EPIC Operating Modes

Report of the OMWG

(prepared by the Operating Modes Working Group)
(edited by L.Chiappetti, IFCTR)
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Please note :

Changes between issue 1.0 and issue 1.A are indicated with a double bar on the right margin.

Table of content

1. Introduction

The *Operating Mode Working Group* (OMWG) has been set up by the EPIC Consortium in order to assess all problems related to the definition of the operating modes of the EPIC experiment, and to verify the suitability of such modes to accomplish the scientific goals of the mission.

The membership of the OMWG is the following :

IFCTR :	L.Chiappetti (convenor), M.Quadrini
Leicester:	A.Holland (formerly A.Wells, D.H.Lumb)
CEN Saclay:	M.Arnaud, D.Schmitt (formerly R.Rothenflug, Y.Rio)
AIT :	E.Kendziorra
ITESRE :	M.Trifoglio
OAP :	S.Sciortino

The OMWG has conducted its work by exchange of information and by periodic meetings. The result of this work *at the moment the document is going to press* is summarized in the present document. We acknowledge the participation to the discussion of other members of the consortium, particulary those involved in the definition of the electronics and in the simulations. The editor wishes to thank S.Mereghetti for a careful reading.

The current issue (1.A) of the document is mainly based on the March 1992 issue (1.0) and (but for the changed document formatting according to EPIC CADM standards) incorporates only minimal changes (bit numbers, readout times, etc.) to be in line with the latest values as tabulated in the ISVR report. All other sections, and in particular all subsections concerning Thomson devices, section 3 and the Appendix have **not** been modified.

For what concerns the current configuration of EPIC experiments, and in particular the arrangement of the CCDs in each camera head, we refer to *the documentation prepared by the Detector Selection Working Group*.

The operating modes currently foreseen for scientific observation with EPIC are different between the MOS- and pn-type CCDs.

The modes currently planned for the MOS-CCDs (EEV and Thomson) are :

Full frame	(see 2.1.1.1 .gFF_MOS_CCD)
Frame store	(see 2.2.1.1 .gFS_MOS_CCD)
Refreshed Frame store	(see 2.2.1.2 .gRFS_MOS_CCD)
Windowing	(see 2.3.1.1 .gW_MOS_CCD)
Fast Windowing	(see 2.3.1.2 .gFW_MOS_CCD)
Timing	(see 2.4.1.1 .gT_MOS_CCD)

The modes currently planned for the pn-CCDs (MAXI) are :

Full frame	(see 2.1.1.2 .gFF_pn_CCD)
Windowing	(see 2.3.1.3 .gW_pn_CCD)
Timing	(see 2.4.1.2 .gT_pn_CCD)
Burst	(see 2.4.1.3 .gB_pn_CCD)

In addition to the above science modes, a controller transparency mode (see 2.5 .gTransparent) is planned to bypass event processing in the controller (EMCE or EPCE) for diagnostic purposes.

2. Overview of operating modes

2.1 Full frame mode

2.1.1.1 .MOS_CCDCCD readout (MOS)

Figure 2.1 shows a typical arrangement of a MOS CCD. Parallel registers, controlled by the S and I clock lines form the photosensitive image area. In order to read out the stored image data, signal charges may be moved out of these registers into either (or both) of the serial readout registers, by the application of clock pulses to the S and I clock lines.

Rows of data in the serial registers may then be moved to either (or both) output amplifiers by applying similar sequences of clocks to the R clock lines. This shift register readout may be described as a "parallel-to-serial" shift,as rows of data are first moved in parallel to the R registers, and then each row is moved serially to the output amplifiers.

Full frame readout mode allows the whole area of the CCD to be used for collecting photons. The bias levels of a CCD are first set to allow the collection of photo-electrons in the pixel array. After a suitable time (which may be determined by factors such as the dark current accumulation, image smearing or count rate limitations) the pattern of signals recorded must be read out.

The Figure 2.2 shows the direction of charge transfer in full frame readout mode:

(1) and (1a) The pattern of signal charges stored in the CCD after a suitable integration period

(2) In the upper figure the charge pattern starts to be shifted towards the output registers, in this case using both serial registers for output. The I and S registers are clocked in opposite directions by changing the order of clock lines pulsed in the sequences.

(2a) In the lower figure an alternative version involves the charge being moved in the same direction to one register only, by clocking S and I registers synchronously.

Taking the upper case only - (3) and (4) show signal charges finally being moved into the readout register and then towards the output amplifier.

As well as *varying the directions of charge transfer*, the mode may be modified by *pixel binning*. This is effected by collecting more than one row in the output register before row readout, and collecting several pixel data in the output node before measurement.

The baseline full frame mode for EEV devices involves an *image integration time* of 50 s. Each row of 768 pixels (plus some overscan) is read out to 2 nodes at a rate of 10-12 µs per pixel. All 1024 rows are then read out in the same manner

Fig. 2.1

Fig. 2.2

to one of the readout registers. Readout will take approximately 4.8 s, producing a image:readout time ratio of about 10:1. *The pixel readout time may reduce in the future whether convenient, affecting therefore also the indicated frame integration time.*

An identical clocking scheme used for Thomson 1024∞1024 CCDs would require an additional 256 pixels per line readout, giving rise to approx. 6.4 s readout time and necessitating a 64 s frame time for a 10:1 ratio.

The intermittent readout allows the CCDs of the focal plane to be multiplexed in turn to a common set of signal processing chains, and some extra time for the event recognition or EDHU computers to process the data.

Summary of programmable parameters of the mode

General notice for all modes : the EPIC instrument programmable parameters will fall in three classes; special adjustments to be made rarely (with prior consultation with the CCD groups); parameters set by the ground control centre at the time of the observation, and parameters which may be requested by the observer. The exact distinction between *user-definable* and *system-definable* parameters has not yet been made. Only parameters which affect operative modes will be mentioned in this document.

The following parameters should be programmable by telecommand :

- Bias levels (they should be adjusted infrequently), with the exception of one or two drain biases.
- Clock level settings (for optimization)
- Choice of one or two readout nodes (case 2 and 2a above) for redundancy or optimization purposes. In general the CCD sequencer will be completely programmable with the program loaded when a new mode is selected : this will enable the choice of the output node together with the pixel sample time.
- Pixel binning (this could be user-definable, however a change in this parameter means the pattern library used by the EMCE has to be changed at the same time)
- Image integration time (user-definable). The baseline image integration time may be defined by the CCD amplifier integration time to maintain a given level of image smear. Longer integration times may be programmed (user-definable) to reduce image smear, particularly for extended objects.
- In addition the lower energy threshold used by the EDU (Event Detection Unit) in the EMCE will be programmable.

2.1.1.2 pn CCD CCD readout (pn)

This will be the standard operating mode for MAXI. The time resolution and the maximum acceptable point source intensity should be sufficient for the majority of observations.

One row of 64 pixels is shifted towards the output nodes every 20 µs. The charges of all 64 pixels are determined by the multicorrelated sampling circuits of the CAMEX chip in parallel. The information is then multiplexed to a fast flash ADC for a better understanding of the readout scheme see figure 2.3.

The 12 CCDs of the camera head are read out sequentially. We need 4 ms to read out one standard CCD chip (64∞200 pixels), this leads to a cycle time of 48 ms and to an integration time of 44 ms per chip.

To reduce the amount of photon smearing, which occurs during thereadout (line shift) of a CCD, we can optionally increase the integration time by a programmable factor n (n =2,4,...). This option could be used for the observation of extended sources with no bright point source in the field of view.

Summary of programmable parameters of the mode

The following parameters should be programmable by telecommand :

- Lower energy threshold for each column (64 per CCD chip)
- Upper energy threshold
- Basic clock frequency (5 or 10 MHz TBV)
- the integration time factor n (see above)

Fig. 2.3

2.1.2.1 Handling at EMCE level (MOS)

This section applies to the Full Frame, Frame Store and Windowing modes.

The Event Detection Unit (EDU) performs a proximity analysis in a 5∞5 matrix for each pixel which passes a preliminary event qualification (masking; this is described in a note by Bouère, Cara, Malnoult & Pigot, dated 28/02/91).

Up to 32 patterns (the exact number has to be defined according to the scientific requirements and the results of experimental tests on the morphology of split events) can be stored in a register (using e.g. 31 values ; the remaining one of the 32 values will be assigned to "all other" unclassified patterns). The code number of the recognized pattern is sent to EDHU with its X-Y location. In order to avoid redundant data, transmission when the energies of contiguous pixels are above the proximity analysis is enabled if the central energy in the matrix is the highest. Two additional features are included : an offset correction is performed to remove trap effects of the CCD read-out register; and a dedicated block eliminates the dead pixels. A block diagram of the EMCE is presented in Figure 2.4 here below. The data format is described in 2.1.3.1 .gFF_MOS_ECE.

It has to be noted that one of the main purpose of the EMCE processing is to get rid of particle tracks (at least the ones which can easily be discriminated from X-rays, that is the ones impinging onto the detector in non-perpendicular directions). In some checkout observations it might be convenient however to transmit all particle events (including the "diagonal" tracks).

Fig. 2.4

2.1.2.2 .Handling at EPCE level (pn)

The charge of each pixel is analysed by a fast 12 bit ADC. Only those events within an energy window defined by adjustable lower and upper hardware thresholds will be read out by the Event Analyser CPU. The main task of this processor is to reduce the number of events to be transmitted to EDHU, if at all necessary. This could imply an algorithm to discriminate those charged particle events, which deposit charges less than the upper threshold of the hardware event filter in adjacent pixels (split events). Also the charge integration of X-ray split events could in principle be performed by the Event Analyser. A more realistic and detailed description can only be given after the EOBB-phase.

