Pixel Array Detectors for Space Applications

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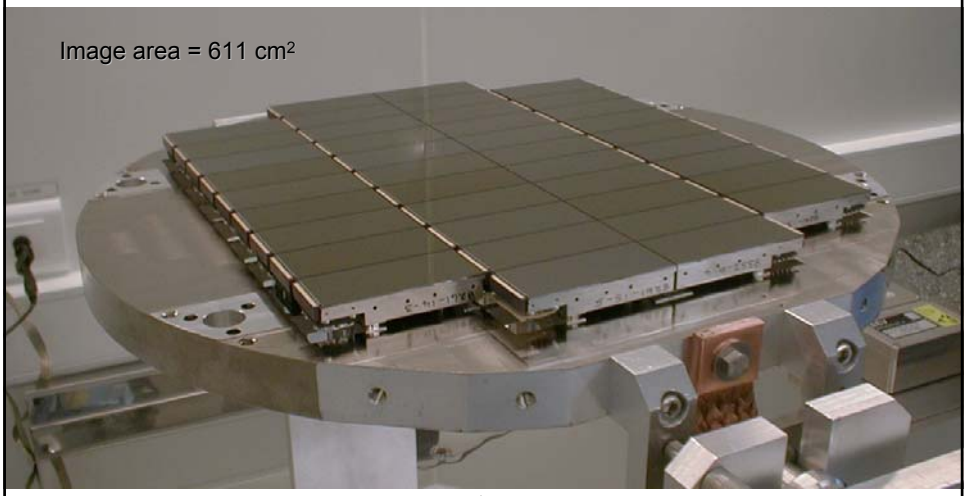
Talk Outline

Technologies and sample applications

- Optical and X-ray Astronomy, Planetary and Solar science
- CCDs
  - Large focal plane arrays
  - Optical - Gaia
  - X-ray – XEUS, Mars-XRD
- CMOS Imagers –Nick Waltham
  - Optical/UV – Solar Orbiter
- Hybrid Pixel Arrays
  - Optical/IR
  - X-ray – Bepi Columbo

Caméra MegaCam

Collaboration between **Commissariat à l'Energie Atomique (DSM DAPNIA)** and **Observatoire Canada-France-Hawaï**



CCD Detector	Marconi CCD 42-90 13,5 µm x 13,5 µm Back Thinned 90 % pic QE 3 sides buttable Flatness ± 8 µm Noise < 3 é	**Focal plane**	40 x CCD 42-90 Array 377 Mpixels 313 mm x 261 mm

Gaia Spacecraft

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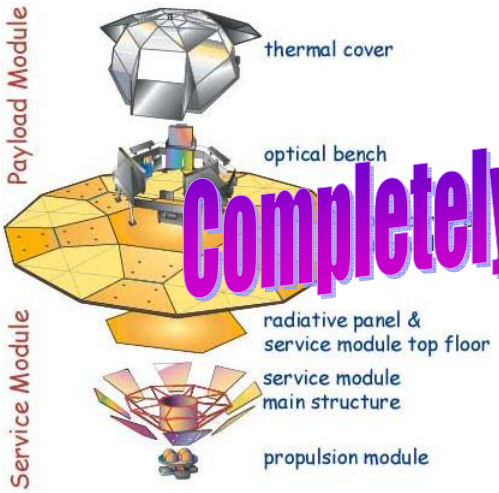
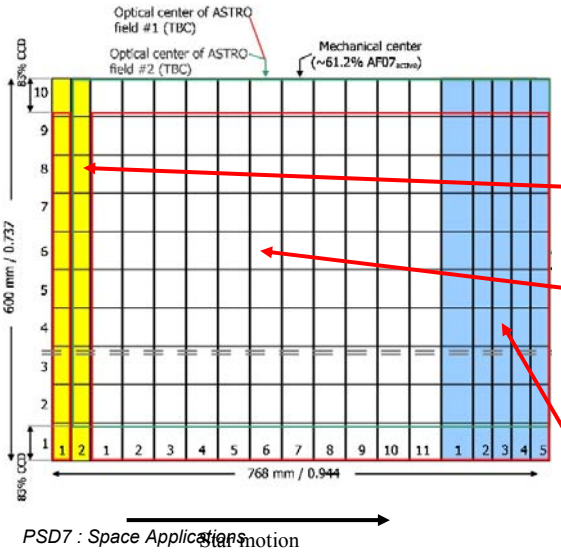


