a_5)} \ .$$

The best fit parameters ($a_0$ ... $a_5$) are written in the figure for this anode. The residuals from this equation are within ±0.1 mm. Assuming this relation the position resolution can be calculated. It was about 1.1 $mm_{FWHM}$ at Mo K (17.5 keV) (Fig.2 right bottom), which is equivalent to 0.48°in the sky in the center of FOV. Combining the slit width of 1.3°, it gives ~1.4°. The position resolution degrades in the lower energy, as they are ~1.0° at 8.0 keV and ~1.6°with the slit.

Fig.2 are results of Mo K in 1600V. However, the pulse height, energy resolution and position resolution change with X-ray energy and high voltage as shown in Fig.3. Here Cu K (8.0 keV) and Mo K were illuminated at 11mm from the anode. In Fig.3 left, the start of curvature at around PH = 1000 ch indicates the beginning of the space charge effect. It is about 1600V for Mo and 1700V for Cu. In Fig.3 middle, the energy resolution becomes worse at higher voltages. The start point of degradation is about the same voltage as the space charge effect. On the other hand, in Fig.3 right, the position resolution is better in higher voltages. It is inversely proportional to the pulse height, but saturates at about 0.9mm. The reasons of saturation would be 1) beam width of 0.2 mm in diameter, 2) verticality of the beam to the anode wire (0.5° = 0.22 mm), 3) change of the dominant noise source; from electric noise to Poisson statistics of electrons. From these figures we can determine the operating voltage as 1650-1700V, since the position resolution in 4-10 keV has the most priority in this mission.

During the test another problem was discovered. When gas gain is more than 5000, i.e. high voltage is higher than 1500V, irregular gas gain occurs when the X-ray stops near the anode. The gain goes up from the 7 mm from the anode as much as 60% in 1600V. The ratio of the irregular gas gain to the normal gain increases proportionally with gas gain. A detailed experiment with slant beam method revealed that the gas gain goes down again to the normal level in the very vicinity (3 mm) of the wire. Because we observe the summation of events across the cell, this irregular gas gain makes a broader peak, a hard tail, or the second peak depending on the high voltage. It is more evident in higher energy where X-ray penetrates the whole cell. The X-ray below 8 keV stops just under the Be foil and does not suffer irregular gas gain very much. This seems a particular problem to Xe and $CO_2$ mixture. We will try to solve this problem by changing the gas mixture. But finally we may have to consider this effect when we optimize the high voltage. Low background is essential for the good sensitivity. The room background rate after anticoincidence was measured to be 2 x $10^{-4}$ c/s/keV/$cm^2$ (2-30 keV), which is as expected.

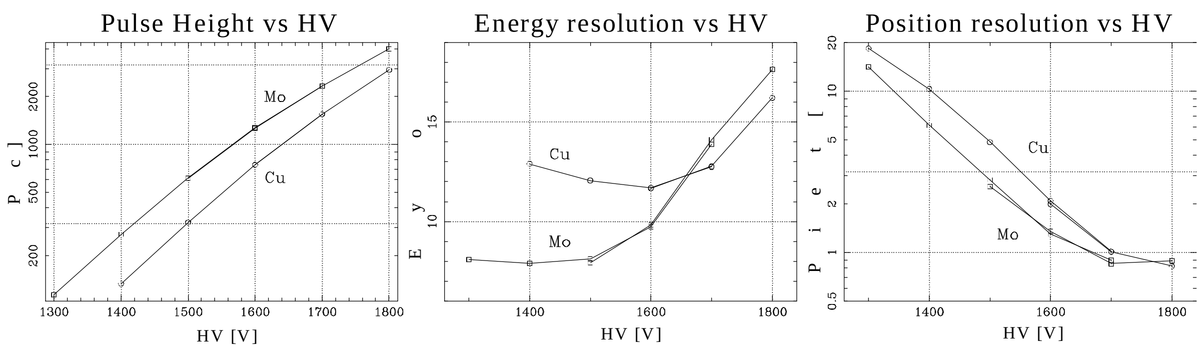


**FIGURE 3**. Left: Pulse height with high voltage. Middle: Energy resolution with high voltage. Right: Position resolution with high voltage.

## SOLID-STATE SLIT CAMERA (SSC)

SSC uses X-ray CCD to achieve a soft X-ray response and a good energy resolution. The energy range is 0.5-10 keV. The CCD chip is 1-inch-square full-frame transfer type, has 1024 x 1024 pixels with a pixel size 24 μm square, and is made by Hamamatsu Photonics (Miyata et al., 1999). We have two SSC cameras, horizon and zenith. Each contains 16 chips. The total number is 32 chips with an effective area of 200 $cm^2$. CCD is used as a one-dimensional position sensitive X-ray detector. In order to achieve fast readouts of many chips, we bin typically 16 pixels on the chip in the other direction. The binning number can be changed by the commands. In the case of 16 binning the readout time of 16 chips is the same as that of 1 chip in 1 pixel readout, which is 10s. Since the shortest dwell time in the equator is 45s (bottom-bottom), the readout must be faster than it.
The energy resolution of the test chip was 152 $eV_{FWHM}$ at 5.9keV (Fig.4 left). Now the depletion layer is 20 μm in thickness, which is being improved.