2.1.3.1 .EMCE-EDHU interface (MOS)

The data processed by the controller (EMCE) has to be forwarded to EDHU along the provided serial data line (the details of which will be documented elsewhere). The format currently foreseen for the full-frame mode is the following :

An *header format* is sent first, once for each CCD chip, with the following format:

Header identifier	1	bits
CCD chip identifier	3	bits
chip operating mode code	3	bits
Window position (X,Y)	21 (20)	bits
Window size (ΔX,ΔY)	21 (20)	bits
Spare	TBD	bits

for a total of 64 bits or 80 bits (48 info bits + header id + padding to an integral number of (bytes or) 16-bit words). It is felt simpler to have an header format common to all operating modes, even if it may contain redundant information.

For each photon event accepted by the EMCE, according to the criteria described in 2.1.2.1 . gFF_MOS_ECE_h , an *event format* is sent, containing the information relevant to a 5∞5 matrix centered on the event. The exact format is yet TBD, and can be easily reprogrammed due to the Xilinx architecture of the EDU : a representative example is given below (but see e.g. the note by Bouère, Cara, Malnoult & Pigot, dated 28/02/91 for alternate formats).

Data identifier	1	bits
Position (X,Y)	21 (20)	bits
Pattern identifier	5	bits
EP energy in pattern excluding EC	TBD	bits
ER energy in 3∞3 matrix excluding EC+EP	TBD	bits
EE energy in 5∞5 matrix excluding EC+EP+ER	TBD	bits
EP ER and EE occupy in total	25 (41)	bits
EC energy of central pixel	12	bits
Spare	TBD	bits (e.g. 0 or 1)

for a total also of 64 or 80 bits (i.e. the event format length is the same as the header format length for this mode).

Note that 21 bits may be needed only in case overscan information is included ¥¥

A *trailer format* (also 64 or 80 bits) is sent afterwards, including a time counter, and the number of events in the frame which are above the energy threshold.

2.1.3.2 .EPCE-EDHU interface (pn)

The data processed by the controller (EPCE) has to be forwarded to EDHU along the provided serial data line (the details of which will be documented elsewhere). The format currently foreseen for the full-frame mode is the following :

Event data is sent directly on the data line, without use of any header. However a time word (31 bits of time, and 1 flag bit set to "1") is sent before all events in a readout cycle (12 CCDs). The individual event is instead tagged with the CCD chip identification. The format currently foreseen for the full frame mode, <u>and all other</u> operating modes, is the following :

Flag bit (set to "0")	1	bits
Chip identifier	4	bits
Position in X	6	bits
Position in Y	8	bits
Energy	12	bits
Spare	1	bits

for a total of 32 bits (4 bytes).

2.1.4 Actions by EDHU

2.1.4.1 . General functions of EDHU

The EDHU will be a device capable to configure itself in several different ways, so that it is able to talk with (and handle the data coming from) at least two different EMCEs. It will be able to handle a number of serial input ports variable, according to the cases, from a minimum of 2 (a fast one for science data and a slow one for HK data and commands) to a maximum of 5 (in case one implements the request that the MOS cameras be able to send science data on 4 independent channels).

If one considers the large number of foreseen operative modes at CCD level, and the additional different characteristics of data handling and formatting at EDHU level (which will multiply the number of "modes" and data format at EPIC system level), it is clearly apparent that the EDHU design shall support a very high degree of versatility (the details of which can only be frozen once the characteristics of the devices upstreams of the EDHU, i.e. EMCE and cameras, are finalised).

The EDHU will therefore be organized on three logical layers:

a) First comes the interface towards EMCEs, comprising as many sections as the input ports. Each section will in its turn be an intelligent interface, both hardware- (PLA) and software-configurable. This allows to adapt each channel to any different "user" (readout chain for a particular chip and mode), and at the same time to take into account the characteristics of the operating mode.
The output of all the individual interfaces, operating independently in parallel, will be organized in buffers of pre-determined (rigid) sizes and formats, made available to the next EDHU layer.

b) The second layer is the Central Control System of the EDHU. Beyond the tasks (of no concern to the present document) of telecommand management, distribution of commands to EMCE, watch-dog and timing control, it shall be aware of the available amount of telemetry, and, in accordance to this, take care of *selections* or *integrations* (in position, time or energy). The results of such processing shall be inserted in (source) packets for transmission.

c) The third layer will be just the interface for the colloquium with the OBDH bus.

2.1.4.2 Specific functions for full frame mode

In the case of the full frame mode the default action (at level b of the EDHU, see 2.1.4.1 . gEDHU above) will be to format the whole data from EMCE (see 2.1.3.1 .gFF_MOS_ECE or 2.1.3.2 . gFF_pn_ECE above) into source packet.

Possible alternate actions include the selection of a subset of information for each event, or the selection of a subset of events based on programmable ranges of some parameters (e.g. position, energy or, for MOS CCDs, pattern type). It is also possible to consider reducing the number of bits for some parameter. Another possibility is the accumulation of histograms (spectra), either as a primary way of reducing data, or as a way of providing limited (count) information on the subset of parameters not transmitted (e.g. residual background events below threshold).

Further details will be worked out in the future.

2.1.5 Output format

Data will be organized in (unsegmented) source packets according to ESA Packet Telemetry standard. Each operative mode, combined with the various formatting actions at EDHU level, will determine one of a possible number of packet layouts, presumably each one associated to its own APID (Application Process IDentifier).

Each source packet is made of (beyond the standard packet header) a data field header and a data field. The data field will most likely be organized in sub-fields of constant size (within a given APID), corresponding to individual events or histograms.

The data field header will contain the information applicable to all events in a packet, like (presumably) the CCD operating mode parameters, the CCD chip originating the events, the start and end time of the frame, etc. The impacts of having separate packets for each chip and frame versus the count rate (and the number of events fitting into a packet, which probably is 512-byte long) will be evaluated in near future.

2.1.6 Associated problems

The full frame mode is necessary to provide the widest angular coverage, but allows no area for storing the signal charges during readout. Use of a mechanical shutter is precluded, and therefore photons continue to fall on the device during readout. In the worst case, for a source near threshold, this basic readout cycle degrades sensitivity by a factor of 11/10. For sources which are detected with high signal to noise, a surface background brightness of 0.009% the peak brightness is generated in the same columns (ie. 9.09% divided by 1024 rows) as the source.

The count rate is limited by the necessity to ensure no more than one photon is absorbed in a pixel in each frame. For the case of a uniformly bright source, a maximum rate of 0.025 photons/pixel/frame may be appropriate and is assumed as baseline in this version of the document. It has to be verified (e.g. by further simulations by the SDAWG whether this value is reasonable or a lower value may be necessary (implying of course lower limiting rates).

For the EEV devices this corresponds to about 3 photons/s/arcmin^2 (about 0.3 mCrab). For a true point source, in which the optics point spread function concentrates half the photons within a 0.5 arcmin diameter, the maximum count rate is somewhat lower. For the Thomson device, the maximum rate of 0.025 photons/pixel/frame corresponds to about 6 photons/s/arcmin^2 (about .6 mCrab). (In first approximation, this limit is inversely proportional to the pixel area which is two times lower for the Thomson device with respect to the EEV device: 27∞27 square microns for EEV instead of 19∞19 square microns for Thomson. This limit does not take into account differences in charge splitting between different devices and will be used before more realistic values be determined by measurements or simulations).

The full frame operation drives the requirement for a low operation temperature. At -95 C, a dark current accumulation rate of about 0.03 electrons/pixel/second (estimate for end of mission with back illuminated CCDs of present dark current performance cf. 0.015 electrons/pixel/sec for standard devices) results in a signal of about 1 electrons/pixel/frame. Shot noise and spatial non-uniformity on this value suggest that the total noise is only degraded by this contribution by about 5% compared with the dominant amplifier noise of 4 electrons rms. Similar numbers should result for Thomson devices as the dark current generation mechanisms are the same. If a cooler temperature is required for radiation damage reasons, dark noise will be eliminated.

2.1.7 Scientific usage

Full frame mode can be utilised in principle as standard mode for all observations except where count rates are too high. Observations of wide fields, and faint sources up to the count rate limit of 0.1 mCrabs (or 0.3 mCrabs/arcmin^2) are appropriate for this mode for MOS CCDs. For the pn-CCD this limit is a factor 100 higher.

In the case of the two-tiered focal plane arrangement foreseen as baseline for EEV CCDs, this is the standard mode for all off-axis serendipitous sources. On-axis detection will use frame store mode as standard (central chips will never be operated in full frame mode).

The surface brightness value corresponding to the limit count rate given above (MOS-CCD) is sufficient to accommodate most extended sources except the brightest galactic supernova remnants or cluster cores.

2.2 Frame store modes

2.2.1.1 .MOS_CCD CCD readout in normal frame store (MOS)

For framestore operation, half a CCD is used to collect image information, whilst the other half is used to store data for the previous image, from which the rows are read out in the same manner as for full frame mode.

This mode applies to the MOS CCDs only. In the present baseline for EEV CCDs the two *central* chips will operate *by default* in frame store mode (they are located on a lower tier, so that the store section is hidden behind the outer chips -which are on a higher tier; hence the central chips are *never* operated in full frame mode, and the outer chips are *never* operated in frame store mode).

Figure 2.5 shows a pattern of data collected in the image section. 512 row shifts are then applied to image and store sections to move the data in a block to the store section. At a clock rate of 100 kHz this takes 5 ms. Whilst the next image accumulates in the image section, the store is read out to one or two output amplifiers. This readout for one CCD takes 2.4 s (with two output nodes) or 4.8 s (fallback to one node), which also represents the frame time for the collection of the next image.

Again there can be variations such as pixel binning and one or two output node operation.