- Astrometric Instrument
  - Sky Mapper (ASM)
  - Astro Field (AF)
  - [illegible] Photometer
- Spectroscopic Instrument
  - Medium Band Photometer (MBP)
  - Radial Velocity Spectrometer (RVS)

Completely Wrong

Astrometric Focal Plane



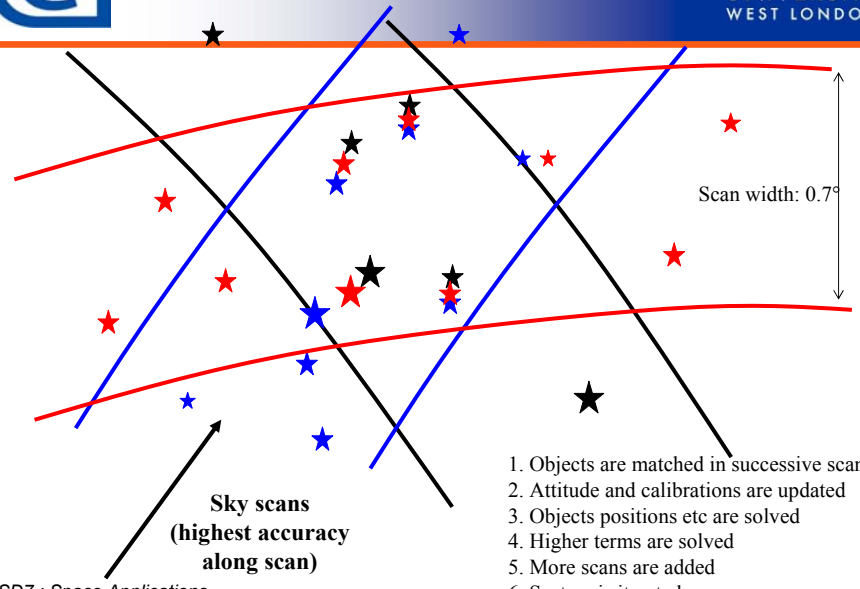
Total field:
- area: 0.6 deg^2
- size: 75 × 60 cm^2
- number of CCD chips: 110+70
- CCDs: 4500 x 1966 pixels

Sky mapper:
- detects all objects to 20 mag
- rejects cosmic-ray events

Astrometric field:
- pixel size: 10 × 30 μm^2
- window area: 6 × 12 pixels
- flush frequency: 15 MHz
- readout frequency: 30 kHz
- total read noise: 6e$^-$

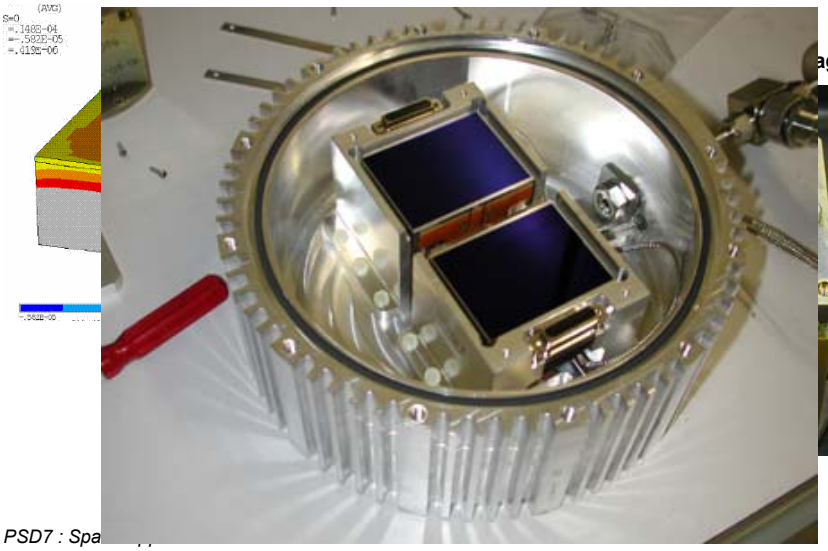
Broad-band photometry:
- 5 colour

Data Reduction Principles



1. Objects are matched in successive scans
2. Attitude and calibrations are updated
3. Objects positions etc are solved
4. Higher terms are solved
5. More scans are added
6. System is iterated