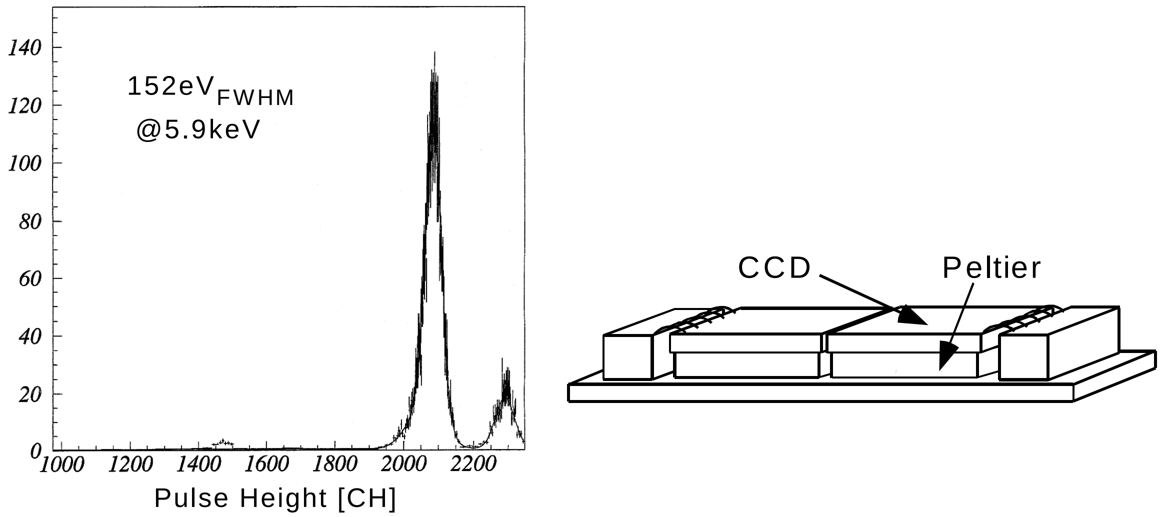


**FIGURE 4**. Left: Spectrum of $^{55}Fe$ (5.9 keV) with SSC test chip. The energy resolution was 152 $eV_{FWHM}$. Right: SSC CCD chips are three-side buttable. 16 chips are placed in one camera in two rows. Two of them are shown. Each chip has its own one-stage Peltier cooler, which cools the chip to -60°C.

A big problem is the cooling of CCD. Since ISS keeps almost the same attitude to the earth, the sun rotates around MAXI in every orbit. Moreover due to the precession of the orbital plane in about 50 days there is no side which is always free from the sun light. In such circumstances it is impossible to make a low temperature such as -60°C with a radiator. Since we have neighboring payloads, we cannot radiate sideways. Since the payload size is limited and we have many openings of the slit cameras, the area of radiator is limited very much. Extending radiator is difficult to build. The possible areas of the radiators are only 0.28 $m^2$ to horizon direction and 0.55 $m^2$ to zenith direction.

We found out the best solution: to cool down the camera with radiator and loop heat pipes to -20°C, to use one-stage Peltier cooler to make the chip temperature -60°C ($\Delta T$ = -40°C) with 1 W/chip, and to put evaporated Al on CCD surface to minimize the radiative heat input. The radiator cooling power of 32 W at -20°C is marginally possible with the area above. Loop heat pipe is a new excellent technology to conduct large heat in a long distance with a flexible tube. MAXI, however, uses the advantage as the thermal diode and the thin piping. With no load, even the silverized-teflon radiator can be warmed up to 40°C by the sunshine. The loop heat pipe conducts heat in one direction and can prevent the reverse heat from radiator to camera. Thin radiator is needed to place the slit cameras as close to the surface as possible to get rid of the shadowing by the neighboring payloads. A problem of the loop heat pipe is in the start up. In the normal use, the condenser and compensation chamber are cooler than the evaporator and heat is added to the evaporator only. In MAXI case, CCD camera (evaporator and compensation chamber) stays in almost the same temperature and radiator (condenser) changes its temperature. Such a usage still needs to be tested.

The CCD is attached directly to the cold surface of the Peltier cooler to minimize the cooling volume (Fig.4 right). The current of Peltier is feedbacked by a thermometer readout implanted in the CCD to maintain the chip temperature at -60°C. One challenging task is Al evaporation with thickness of about 2000Å on the CCD surface which will act as a light shield. With this, we can omit additional light shield and associated launch safety mechanism. The Al coating will also reduce the heat input to the chip, which will reduce the power requirement of the Peltier cooler making the camera simpler and lighter.

Another big problem is the contamination by exhausts of Space Shuttle and ISS propulsion module to the radiator and CCD chips. We plan to put 100 W heater on the radiator and apply reverse current to Peltier cooler to warm them up. Both will raise their temperature to 0°C ~ room temperature and help to prevent the contamination.

## CONCLUSION

MAXI is an X-ray all-sky monitor approved for the JEM Exposed Facility of the ISS. It is optimized to monitor the faint X-ray sources with flux levels down to 1 mCrab, and is composed of large-area proportional counters and X-ray CCD arrays. The fan-like field of views will scan the full sky during each orbital revolution of ISS. We made a test counter and test chips in 1998. Those are being tested in RIKEN, NASDA and Osaka-university. Their expected performances were confirmed. Since it is the first astronomical mission on ISS, several problems came out. We, however, solved or are solving them to make the flight models in the next step after some modification. The launch is scheduled in 2004 summer.

## ACKNOWLEDGMENTS

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