Summary of programmable parameters of the mode

The following parameters should be programmable by telecommand :

- Frame store time (image integration time) is not programmable as there is no need to (there is no smearing)
- Pixel binning
- Choice of one or two output nodes (possible but limited)
- Selection of the particular chip to be used in frame store mode

Fig. 2.5

2.2.1.2 .MOS_CCD CCD readout in refreshed frame store (MOS)

Refreshed frame store mode will enable the imaging of bright sources (point-like and extended) by undersampling the X-ray flux. The mode is a variant upon normal frame store hence it is implicit it applies to central chips only, and works as follows. The image is transferred to to the store section as in the normal mode. The stored image is then read out whilst photons accumulate on the new image (the readout would typically take 2.4 s for an EEV CCD). After readout the new image is then transferred to the store section : this image will contain far too many X-rays and will be rejected. A new image is integrated for a *short* time period (of the order of 50 ms) and is then transferred to the store section. The old image in the store section would then be stacked into the serial register and could be discarded by performing 1 line readout. The image in the store section will now contain photons integrated for the imaging period plus the two *adjacent* frame transfer periods. This mode will enable imaging spectroscopy to be performed on relatively bright sources. Only the timing information will be limited due to the time-slice nature of the exposures.

For the EEV CCD, assuming a line transfer rate of 10 µs per line, the frame transfer operation would take 5.1 ms. If a 10:1 integration to readout ratio is used, the image could be integrated for a minimum of 51 ms. Therefore the total image integration time would be 56.1 ms. Integration interval will be spaced by the stored image readout times (2.4 s in the example).

2.2.2 Handling at EMCE level (MOS)

This is identical to what described in 2.1.2.1 .gFF_MOS_ECE_h .

2.2.3 EMCE-EDHU interface

The format currently foreseen for the frame store mode is identical to the 64-bit format described above in 2.1.3.1 .gFF_MOS_ECE.

2.2.4 Actions by EDHU

So far make reference to 2.1.4.1 .gEDHU for a description of the functions of EDHU. The operations in frame store mode will be similar to the ones described in 2.1.4.2 for full frame mode, as the input data stream has the same format (but possibly an higher rate). The case of the refreshed frame store will be worked out in the future.

2.2.5 Output format

This will be analogous to what described in 2.1.5.

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2.2.6 Associated problems

If the store section is not shielded from photons, then a background signal will be superposed on the images. If pointed to a nominally blank section of sky, this background will vary across the array from 0% to 100% additional diffuse background, depending on the amount of time spent by pixels in the store section. As this mode is used only for high signal-to-noise observations, this should not be a problem. Judicious spacecraft pointing and orientation will be required. Alternatively, a passive shutter might be deployed for these observations. A report on the matter is available (LU/EPIC-002 by D.H.Lumb, 28 Nov 1989).

An alternative mechanical arrangement would use the store section area by shielding with another CCD, which might operate in full frame mode. This is the case of the two-tier 8-CCD focal plane arrangement.

2.2.7 Scientific usage

2.2.7.1 normal frame store mode

A frame time of 2.4 seconds implies an order of magnitude higher count rate capability than the full frame mode, ie. 6 mCrabs/arcmin^2 or 2 mCrab per point source. Therefore a significant number of objects which cannot be observed in the normal full frame mode can be observed with frame store, including a sizeable fraction of those sources which represent the target observations of the present generation of observatories.

The advantages of using frame store for compact sources, instead of windowing or timing mode include:

a) Use of a STANDARD mode with well understood characteristics and calibration - compared with variable parameters which might be associated with a user-defined mode.

b) Observation of crowded fields, or imaging of areas around point sources (eg. dust haloes etc.) may be more appropriate for some point sources than multiple or large area windowing.

In addition, a number of extended sources such as the brightest young galactic supernova remnants and cluster cores have an extent of about 10 arcmin comparable with the area presented by framestore operation. Whilst the overall count rates may be attainable with full frame mode, or interesting areas accessed via windowing mode, framestore mode allows a large area to be imaged with negligible smearing and better accommodation of spatially varying brightness (particularly where the event recognition algorithms limitations may reduce count rate capability).

2.2.7.2 refreshed frame store mode

One of the current limitation of the EPIC instrument using MOS CCDs is its inability to image high-flux sources without encountering the problem of X-ray pile-up, where two or more photons combine in the image. Normal frame store and windowing modes enable EPIC to image higher flux sources than the standard full frame mode. However, even these imaging modes have low limiting rates and, for example, would not permit imaging with spectroscopy of the Crab.

Refreshed frame store will allow imaging of bright sources. Taking the usual limit of 1 photon per 40 pixels would enable 9800 photons to be accumulated in the image. This corresponds (with an integration time of 56.1 ms) to imaging an X-ray flux of 17.5 Crab over the total area !! Naturally this rate would be lower for observations of point sources. (Even if the ratio of 1/40 would lower to a more realistic value of 1/250, this would still enable 1600 photons to be contained within one image, that is a rate of 2.8 Crabs).

The flux which could be imaged with spectroscopy using this mode exceeds that of windowing mode (see 2.3 . gW_mode) by more than a factor 80. It is possible that using refreshed frame store, the (more complex) windowing mode could be removed altogether. The shortfall in the timing capabilities of the refreshed frame store mode could be covered by the use of the timing mode. Thus an observation of a bright source might consist of an operational period in refreshed frame store, and one in timing mode (this shall not necessarily occur in sequence: one camera unit may operate in one mode, and another in the other one *at the same time*).

2.3 . Windowing modes

2.3.1.1 . _MOS_CCD CCD readout (MOS)

In principle, the size of window (and the number of windows ?) which may be set during windowing mode (see figure 2.6 for a scheme of operation) could be varied at will. However, the following discussion treats only the case of a "point source" window as an example, other example timings may be deduced from this.

The windowing mode can be used on both central and outer chips.

The numbers in the next section are unchanged as there are still unresolved differences between my numbers, those of A.Holland (point 14 of 18 Sep 90 notes) and D.Lumb (mail of 4 Dec 90).
A point source, imaged with 30 arcsecs HEW resolution might be examined with a box of 1 arcminute on a side (this allows about 90% of photons to be collected, *assuming negligible spacecraft drift*). This area is equivalent to ca. 80∞80 EEV pixels or ca. 115∞115 Thomson pixels. The principle is to read out these areas with normal sampling, but to reject the remaining pixels by readout without sampling. The window may be first located on a given CCD quarter of 512∞384 (EEV) or 512∞512 (Thomson) pixels. For the sake of argument, suppose the window is located at the centre of a CCD quarter, and readout is to the serial register at the opposite side of the chip.

EEV Device:

The unwanted rows (216 + 512) are first read out to the serial register (10 µs/row). Then the combined row of 384 pixels is read out without sampling (1 µs/pixel), resulting in the clear out of the dead pixels in 7.66 ms.

For each of the required 80 rows, the first and last 152 pixels should similarly be read out without sampling (.152 ms each), whilst each of the 80 pixels to be sampled normally takes about 11 µs. Thus a total line time is 1.18 ms, and during this data read period of 94.4 ms, the next window can be integrated in the other CCD half.

On completion of the data read period, the next shift out of unwanted pixels can occur. Image smearing is about 7.7/94.4 or 8.2%/728 rows.

In the window, a count rate of 1/40 pixels average would lead (no. of pixels in window divided by 40) to a maximum limit of 145 cts/frame (optimistic) or about 1700 cts/s (170 mCrabs).

Thomson Device:

The unwanted rows (198 + 512) are first read out to the serial register (10 µs/row). Then the row of 512 pixels is read out without sampling (1 µs/pixel), resulting in the clear out of the dead pixels in 7.61 ms.
For each of the required 115 rows, the first and last 198 pixels should similarly be read out without sampling (.198 ms each), whilst each of the 115 pixels to be sampled normally takes 11 µs. Thus a total line time is 1.66 ms, and the data read time is 190.9 ms. Image smearing is 7.6/190.9 = 4%/710 rows.

In the window, a count rate of 1/40 pixels average (ca. 300 cts/frame) would lead to a maximum limit of (optimistic) 1700 cts/s or 170 mCrabs (very similar to the EEV device).

Summary of programmable parameters of the mode

The size and position of the window (or windows, and the number of it in the case more than one are used) are programmable parameters of the mode.

Fig. 2.6

2.3.1.2 MOS_CCD CCD readout: fast window mode (MOS)

There is some concern that the standard "timing mode" for MOS CCDs (see 2.4.1.1 .gT_MOS_CCD) could be affected by a degraded signal over background ratio arising from the fact that the background of the whole CCD matrix is summed concurrently with the source signal at the readout node. The restriction of a "timing operating mode" only to the relevant part of the matrix, where the variable source is observed, could be a solution to these problems.

The Fast Window Mode (FWM) considers only, inside the matrix, a set of columns containing most of the source signal (this set could have, for instance, a width two times the assumed HEW).

The FWM, which is applicable to the MOS CCDs only, and will be used only for the central chips in the two-tiered arrangement for EEV CCDs, operates as follows: (see Figure 2.7 below).

EEV Device:

Considering a point source spreaded on a 80∞80 pixels square (HEW = 40 pixels), the 80 columns corresponding to the source are analysed by:

a) summing 80 rows on the serial register using 80∞10 µs = 800 µs

b) eliminating the n first pixels of the serial register to reach the relevant columns using n∞1 µs

c) reading 80 pixels of the serial register using 80∞(1 + 10 µs) = 880 µs

d) clocking p times the serial register to clean the part of the serial register corresponding to the analysed columns using p∞1 µs with p = MAX [(N-80-2n),0] where N is the number of pixels in a row: 768 pixels + some overscans for the EEV device read by one node , half this number if using half the serial register. In the best case with a centered point source on the serial register p = 0; in the worst case p = N-80.