AF CCDs

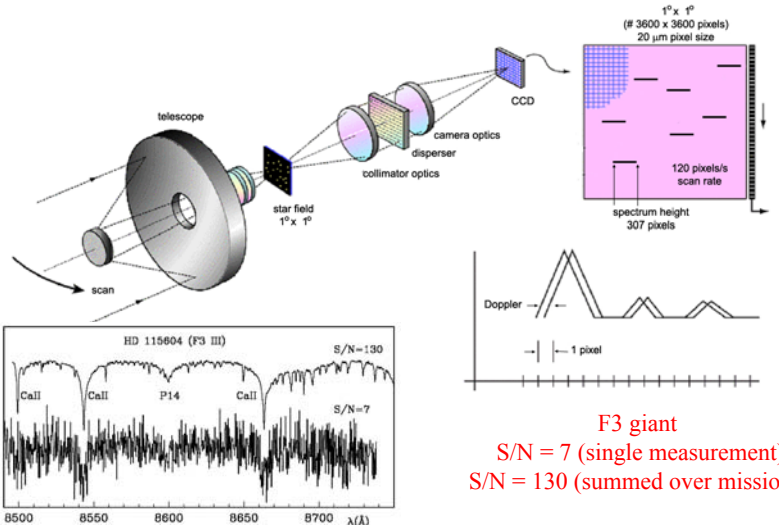


PSD7 : Spa

Astrium AF FPA Breadboard Demonstrator

PSD7 : Space

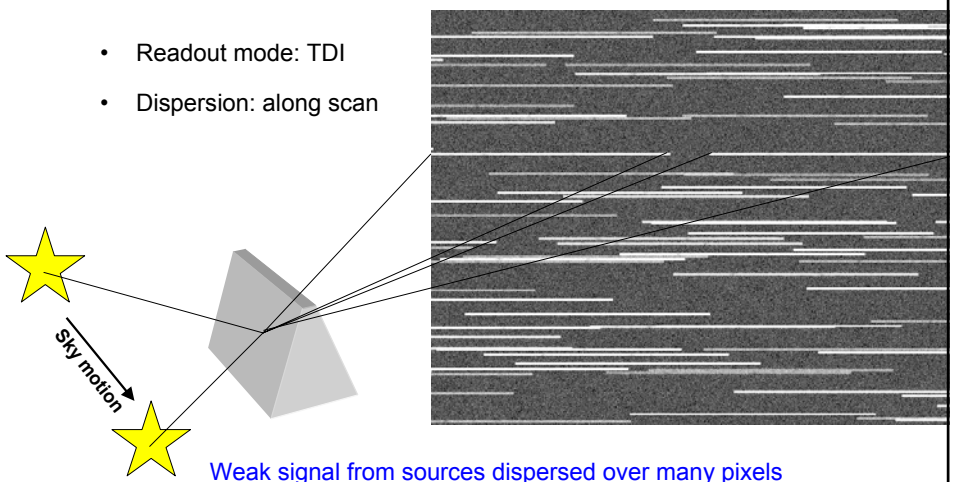
Spectrometer Telescope – MBP + RVS



F3 giant
S/N = 7 (single measurement)
S/N = 130 (summed over mission)

Gaia RVS Scan mode

- Readout mode: TDI
- Dispersion: along scan

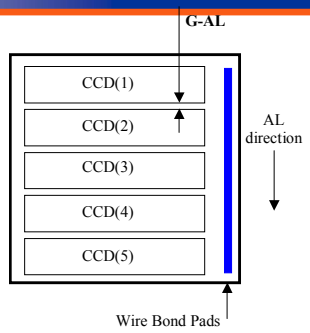


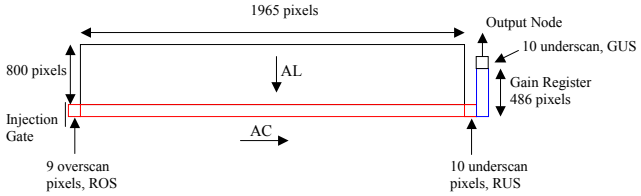
Weak signal from sources dispersed over many pixels
– at worst - 0.5 e^-/pix on a 30 electron sky background = challenging!