For one readout node, each 80∞80 pixels square, in the relevant columns, is analysed in a constant time ranging from 2.08 to 2.4 ms corresponding to a shift time of 0.8 µs and 1.28 to 1.6 ms of exposure time. For half the serial register, the time to sample each square ranges from 1.88 to 2.08 ms.

Thomson Device:

A point source is spread on a 115∞115 pixels square on a Thomson type CCD (HEW = 57 pixels); The 115 columns corresponding to the source are analysed by:

a) summing 115 rows on the serial register using 115∞10 µs = 1150 µs

b) eliminating the n first pixels of the serial register to reach the relevant columns using n∞1 µs

c) reading 115 pixels of the serial register using 115∞(1 + 10 µs) = 1265 µs

d) clocking p times the serial register to clean the part of the serial register corresponding to the analysed columns using p∞1 µs with p = MAX [(N-115-2n),0] where N is the number of pixels in a row (1024 + some overscans = 1060 pixels for the Thomson device) if the whole matrix is read by one node, half this number if half the serial register is read.In the best case with a centered point source on the active part of the serial register p = 0; in the worst case p = N-115.

Fig. 2.7

For one readout node and using the whole serial register, each 115∞115 pixels square, in the relevant columns, is analyzed in a constant time ranging from 2.89 to 3.36 ms corresponding to a shift time of 1.15 µs and 1.74 to 2.21 ms of exposure time. Using half the serial register, the time to sample each square ranges from 2.62 to 2.83 ms.

Summary of programmable parameters of the mode:

The following parameters should be programmable by telecommand:

- Size of the set of columns to be analysed
- Number of lines to sum between successive serial register readings
- First column to be analysed
- Node used
- Choice to read the whole matrix or part of it in the image section and on the serial register
- Vertical clocking speed

2.3.1.3 _pn_CCD CCD readout (pn)

Fields of view containing a bright point source (> 5 mCrab) must be observed in windowing mode in order to avoid photon pile up.
We presently plan to have only one window in one of the 12 CCDs at a time (with maximum size 32¥¥m¥: see figure 2.8 for a detailed scheme. In windowing mode the maximum countrate is 100 mCrabs.

Windowing mode offers the opportunity to read selected parts of the focal plane more frequently, thus allowing for higher source count rates.

For the calculation of read out times and maximum count rates, we have to distinguish between two cases (submodes).

A. Small window in one CCD

There will be one window selected in one of the 12 CCDs. For this CCD only the pixels within the window are read out, the information from the remaining part of that CCD is lost. All other 11 CCDs are read out similar to the full frame mode, the only difference being a slightly different integration time. With the present generation of CAMEX chips, the correlated sampling of one line with 64 pixels takes 15 µs. Within this time appr. 48 pixels from the previous line are multiplexed with 3.2 MHz to the ADC. For our calculations we have assumed a window size of 48∞20 pixels (197" x 82"). It will take us 480 µs to read such a window (20∞15 µs to read pixels within the window plus 180 µs to shift the 180 lines not converted). The time of 4 ms, needed to read out one of the other CCDs, is used as exposure time for the "window CCD". This leads to a total cycle time of 4.48 ms for the "window CCD" and 11 x 4.48 ms = 49.28 ms for each of the remaining 11 CCD chips, see Figure 2.8a.

B. Large window in more than one CCD

One also can select a larger window, which overlaps several CCDs. Such a case is illustrated in Figure 2.8b. As an example we have chosen a window which covers 1/4 of the focal plane area. Such a window could be read within 11 ms. The remaining part of the focal plane is not analysed.

As in this case the ratio of integration time to read out time is only 5:1, image smearing during read out might become a problem, especially for extended sources with a non-uniform surface brightness. Image smearing can be reduced significantly in refreshed window mode. At the end of the integration period, the image is transfered within 0.1 ms into the outer part of the CCD, which is not exposed to photons from the target source. During the 2 ms needed to read the 100 image lines, the source image will thus be disturbed by background photons only. After read out into the CAMEX, the image part of the CCD will be reset by a fast transfer of 100 lines, which will again take 0.1 ms. This sequence is illustrated in Figure 2.8c. The effective read out time is 2.2 ms per CCD. In our example, the ratio of integration time to transfer time amounts to 11 ms : 0.2 ms = 55.

Summary of programmable parameters of the mode

The size and position of the only window are programmable parameters of the mode. This needs to be revised according to the changes above.

Fig. 2.8a

Fig. 2.8b

2.3.2.1 Handling at EMCE level (MOS)

This is identical to what described in 2.1.2.1 .gFF_MOS_ECE_h for the normal and fast window modes. Events above threshold are accepted. No other rejection criteria are foreseen.

2.3.2.2 Handling at EPCE level (pn)

This is identical to what described in 2.1.2.2 .gFF_pn_ECE_h .

2.3.3.1 EMCE-EDHU interface (MOS)

The format currently foreseen for the normal windowing mode is identical to the 64-bit format described above in 2.1.3.1 .gFF_MOS_ECE.

In the case of the Fast Window mode an header format of 64 bits is sent first and a trailer format sent at the end as described in 2.1.3.1 .gFF_MOS_ECE. For what concerns the window position, X will correspond to the first column to be analized, ΔX and ΔY to the size of the column set and to the number of rows to sum on the serial register.

For each photon event accepted by the EMCE an event format is sent. A tentative format might contain the following information:

Data identifier	1	bits
Position in the column set	8	bits
Time	19 or 11	bits
Energy	12	bits
Spare	TBD	bits

for a total of 40 or 32 bits (the latter might be more convenient if handling 16-bit words is preferred)

The "time" in the above list is just a relative counter since the beginning of the integration, expressed in number of cycles (a cycle is the basic summation time, step a in 2.3.1.2, one of the small squares in fig. 2.7). It will be processed by the EDHU (see 2.3.4 below).

2.3.3.2 .EPCE-EDHU interface (pn)

The data processed by the controller (EPCE) is forwarded to EDHU along the provided serial data line, with a protocol identical to the one described in 2.1.3.2 .gFF_pn_ECE above.

Note that, unike the MOS case, event data is sent directly, without use of any header. The window position and size is not transmitted with the data. As above the individual event is instead tagged with the CCD chip identification.

In line of principle (as the maximum window size is 32∞32 pixel) it could be possible to reduce the number of bits for X from 6 to 5, and the number of bits for Y from 8 to 5 (hence the total from 32 to 28). The bit allocation for the remaining information is unchanged. However the complication in the processing is not worth such a reduction, therefore it is suggested to use for the windowing mode the identical format described in 2.1.3.2 .gFF_pn_ECE above.

2.3.4 Actions by EDHU

So far make reference to 2.1.4.1 .gEDHU for a description of the functions of EDHU. The operations in windowing mode will be similar to the ones described in 2.1.4.2 for full frame mode, as the input data stream has the same format (but generally at an higher rate).

The case of the fast window mode will be worked out in the future. It can however be foreseen that the EDHU shall convert the individual event "time" (relative counter, see 2.3.3.1) into spacecraft time, taking into account the programmable duration of a summation cycle.

2.3.5 Output format

This will be analogous to what described in 2.1.5.

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2.3.6 Associated problems

2.3.6.1 Normal Windowing mode

In order to guarantee all photons from a source are collected, the window box for the MOS CCDs must be relatively big. For example due to scattering, only about 85% of source photons are contained within a circle of 2∞HEW diameter, and any spacecraft attitude jitter must be added to the acquisition area (or the window position must be continually updated).

To obtain contemporaneous background data another window should be set up on the chip, leading to a doubling in readout time, and halving of count rate. The realization of 2 windows is not trivial, though technically possible, and should be avoided. An associated problem with the usage of two windows, would be the imbalance in count rates between the "source" and "background" windows in the case of moderately strong sources (for 1 arcmin^2 windows the former has 20 cts/s and the latter 0.3 cts/s). Also the background could be intrinsically patchy on the arcmin scale.

Other possibilities when background is of concern include sampling (infrequently) the area outside the window, to establish an estimate of the integrated image background, or just using an elongated (rectangular) window.

The above calculation of count rate limit is optimistic because the peaked nature of photon distribution within the window implies the 1/40 photon per pixel limit should apply to the central area, not just the average over the whole window.

Window mode will be subject to similar smearing as the full frame mode which is not evident in frame store mode (unless windowing mode itself is based on frame store mode !!).

2.3.6.2 Fast Window mode

The FWM parameters could need to be adjusted during the observation of the source, as any pointing shift particularly along the serial register has to be compensated. This operation could *in principle* be done on-line by a redefinition of one of the parameters (first column to be analized) at EDHU level, either :

∑ using Optical Monitor or AOCS data (discouraged because of severe impacts at *system* level)
∑ using the remaining spatial information along the horizontal axis provided by this mode (e.g. verifying the balance between a central "source" vertical strip and two outer strips in the window)
∑ uplinking periodically a new value of the first column, monitoring the drift on the ground (taking advantage of the continuous visibility of the satellite).

The two-stage (integration and summing) nature of this mode is liable to produce a significant (of the order 50%) cross-talk between adjacent time bins, which somehow degrades the nominal time resolution (details on this are presented in a note by Sarra and Mereghetti, dated August 26 1991, available on request).

2.3.7 Scientific usage

2.3.7.1 Normal Windowing mode

The general use of windowing mode is for point objects with higher flux than observable with framestore mode, where millisecond timing information is not important. The pn-CCD will however provide a time resolution of 4.5 ms in this mode.

Also, bright knots within extended sources (SNR knots etc), and compact slightly extended objects may be imaged with this mode.

The need for windowing mode may be removed if the refreshed frame store is used to image higher flux sources. However the latter mode will produce time slices of data and will be not good for timing studies.

2.3.7.2 Fast Window mode

The FWM will be used for point sources. These point sources do not need to be isolated in the field of the CCD since the analysis is restrained to those columns corresponding to the source.

This mode could enable timing studies for fainter point sources, where timing mode cannot be used due to the low statistics. On the other hand, bright sources may be undersampled on a reduced set of columns, increasing the readout speed and hence the timing resolution, or observed on a defocalized set of columns to ensure no more than one hit in each analyzed section of column, so keeping good spectroscopic performances.

2.4. Timing modes

2.4.1.1 MOS CCD CCD readout (MOS)

The discussion of the previous operating modes for MOS CCDs show that the serial readout nature of CCDs prevents the attainment of high time resolution. Timing mode circumvents this limitation, but only at the expense of removing all spatial information.

The timing mode sequence is simple: a continual cycle of a row shift followed by a pixel shift and read, then row shift etc.. The result is to collect (add) all data from a diagonal strip of pixels into the output register before measurement. With a 10 µs row shift and 11 µs pixel shift and read, pseudo-pixels are read out every 21 µs. Figure 2.9 shows two such rows being read out. One will be read out at the amplifier at cycle *n*, whilst the next at cycle *n*+7 ie. approx. 0.15 ms later.

If a point source were confined within a single CCD pixel area, the individual cycle time would be the attainable time resolution. In fact due to the extended nature of the point response function, a photon might be incident on the diagonal strip at any time whilst the strip is crossing the PRF. The probability is affected in detail by the shape of the PRF, but qualitatively, there is a 50% chance of the photon arriving in one of the 40 (EEV) or 57 (Thomson) pixels across the linear size of the HEW of 30 arcsecs. Thus timing precision is of the order 50 pixel periods or about 1 ms - *if the spacecraft attitude is correctly known*.

The count rate limit is again determined by pulse pile-up. In this case, as no imaging information is available, and the pixel binning reduces the fraction of apparent split events, the maximum rate may be closer to 1 photon/10 pseudo-pixels. In this case the maximum rate is 1 photon per 210 µs, or about 4750 cts/s, that is about 0.5 Crabs. Again the value of 1/10 is used as baseline, but a lower value may be more realistic.

Summary of programmable parameters of the mode

The following parameters should be programmable by telecommand :

- Node used
- Clocking speed

Fig. 2.9

2.4.1.2 . CCD readout: timing mode (pn)

In the case of MAXI a time resolution of 20 µs can be achieved in two possible high time resolution modes. The main timing mode is described in this section, while the alternate burst mode is presented in the next section. *In both these operating modes only one single CCD is read out* (the other chips are not read out at all) and we get the full spatial resolution of 150 µm only along the X-axis, i.e. perpendicular to the direction of line transfer. These modes are different from the MOS-CCD timing mode.

20 pixels of one column, i.e. along the transfer direction, are integrated prior to conversion. This integration takes 20 µs. The information from this strip of 20∞64 pixels is then converted and read out within 20 µs: for details see figure 2.10

In timing mode we can continuously monitor the source with a time resolution of 20 µs, but there is an increase of the effective pixel size by a factor of 20, which leads to a relatively low maximum point source flux.

Summary of programmable parameters of the mode

The following parameters should be programmable by telecommand :

- Chip to be operated in timing mode

2.4.1.3 _CCD readout: burst mode (pn)

In burst mode the maximum point source flux is very high, because we read out each pixel. A drawback of this mode is its low effective observation time of only 4.6%; we can monitor the source for only 0.2 ms every 4.4 ms.

The target image should be placed within the top rows of the CCD. While this top part of the CCD is exposed to source photons, the image charges are transfered continuously to the output nodes with a frequency of 1 MHz. After 0.2 ms the image taken within the first microsecond of the exposure has been shifted 200 lines down to the anode and the stored burst exposure is then read out within 4 ms. ¥
The maximum point source flux for this mode is very high. In burst mode, the source should be placed within the top 20 rows of the CCD. After an integration time of 18 mm: the detailed timing is shown in figure 2.11.

Before we can start a new sampling period, we have to erase the picture accumulated during the readout time. This is done by shifting all 200 lines within 200 µs towards the output nodes, while the on-chip reset switches are kept closed. Thereafter the next exposure starts immediately.

Summary of programmable parameters of the mode

The following parameters should be programmable by telecommand :

- Chip to be operated in burst mode

Fig. 2.10

Fig. 2.11

2.4.2.1 .MOS_ECE_h Handling at EMCE level (MOS)

The function of the EDU in the timing mode is not yet well defined. A proposal is to transmit energy and time for pixels whose energy is within a programmable range. Time and position are equivalent in this mode and can be expressed as a relative counter in units of $\Delta\tau$ (the pseudo-pixel time of 21 μs).

2.4.2.2 Handling at EPCE level (pn)

The processing is basically the same as for the full frame mode (see 2.1.2.2 .gFF_pn_ECE_h); details are TBD.

2.4.3.1 .EMCE-EDHU interface (MOS)

The data processed by the controller (EMCE) has to be forwarded to EDHU along the provided serial data line. The format currently foreseen for the timing mode is the following :

An header format of 64 bits is sent first, and a trailer format later, in the same way and with the same format described in 2.1.2.1 .gFF_MOS_ECE_h above.

For each photon event accepted by the EMCE, according to the criteria described in 2.4.2.1 .gT_MOS_ECE_h, an event format is sent, containing the information relevant to an event, with the following format:

Data identifier	1	bits
Time	19	bits
Energy	12	bits
Spare	TBD	bits (e.g. 0)

for a total also of 32 bits (i.e. the header format length for this mode is twice the event format length; note however the header contains redundant information).

Note that since the 19-bit (or 16-bit ?) "time" counter recycles, it is necessary to define a start time (T_0) for the relative counter. This information could be sent in the header format.

2.4.3.2 EPCE-EDHU interface (pn)

The data processed by the controller (EPCE) are forwarded to EDHU along the provided serial data line, identically to what described above in 2.1.3.2 .gFF_pn_ECE . The event format is the same described in 2.1.3.2 .gFF_pn_ECE , for the following considerations.

As only one chip at a time will be operated in this mode, it is not necessary that the individual event is tagged with the CCD chip identification. However, to preserve an unique format for all modes, it is preferred to keep the "chip id" field present as spare bits.

In the case of the burst mode the remaining fields are exactly as for the full-frame mode (see 2.1.3.2 . gFF_pn_ECE). In the case of the timing mode, as 20 pixels within each column are integrated prior to conversion, one gets only 10 "reduced pixels" per column, and the number of bits for Y could be reduced to 4. Again (see also 2.3.3.2.gW_pn_ECE) it is however preferred to keep the same format used for the full-frame one.

2.4.4 Actions by EDHU

So far make reference to 2.1.4.1 .gEDHU for a description of the functions of EDHU. The operations in timing will be similar to the ones described in 2.1.4.2 for full frame mode, as far as the differences in the input data stream allow. In particular the EDHU shall convert the individual event "time" (relative counter, see 2.4.2.1) into spacecraft time, taking into account the duration $\Delta\tau$ of a pseudo-pixel.

It is likely that, if direct transmission of event data is not possible, one has to resort to binning into light curves (in selected energy ranges).

2.4.5 Output format

This will be analogous to what described in 2.1.5.

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2.4.6 Associated problems

In the case of the MOS CCDs, the pixels in the diagonal stripe take approx. 512∞21 ms to cross through the field of view, ie. any photons from the diffuse background or other sources in the field may be collected, leading to a high background rate. However, as timing mode will be used for high signal-to-noise observations, this may not be important.

The modulation of timing information due to spacecraft drift or telescope performance will dominate the timing precision, and the CCD performance must therefore be calibrated only on an end-to-end test.

2.4.7 Scientific usage

Timing mode for the MOS CCDs will be used for point sources in fields which have no other bright sources. This is the only MOS CCD mode with high time resolution, and will be particularly appropriate for compact binary objects where variability on timescales down to milliseconds is observed.

For the pn-CCD the two timing modes will only be used for those rare cases where either a time resolution better than 2 ms is required or for the observation of bright sources (> 100 mCrab).

2.5 .Transparent mode

The controller transparency mode is foreseen for diagnostic purposes. The raw energy content of each pixel is transmitted without processing at EMCE level.

This mode is likely not to be used for science, therefore its presence in this document is for reference only.

For MOS CCDs in this mode, one CCD in the focal plane mosaic will be read out and all of the pixel contents will be telemetered for diagnostic purposes. This may be performed e.g. at a range of operating temperatures (for example to assess dark current spikes). Each pixels should be read out (with reset) in 20 µs.

In the case of the pn-CCDs a 32-bit information will be transmitted for each pixel, with the same bit allocation used for all other modes. Only one CCD chip will be operated at one time. In order to reduce information to be handled by EMCE, EDHU and telemetry system, only some columns of the chip will be read out. This can be achieved by setting the lower thresholds for such columns to zero, whereas for the remaining columns the thresholds are set higher or equal to the upper thresholds. In order to cover the entire CCD the active columns will be shifted over the chip.

Handling at EMCE level will be by definition none. At the level of EMCE-EDHU interface, the raw energy data will be forwarded with a protocol similar to those described above for the science mode. The action by EDHU will probably be a plain formatting into the telemetry source packets.

In the case of the MOS-CCDs the EMCE-EDHU data transfer will comprise a 64-bit header and trailer format (identical to the one described in 2.1.3.1 .gFF_MOS_ECE), and an event format as follows :

Data identifier	1	bits
Raw pixel energy	12	bits
Spare	TBD	bits (e.g. 3)

for a total of 16 bits (the length of the header format is 4 times the one of the event format).