RVS CCD Baseline

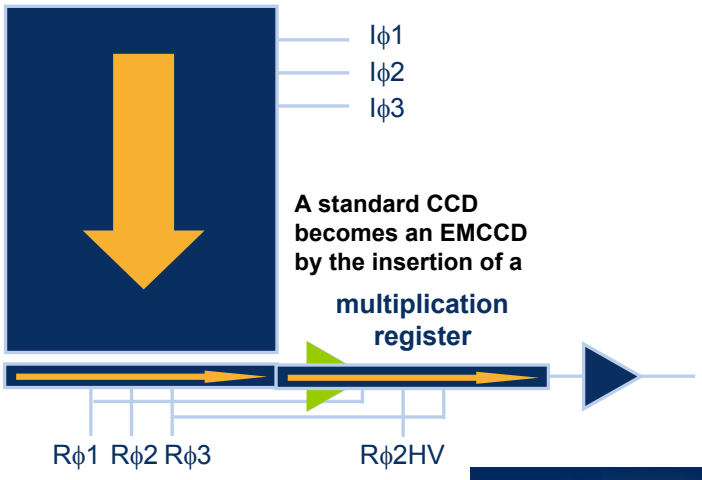
- Focal plane constructed from 4 modules
- Each CCD module having 5 CCDs
- Each CCD clocked in parallel having L3 register on High-Rho silicon

- Gain increases with decreasing temperature Early testing of L3 on High-Rho Si show decreased gain
- New devices being delivered to compensate for this effect



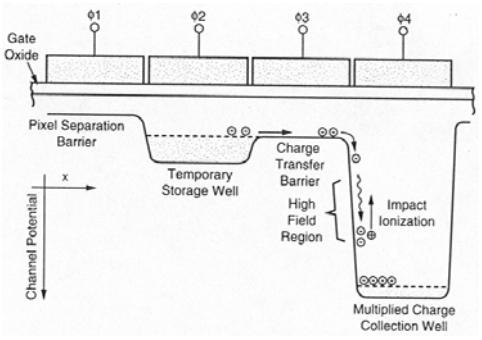


L3Vision CCD



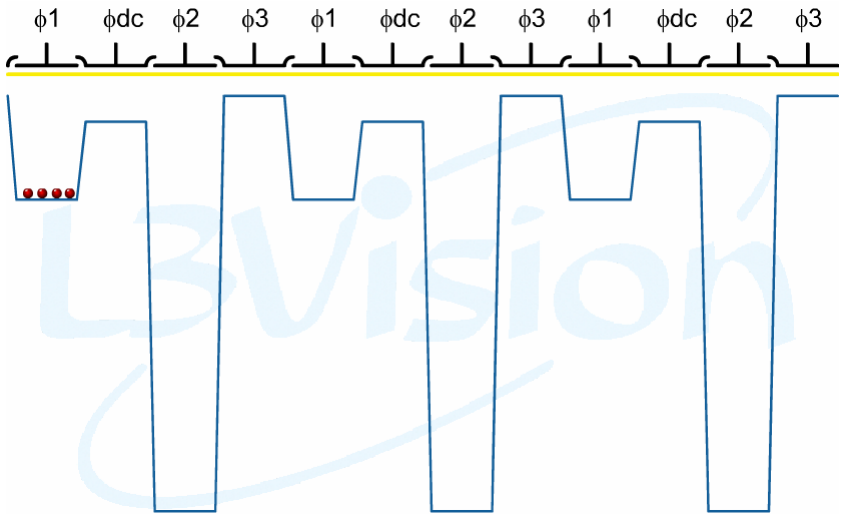
e2v Low Light Level CCDs - "L3Vision"

- Operational principle demonstrated by Hynecek in 1992
- Refined and further developed by E2V
- Initially developed in CCD65 525/626 TV format
- 512x512 and 1024x1024 variants
- Red-enhanced using high resistivity silicon under development
- 4-phase structure showing injection and multiplication of charge from storage to high field region

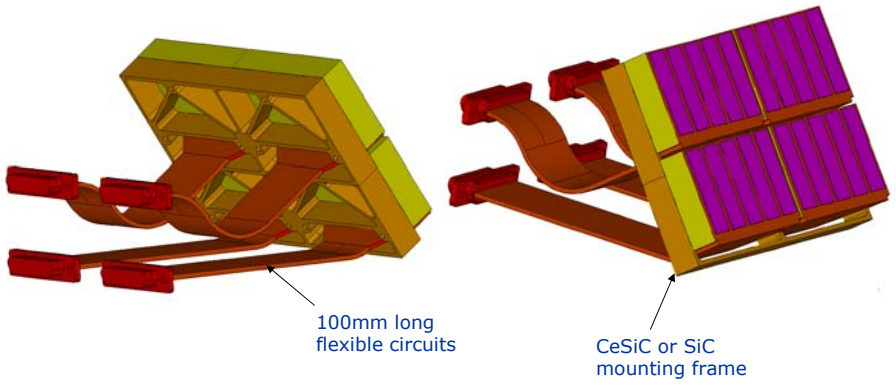


From Hynecek, IEEE Trans. On electron Devices, v.39, no.8, 1992

Operation



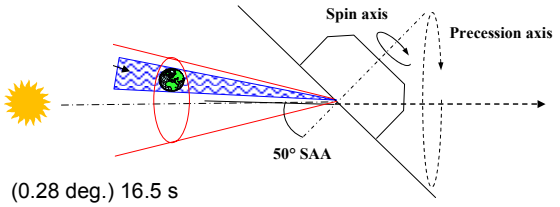
Assembly of RVS CCDs



Lateral Drift due to the Scan Law

Satellite scanning law:

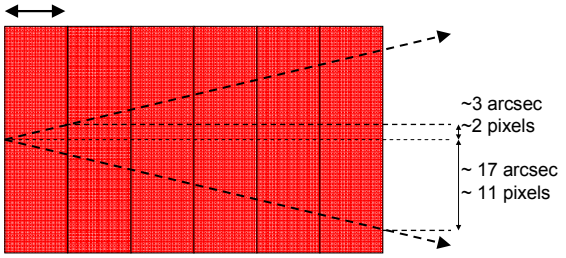
- Spin: 6 hours
- Precession: 70 days



(0.28 deg.) 16.5 s

Spectrum motion:

- Sine transverse component
- Max. amplitude: 0.17 arcsec/s

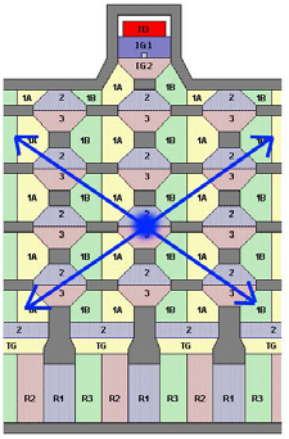


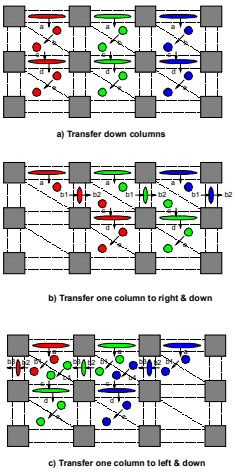
2D CCD Concept

Aim : Development of technology to enable movement of the image laterally to track moving object without the need for a mechanism

Requirement:

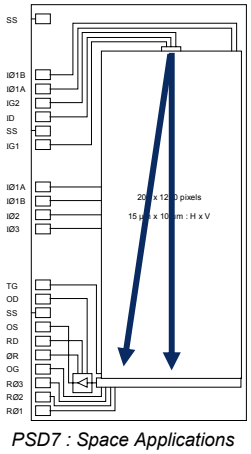
- **In Gaia RVS the scan law results in star motion by +/- 11 pixels over FPA in a 6 hour period**

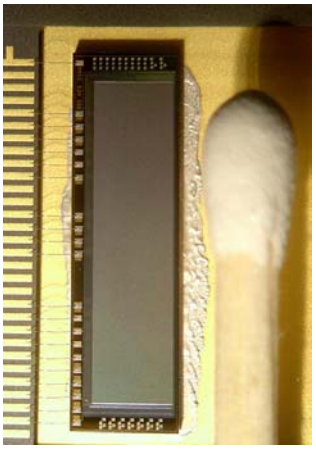


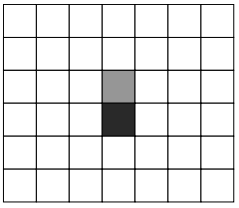


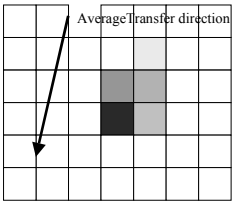
Die Layout and Charge Transfer

- Single column injection node at top of CCD
- 10x15 μm pixels
- Possible CTE effects