In the case of the pn-CCDs the same format described in 2.1.3.2 .gFF_pn_ECE will be used.

In order to assess the data rate of this mode, one could make the following considerations :

Since one pixel is read out in 10 µs, and the content of one pixel is 12 bits (excluding overheads), if no intermediate buffering is used, this requires at least 1.2 Mbit/s on the EMCE-EDHU line.
Buffering at EMCE level, the transmission of the 1024∞1024∞12 bits could be spread out over the frame integration time of TBD s. For the usual integration times of 50-64 s, the rate amounts to about 200 kbit/s.

Anyhow, to downlink a 1024∞1024 array with a depth of 12 bits, at the nominal bit rate of 40 kbit/s, takes 5.2 min.

This might suggest that the integration time could be much longer than the usual time (this is operatively no problem, as during such diagnostic operations the entire spacecraft will not be taking science data; on-board adding of more frames at EDHU level prior to transmission is discouraged). The long integration time might be useful to provide a better estimate of the pixel-by-pixel dark current map, to diagnose radiation damage, or the effects of low-level signals (below detection level) which may cause a slight bias within the event recognition algorithms. It could be used also for optically stimulated flat field diagnosis.

However calibration frames taken with an X-ray source must be run with the same integration time as normal science mode, and in general the integration time shall be considered a programmable parameter, totally independent on the time taken to telemeter the data.

Consideration might be given to intermittent transmission of a (variable) subset of raw pixel data from every frame at the same time as normal science data.

3. Overview of scientific objectives

Important notice

Some estimates of count rates are given throughout this document by reference to the Crab Nebula. However the transformation between count rates and Crab units needs to specify what mirror is used. As a rule, in this document we quote figures in milliCrab, computed assuming that the mirror full area is utilized. For the other MOS CCD camera, i.e. for the camera behind the mirror with gratings, these milliCrab estimates must be multiplied by a factor of two since the area is divided by 2.

Count rates are also dependent upon pixel read times (these may decrease in the future), the integration to readout ratio (currently assumed as 10:1) and the X-ray confusion limit of 1 photon per 40 pixels, and of course on source spectral shape and final CCD efficiency.

And of course the data rates depend on the format chosen for the transmission.

All these parameters are subject to change. The values indicated here are consistent with the current baseline.

3.1 Spectral studies

By definition the EPIC instrument is designed to optimally exploit the throughput of the XMM optics, and perform spectral studies with the medium-high resolution of the CCD detectors. The energy information is transmitted in all operative modes (see chapter 2).

The standard mode for spectral studies is of course the full frame mode or the frame store mode (which is the default operating mode for the central MOS chips). The actual mode chosen for spectral studies depends on the source intensity and on the source type (point source, extended source, see also 3.3gExt_sources below).

It has to be stressed that the CCD devices suffer from a limitation, which is at the same time an advantage. In order to be able to measure the spectrum of very weak sources, there is a limitation on the maximum count rate in each mode. This derives from the need of avoiding a pile-up effect (only a single photon shall deposit its charge in a pixel during each one frame readout, in order for this charge to be proportional to the energy of the photon). A discussion of the maximum count rates in each mode is given in the Appendix.

3.2 Temporal studies

3.2.1 Crab nebula pulsar

A simulation of the observation of a Crab-like nebula has been performed in Saclay with a Monte-Carlo program which includes the combined mirror-detector response with a 30 arcsecond PSF, and a MOS CCD.

The nebula was assumed to have a 2 arcmin diameter, an uniform surface brightness and a Crab spectrum ($9\infty E^{-2}$ ph/cm^{2}/s/keV with interstellar absorption). The pulsar was put in the center of the nebula , with 100 mCrab intensity and a period of 33 ms. The pulse shape was taken as a square over 10% of the period. The characteristics of the timing mode were those given in 2.4.1.1 . gT_MOS_CCD . The pulse shows up clearly in a simulation of an observation of duration 2 s, using the usual folding techniques with the input data binned at 21 µs. However the analysis of the energy spectrum indicates that there is a strong photon pile-up in this case.

3.2.2 X-ray pulsars

Table 3.1 gives as examples the observing mode which is needed for 5 X-ray pulsars (W for windowing, T for timing). For some pulsars, their relatively high flux commands that the mode be the timing mode, although their period be long (*see however below for a comment on fast window mode*). The last column figures correspond to the expected bit rates computed from the flux with 64 bit/event (W) or 32 bit/event (T). These rates show that in most cases data compression is needed.

Source	Flux (mCrab)	Pulse Period(s)	Operating Mode	Bit rate (kbit/s)
SMC X-1	60.	0.71	W	38
Her X-1	310.	1.24	T	99
Cen X-3	480.	4.84	T	153
LMC X-4	60.	13.5	W	38
GX 1+4	380.	115.	T	122

(data from White et al., 1983, Ap.J., **270**, 711)

It is worth emphasizing that one of the main applications of the fast window mode will be *phase-resolved spectroscopy* of bright x-ray pulsars. In fact a large fraction of the "classical" accreting systems have fluxes for which pile-up effects will become not negligible in the other modes, thus affecting their spectral study. Although the presence of time gaps in fast window mode will reduce the overall efficiency of the obervation, this will not be problem, given the brightness of these sources, which in general have pulse periods in the range from a few seconds to a few minutes. A typical observing sequence could consist of a short exposure in timing mode, in order to precisely measure the period, followed by a long fast window mode pointing, which, unless the source period is a multiple of the read-out/exposure cycle, will provide a uniform phase coverage of the source.

3.3 .Imaging of extended sources

In most cases, the imaging of extended sources will be performed, in the case of the MOS CCDs, with the full frame mode. However other modes like frame store or windowing mode will be used in special cases, i.e. when a bright point source or spot is included in the extended source.

The frame store mode is however possibly still justified for spectral studies of point sources brighter than the maximum allowable for full frame. A discussion about the reciprocal merits of frame store and windowing mode depends also on the focal plane arrangement of chips. See also a November 1989 note by R. Rothenflug on use of windowing, and a comment by D. Lumb on greater simplicity of frame store.

3.3.1 Count rate limitations versus modes

One can apply the considerations on the maximum allowed count rate, reported in the Appendix, to the case of extended sources. The criterion of 0.025 (1/40) photons/pixel/frame can be changed in a condition on the surface brightness, i.e.:

$B \infty t \infty s < 0.025$ photons

where B is the local surface brightness of the X-ray source, t the exposure time and s is the angular area of one pixel. Using for s a value of $1.6\infty10^{-4}$ arcmin^{2} (EEV) or $8.3\infty10^{-5}$ arcmin^{2} (Thomson) this gives:

EEV device: $Bt < 150$ EPIC cts/arcmin^{2}
Thomson device: $Bt < 300$ EPIC cts/arcmin^{2}

For EPIC, 1 milliCrab is about 10 cts/s and neglecting in first approximation the influence of the true spectrum shape one can express these constraints in terms of mCrab/arcmin^{2}. One can also derive useful constraints in Einstein IPC cts/s/arcmin^{2} or HRI cts/s/arcmin^{2} with the following rough transformations: 1 mCrab = .7 IPC cts/s = .15 HRI cts/s.

In the full frame mode, t=50 s :
EEV device: $B < 3$ EPIC cts/s/arcmin^{2} or 0.3 mCrab/arcmin^{2}
Thomson device: $B < 6$ EPIC cts/s/arcmin^{2} or 0.6 mCrab/arcmin^{2}

In the windowing mode, t is of the order of 0.1 s, hence $B < 1700$ EPIC cts/s/arcmin^{2} or 170 mCrab/arcmin^{2} (see paragraph 2.3.1.1; .gW_MOS_CCD for a 1 arcmin^{2} window (for both EEV and Thomson chips).

3.3.2 Observations of supernova remnants

A number of SNRs have been observed by the Einstein satellite. A list of 44 observed SNR has been provided, together with their IPC flux, by Seward (1988; in Proc. of the IAU Coll. 101 "SNR and the interstellar medium" (Penticton 1987), Cambridge University Press, eds. Roger and Landecker, pag. 115). An examination of such table shows that most objects except 4 historical SNRs could be probably observed in the full frame mode. For instance simulations for Cygnus Loop using images obtained with Exosat indicates that there is no limitation due to surface brightness in that particular case. However true observational scenarii must take into account real surface brightness distributions and true spectra observed for SNRs.

3.3.2.1 The special case of historical SNRs

Table 3.2 gives the relevant figures for the 4 brightest historical SNRs derived from published HRI maps:

a) The observation of the Crab seems impossible with a classical mode. However the Crab nebula has a spatial extent of about 5 arcmin^2. For the MOS CCD camera behind the mirror with gratings, the maximum rate will be about 300 mCrabs for a 1 arcmin^2 window. So the Crab nebula can at least theoretically be observed in parts with this camera in windowing mode. However as the pointing accuracy will be around 1 arcmin, one will need a great number of observations to observe the whole nebula. Morevover as the nebula brightness is not uniform, there will be probably some pile-up during the observation of the Crab nebula center.

b) The three other objects could be observed with the windowing mode. Each object will need an adapted scenario to the surface brightness distribution. For instance, Kepler can be observed with a 5∞5 arcmin^2 window: such a window will be read in about 1.5 seconds.

This reading time limits the surface brightness to about 200 EPIC cts/s/arcmin^2 or 3 HRI cts/s/arcmin^2, value well above the maximum in surface brightness for Kepler SNR.