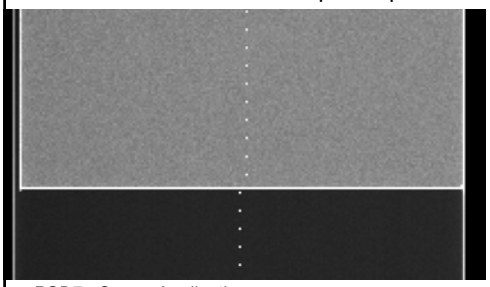


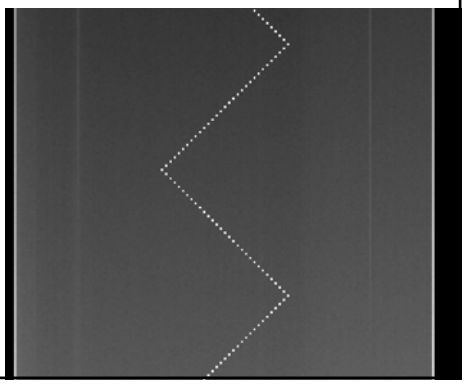




Examples of 2D Transfer

- Images demonstrating 2D transfer
  - Whole image shift 3 pixels to right & Zig-zag injection
- Measured CTI < $4x10^{-9}$
  - No measurable deferred charge after 10^5 x 5 left & right shifts @165K
  - Design and processing defects negligible
  - Not a real measure of trapping since charge moves over same pixels
- Possible uses in adaptive optics

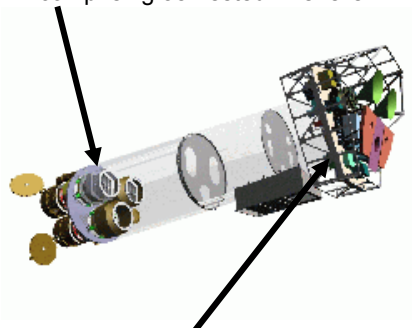


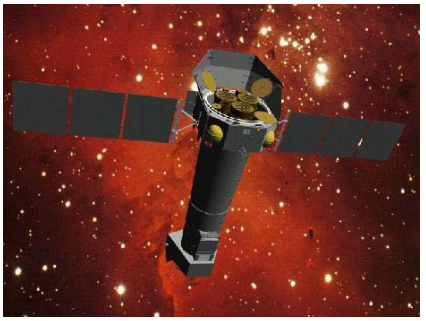


X-ray Astronomy

The ESA XMM/Newton Spacecraft

3 co-aligned optics, each comprising 58 nested Ni shells

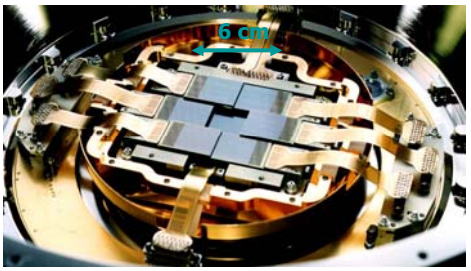


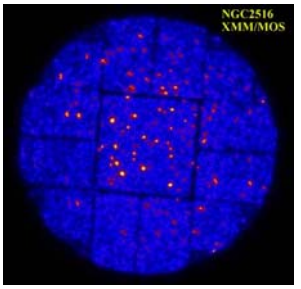


Focal plane detector arrays providing imaging and spectroscopy

XMM EPIC MOS Cameras

- 2 EPIC MOS cameras, having focal plane arrays of 7 CCDs
- Very successful operation
- Share their telescopes with the 2 RGS instruments
- Broad-band from 0.3-10 keV, 35 μm depletion depth
- Highest spectral resolution of the MOS/pn cameras
- Use open electrode - improvement in sub-keV resolution possible





Future X-ray Astronomy in ESA XEUS

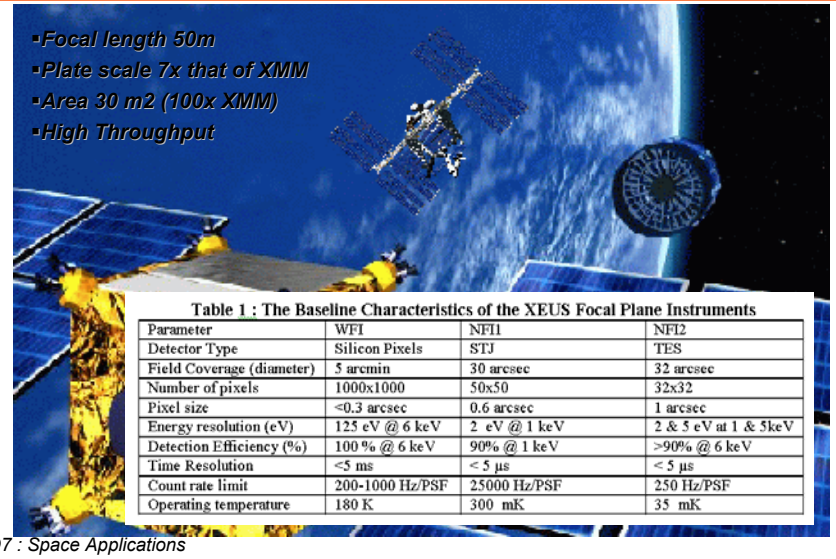
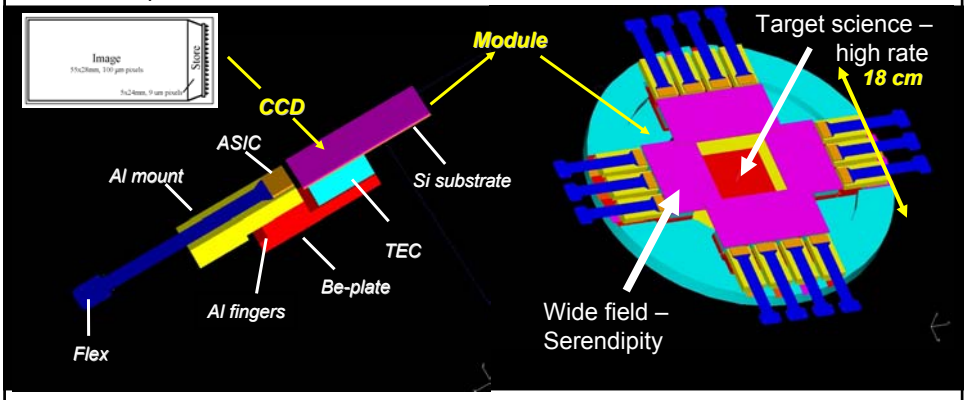


Table 1 : The Baseline Characteristics of the XEUS Focal Plane Instruments

Parameter	WFI	NFI1	NFI2
Detector Type	Silicon Pixels	STJ	TES
Field Coverage (diameter)	5 arcmin	30 arcsec	32 arcsec
Number of pixels	1000x1000	50x50	32x32
Pixel size	<0.3 arcsec	0.6 arcsec	1 arcsec
Energy resolution (eV)	125 eV @ 6 keV	2 eV @ 1 keV	2 & 5 eV at 1 & 5keV
Detection Efficiency (%)	100 % @ 6 keV	90% @ 1 keV	>90% @ 6 keV
Time Resolution	<5 ms	< 5 μs	< 5 μs
Count rate limit	200-1000 Hz/PSF	25000 Hz/PSF	250 Hz/PSF
Operating temperature	180 K	300 mK	35 mK

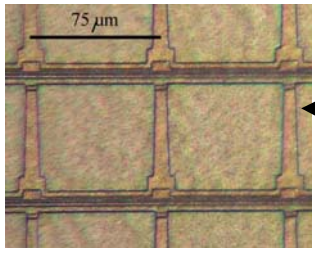
The future : The XEUS WFI

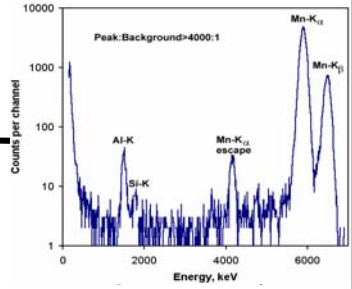
- An X-ray camera for XEUS : dual technology to cover the target and serendipetous science
- Much larger array than XMM EPIC
- High rate DEPFET central array, surrounded by a CCD outer ring
- One possible CCD construction shown



New Large Pixel Design

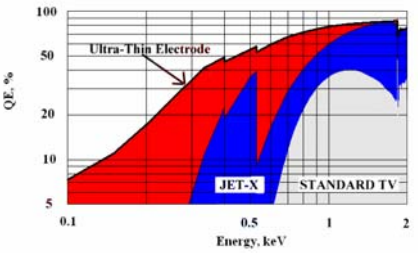
- PSF over-sampling requires pixel <150 μm
- New designs from e2v having 75 μm and 100 μm pixels have been evaluated
- Design developed from EPIC MOS CCD structure (4-phase)
- Optimised for future ultra-thin electrode (retains spectroscopy)
- Inherently radiation hard
- Developed on CCD66 test structure - small