Table 3.2

Name	Diameter (arcmin)	HRI Range in B (cts/s/ arcmin^2)	EPIC (cts/s)	Mean B (cts/s/arcmin^2)
Crab	2.5	....	10000	....
CasA	5	0.6 -5.0	900	46
Tycho	8	0.05-0.2	300	6
Kepler	3	0.1 -0.7	110	16

3.3.3 Clusters of galaxies

The full frame mode will typically be used for the observations of clusters of galaxies. However a delicate situation arrives when a strong X-ray galaxy exists in the center of the cluster like M87 in Virgo or NGC1275 in Perseus. One can simulate the observation for the Perseus cluster using published results. NGC 1275 will give 50 cts/s in one FPI, thus violating the condition for observation of point sources with the full frame mode (limited to 1 cts/s). Such source can be observed with the windowing mode (MOS CCDs); the pn-CCD can still observe such source in full frame mode.

Such extended sources with bright point-like X-ray sources could be observed by EPIC in two steps: one for the observation of the bright source with a windowing mode and the other with a full frame mode for the diffuse emission. These two steps only concern one CCD, the others ones will be put in full frame mode for the observation of the other parts of the source. Alternatively one could observe at the same time using two different focal camera units in the two different modes.

3.4 Imaging of diffuse background

The diffuse background represents the lowest level of surface brightness to be observed by EPIC, and hence most appropriately addressed by the full-frame mode. However the importance of the 10% smearing effect should be assessed if one is interested in the isotropy of the background. This may lead to the suggestion of use of the frame-store mode for some observations.

Also consideration should be given about the orientation of individual EPIC FPCs (e.g. orthogonal or 60-degrees) to have misaligned smearing.

APPENDIX: Calculation of limiting count rates

A.1 Introduction

This section is an extensive rewriting of material added in appendix to draft 0.0, and tries to organize within an unified scheme material from various sources, including : the document and notes for the pn-CCD (provided by E.Kendziorra, and used as input to the previous and this draft also for chapter 2); a REVISED version of the note "Re-assessment of EPIC science data rate" (originally issued by D.H.Lumb on 27 Nov 1989 and publicly available; this document however makes reference to a later version); material by Saclay (note by Cretolle and Cara, 14 March 1990; plus miscellaneous tables used as input to previous sections); a thorough discussion by R.Rothenflug about the background. The original material is available on request.
It does not include the simulations discussed in the note "A preliminary assessment of EPIC telemetry rates" by L.Chiappetti, 24 Nov 1992.

The attempt here is to handle everything in parametric form, allowing recalculation of the results when the input parameters are changed.
The purpose is: determine the limiting countrates for each mode; determine the corresponding bit rates; discuss some scientifically more representative cases for each mode.

A.2 Criteria for calculation

A.2.1 .gLimit_CR The limiting count rate

The main point in the calculation of the limiting count rate (which is essential for a discussion of the capabilities of the modes, and from which the maximum bit rate in any mode can be computed) is that one wants to avoid photon pile up: two photons should not be allowed to fall in the same pixel, otherwise the charge deposited in the pixel does no longer allow to derive the individual photon energy.

This criterion is generally expressed in a more conservative form : it is not allowed to have more than one photon every n pixels in a frame readout.

The **first parameter** n is therefore given by the condition:

observed < 1/*n* photon/pixel/frame

This document consistently uses the canonical value of less then 1/40 photon per pixel and integration time (*n*=40) unless otherwise stated (e.g. *n*=10 or 12 for the timing modes). It has however been suggested that lower values of 1/*n* (*n*=200-500 for imaging modes, and 40 for timing) might be more realistic.

The **limiting count rate criterion** is then expressed by:

$$T \infty I_0 \infty f \infty (A_{pixel}/A_f) < 1/n$$

where T is the integration time, I_0 is the limiting count rate, f is the fraction (0.0-1.0) of counts falling into a selected area A_f, while A_{pixel} is the area of one pixel.

The **second parameter** T is determined by the operating mode.

The extent of the area A_f is determined by the case under study. Typically for point sources one sets A_f to the

HEW of the PSF, therefore f=0.5 by definition.

In the case of extended sources one sets f=1, and rewrites the limiting criterion in terms of the surface brightness $B=I_0/A_f$ (cts/s/arcmin^2) as used extensively in chapter 3 above:

$$T \infty B \infty A_{pixel} < 1/n$$

The parameters of the instruments are reported in table A.1,for the baseline focal length of 7.5 m and for both the baseline case of a 30 arcsec HEW, and the possi- bility of a 10 arcsec HEW. The A_{pixel}/A_{HEW} is reported in the last column. In the case of the pn-CCD only, in the event of a 10 arcsec HEW it could be worth fabricating chips with a smaller pixel size. Given the present situation about the optics, the 10 arcsec case is not considered further in this document.

Table A.1

CCD type	HEW (arcsec)	pix size (µm)	pix area (mm2)	chip size x∞y pix	no.pixel in HEW
MOS EEV	30	27∞27	0.00073	768∞1024	1282
MOS Thomson	30	19∞19	0.00036	1024∞1024	2589
pn MAXI	30	150∞150	0.02250	64∞200	42
MOS EEV	10	same as above			142
MOS Thomson	10	same as above			288
pn MAXI	10	75∞75	0.00560	128∞400	18

An HEW of 30 arcsec is 0.93 mm^2. An HEW of 10 arcsec is 0.104 mm^2.

One may then rewrite the limiting count rate criterion explicitly :

$$I_0 < (A_{HEW}/A_{pixel}) / fTn \qquad (1)$$

(in the standard case f=0.5 n=40 and one has :

$$I_0 < 0.05 \infty (A_{HEW}/A_{pixel}) / T$$

A.2.2 .Conversion to bit rate

To convert count rates to bit rates, one might, if interested in maximum values, consider that the target source is at the limiting rate I_0 specific to the operating mode under consideration. However besides the source rate one has additional contributions from the X-ray diffuse background and from the charged particle background. Summarising :

Source rate	$C_s < I_0$	cts/s
Diffuse background	$C_x = 3$	cts/s
Particle background	$C_p = 24\text{-}50$	cts/s

The values for the background are justified further below in A.2.3.
To convert the total (count) rates into bit rates, one applies the following formula, which gives N in bit/s :

$$N = C_s S_s B_s + C_X S_X B_X + C_p S_p B_p$$

where the S_i are the *pixel splitting factors* (which take into account of the probability that the charge of one event is split among adjacent pixels), and the B_i is the *bit allocation* (bit/event).

Concerning the pixel splitting factor, the following **preliminary** estimates are used (more adequate values will result only from direct experimental measurements) :

for source X-rays:	$S_s = 1.5$ same as
for diffuse X-rays:	$S_X = 1.5$
for particles:	$S_p = 4$

They will be applicable if the EMCE would forward the information about individual pixels. However, in the case of MOS CCDs, with the current EMCE-EDHU protocol, it is foreseen to transmit a 5∞5 matrix around a "good" event, therefore split pixels are never transmitted individually, and all S_i=1.

The bit allocations B_i depend on the mode (see discussion in chapter 2), and on the compression scheme used (e.g. transmitting information like CCD chip id, or row position, only when changed; in line of principle this could be different for X-rays and particles due to the different spatial spread of the charge). We do not envisage so far any compression scheme for the EMCE-EDHU communication. If compression has to be performed, this should be done downstream of the EDHU. The bit allocation on the EMCE-EDHU line is the same for X-rays and particles and amounts to :

MOS:	FF,FS,W modes	64 bits
MOS:	timing mode	32 bits
pn :	all modes	32 bits

A.2.3 .Background rates

A.2.3.1 The X-ray diffuse background

The diffuse background is made of two components: a galactic one dominant at low energies (E < 1 keV) and an extragalactic contribution dominant at higher energies. The galactic background itself has a thermal origin, but some recent measurements indicate that one needs probably two components with different temperatures and interstellar absorptions to describe this emission :

a) a component with a relatively low temperature ($3\infty10^5$ K) and an emission measure around 10^{-2} cm^{-6} pc (Labov and Bowyer 1990, preprint).

b) a one-million degree component. From Rocchia et al., 1984 (Astron. Astrophys., **130**, 53) one can adopt the following plasma parameter values as representative of a large part of the sky:

temperature = $1.1\infty10^6$ K
$n_e n_H V = 1.2\infty10^{-2}$ cm^{-6} pc

The thermal spectrum was computed using a code available in Saclay including emission from lines and continuum radiation. The soft X-ray background intensities of both components can vary from place to place in the sky, but a mean estimate is sufficient for the purposes of this document.

The total background is the sum of this galactic background and the extragalactic background. The latter component (component c) is given by the following formula:

$dN/dE = 11\ E^{-1.4}$ ph/cm^2/s/keV/steradian (E in keV)

Finally, one must take into account the interstellar absorption which can be different for the galactic component which has a local origin and for the extragalactic component. We adopted the following values :

galactic component a	10^{17}	atoms/cm^2
galactic component b	$6\infty10^{19}$	atoms/cm^2
extragalactic component	$4\infty10^{20}$	atoms/cm^2

The total spectrum was convolved with the EPIC response using the effective area given in the proposal for the full mirror area. For the solid angle of 1 MOS CCD (about 81.5 arcmin^2) the total background produces 0.7 cts/s.

For one EPIC camera, corresponding to the field of view of 7 MOS CCDs, one obtains about 5 cts/s with the following contributions :

component a	0.7 cts/s
component b	2.9 cts/s
component c	1.4 cts/s

Lowering the value of N_H (for the galactic component b) to 10^{17} cm^{-2} increases the computed background rate to about 7 cts/s for one EPIC camera.

In the case of the pn CCD, one can do the same estimate with a change of the depleted zone width and keeping all other parameters. One gets about the same figure.

A.2.3.2 The particle background

Based on EXOSAT and COS-B rates the estimate of the number of charged particles that would cross the focal plane per second, each triggering a signal from the ADC, varies from 24 to 50. A conservative estimate of 50 cts/s in adopted in this document.

A.3 Application to the operating modes

One may apply formula (1) of section A.2.1gLimit_CR, assuming (according to the discussion in chapter 2 and A.2.2gConv_bitrate) no pixel splitting, and the bit allocations corresponding to the modes, and produce the following tables.
Table A.2 is computed for the canonical 30 arcsec HEW. See table A.1 for the factor A_{HEW}/A_{pixel} used. In the table below the following symbols indicate respectively :

T	the time resolution of the mode (readout time)
n	the number of photon/pixel/frame (see A.2.1gLimit_CR)
I_0	the resulting limiting count rate (also the corresponding flux in Crab units is given)
N	the bit allocation of the mode

The modes are indicated as FF,FS,W,T,B for Full-Frame, Frame-Store, Windowing, Timing, Burst respectively.

All calculations are done for a point source, and the full area mirror.

The resulting bit rate is the one related to the source counts plus a background rate of 3 + 50 cts/s (i.e. including no rejection, see A.4gSci_case below).

Table A.2

CCD	Mode	time T		n	I_0 (cts/s)	Corresp. flux	N	bit rate (kbit/s)
MOS EEV	FF	50.00	s	40	1.3	0.13 mCrab	64	3.5
MOS Thomson	FF	64.00	s	40	2.0	0.20 mCrab	64	3.5
pn MAXI	FF	48.00	ms	40	43.2	4.3 mCrab	32	3.1
pn MAXI	FF	24.00	ms	40	86.5	8.7 mCrab	32	4.5
MOS EEV	FS	4.80	s^{a}	40	13.4	1.3 mCrab	64	4.2
MOS EEV	FS	2.40	s^{b}	40	26.7	2.7 mCrab	64	5.1
MOS Thomson	FS	6.40	s^{a}	40	20.2	2.0 mCrab	64	4.7
MOS EEV	RFS	56.1	ms	40	1142	114 mCrab	64	76.
MOS EEV	W	94.4	ms^{1}	40	678.	68. mCrab	64	46.8^{5}
MOS Thomson	W	190.9	ms^{1}	40	679.	68. mCrab	64	46.8^{5}
MOS EEV	W	94.4	ms^{1}	40	1508	151 mCrab	64	100.^{6}
MOS Thomson	W	190.9	ms^{1}	40	1507	151 mCrab	64	99.8^{6}
pn MAXI	W^{A}	4.48	ms	40	530	53 mCrab	32	18.7
pn MAXI	W^{B}	13.20	ms	40	189	19 mCrab	32	7.7
pn MAXI	W^{C}	5.92	ms	40	467	47 mCrab	32	16.7
pn MAXI	W	3.065	ms	40	1005	0.1 Crab	32	34
MOS EEV	T	0.84	ms^{2}	40	76307	7.6 Crab	32	2443^{7}
MOS Thomson	T	1.19	ms^{2}	40	108772	10.9 Crab	32	3488^{7}
MOS both ?	T	21	ms	10	4761	0.5 Crab	32	152 ^{8}
pn MAXI	T	20	µs^{34}	40	5192	0.5 Crab	32	168
pn MAXI	B	20	µs^{49}	40	103837	10.3 Crab	32	3324

Data computed for an HEW of 30 arcsec unless otherwise stated.

a: case for one output node
b: case for two output nodes
1: T for a 1 arcmin window (see 2.3.1.1 .gW_MOS_CCD)
2: T is not a true exposure, but the timing precision described in section 2.4.1.1 .gT_MOS_CCD , third para.
3: for the pn timing mode the effective pixel size used extends20 times in the y-direction hence is 150∞150∞20
4: for the pn timing and burst mode the meaning of the cycle time T is explained in sections 2.4.1.2 . gT_pn_CCD and 2.4.1.3 .gB_pn_CCD respectively
5: values calculated for A_f=HEW f=0.5 as usual (not representative)
6: values calculated for A_f=1 arcmin^2 f=0.9 (see 2.3.1.1 .gW_MOS_CCD)
7: values calculated for A_f=HEW f=0.5 with usual formula (not meaningful in this case)
8: values calculated as follows : limit of 1 photon every n pseudopixels where a *pseudo*pixel is the sum of all pixels along the diagonal; n=10; T is readout time for 1 pseudopixel; the limiting rate is then 1/nT
9: note that for the pn burst mode (and the fast window mode too) the duty cycle is << 100% (see text)
A: 48∞20 pixel window ; B 192∞200 pixels window; C 128∞128 pixel window

A.4 .Scientifically representative cases

The Crab will produce about 10^4 counts per second per telescope (including detection efficiency effects; see notice to chapter 3).

If one assumes that the data allocation per pixel is the one described in chapter 2, then each MOS focal plane produces in the absence of source photons:

$N=64 \infty ((3\infty S_x)+(50\infty S_p))$ bit/s

considering $S_x=S_p=1$ for the EMCE-EDHU protocol; this gives 3.4 kbit/s. *Concerning the minimum data rate which must be handled by the EMCE's event recognition circuits one should consider pixels sent individually, with the proper splitting factors, and an allocation of 36 bit/event, obtaining 7.4 kbit/s.*

One may also consider that the application of an energy upper level veto in the EDHU may reduce the background events (say 50% of particle events), and the data remaining downstream of EDHU will be

$N = 64 \infty ((3\infty S_x) + (25\infty S_p))$ bit/s

or 1.8 kbit/s

Full Frame Mode:

The brightest extended source observable in full frame mode would probably be an object such as the Tycho SNR, with an expected count rate of about 150 cts/s. With no compression and no background rejection the total data rate is

3.4k + 150 ∞ 64 = 13.0 kbit/s

For comparison consider a field of view with, say one point source in each of 6 CCDs, each source close to the upper limit of 0.1 mCrab. This is 1 count per second, the total bit rate in this case is:

3.4k + 6 ∞ 64 = 3.8 kbit/s

Framestore Mode

Framestore mode is very similar to Full Frame mode, except that the chips operated in this mode require in line of principle one less X position bit (this is currently not exploited), and they may produce an order of magnitude greater count rate.

Typically the brightest extended source we might observe could be Cas A, with a count rate of 400 cts/s in a 4 arcmin area, (which would lead to several counts per row, eg. 8). Therefore the Cas A bit rate would be without compression

400 ∞ 64

and adding this to the continuing data rate from the other CCDs of about 3.4 kbit/s, a total rate of 29 kbit/s is required.

This is a maximum rate, more realistic rates for a 'typical' source such as a single point source of 1 mCrab flux (10 cts/s) in the frame store CCD leads to a data rate of

10 ∞ 64

or 0.7 kbit/s in addition to the 3.4 kbit/s of the other CCDs (total 4.1 kbit/s).

As with full frame mode, the total science data rate depends not only on flux, but on source morphology and data compression technique.

Windowing Mode

Windowing Mode is yet more difficult to examine in terms of bit rate, as the data content depends not only on the source, but also the size of the window. The example given in table 3.3 of the EPIC Proposal was illustrative of the sort of science one could perform on a point source (window set as 1 arcmin^2 around source), or a bright knot in a SNR etc.

In this example, it can be assumed that it takes approx. 50 ms to clear out pixels from outside the window (not to be measured), and a similar time to read pixels within the window. For this argument we could assume an image time of 10∞ the total readout time. We then have a count rate limit of about 150 cts/s in the window or 15 mCrab.

The data bit allocations could be the same as for full-frame, or as the EMCE sets up the window position by default one might need only the x and y data *within* the window.

For the worst case without data compression, the additional data produced by the windowing mode CCD is:

150 ∞ 64

or about 9.6 kbit/s in addition to the 3.4 kbit/s from the other CCDs. Simple windowing mode of one source is therefore not thought to be a large impact on telemetry, and even less so if data compression is utilised

Timing Mode

In timing mode, every pixel must be time-tagged in order to perform any event recognition through a proximity analysis. This time tagging must be done to a precision much greater than the effective time resolution of the MOS CCD instrument.

At a pixel repetition rate of 20 µs, sub-second timing must be tagged with a 16-bit resolution and energy data at 12 bits (according to 2.4.3.1 .gT_MOS_ECE we use a total of 32 bits). Because there is a measure of on-chip pixel binning, the charge splitting fraction will be less than for imaging mode, whilst the background rate in the timing mode CCD will be 5-10 cts/s (160-320 bit/s). The source bit rate then scales simply with event rate - ie. 1 mCrab = 320 bit/s, 10 mCrab = 3.2 kbit/s, etc..

The maximum count rate might be taken as <1 photon per 12 binned pixels (a higher rate than 1 per 40 required for image event recognition). In other words a rate of 1 photon per 250 µs or about 0.4 Crabs can be tolerated in timing mode. The corresponding bit rate will be 128 kbit/s.

Conclusions

The bit rate cannot simply be scaled from source count rates. If no data is to be lost, and no on-board recognition or rejection performed, the bit rates depend on as yet unquantified charge splitting fractions. Prudent estimates show that background rates alone will produce in excess of 7 kbit/s per telescope (3 kbit/s if the currently envisaged EMCE-EDHU protocol is used).

This protocol (or conversely simple data encoding), and energy veto rejection of some charged particle events allows a significant reduction in data rates. A technique which allows maximum data transmission for faint sources or background studies and some data compression for brighter sources may be appropriate, and should be examined as part of the system design. In this case a bit rate of around 10 kbit/s/ telescope would always be utilised, except for those exceptional sources described above. Most sources do not necessarily load the telemetry by a large margin in addition to the uncompressed background rate.