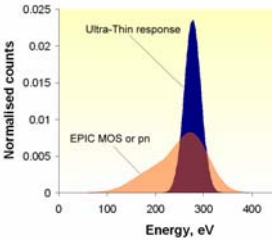




Ultra-Thin Electrode

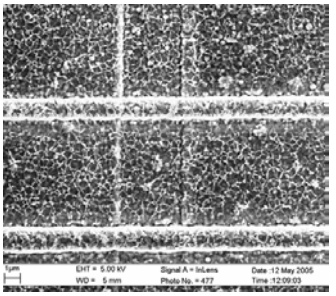
- Ultra-thin electrode trials underway (40 nm)
  - Will produce good low-energy QE same as that of EPIC/MOS
  - 30% @ 300 eV, 50% @ 500 eV
  - Maintains depletion for high-energy - better than EPIC/MOS
- Spectral response
  - 170 nm poly demonstrated on CCD12 for Jet-X in early 1990's
  - 40 eV @ C-K (277 eV)
  - Compare to XMM (pn or MOS), 80 eV @ C-K for Open Electrode or Back Illumination

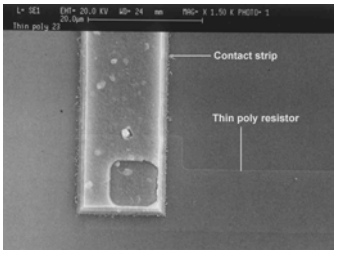




Thin Polysilicon Electrodes

- Need to decrease polysilicon thickness whilst retaining sheet resistivity
- Thermal processing increases grain boundaries – light post processing
- Investigated doping of poly layers to give adequate sheet resistance
- Test structures formed from resistive sheets
- Lessons-learned now being implemented on the CCD66 device format
- Aim to use the developments in the XEUS prototype





High Energy Quantum Efficiency

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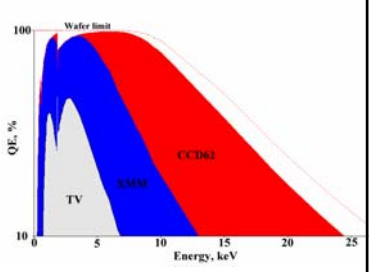
- Depletion depth is a measure of detection efficiency
- We have demonstrated increased depletion depth from 35 – 220 μm using high purity Si + modified bias
- e2v currently developing a large area (2kx2k) format with target 300 μm depletion for astronomy



- Hard X-ray response is required for on-axis detection
- However, for the E-WFI CCDs we need to optimise for high sensitivity and source detection

Detectors for Maximum Source Sensitivity

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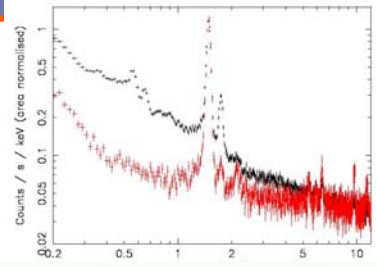
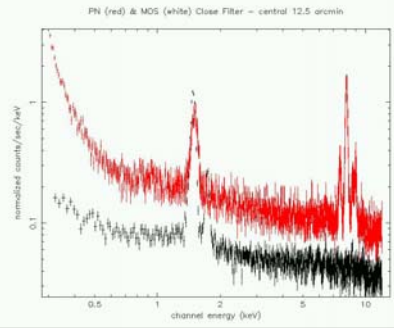
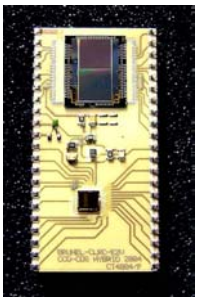
- Optimal sensitivity combines
  - Expected source spectrum
  - Mirror efficiency (basically <2 keV)
  - Detector QE
  - Detector background
  - Sky background
- Figure 1 of EPIC MOS background for open and closed filter positions
- Predicted background from 30-300 μm should be 6x higher
- pn:MOS background ~ 3:1
- Figure 2 of comparing MOS and pn backgrouns

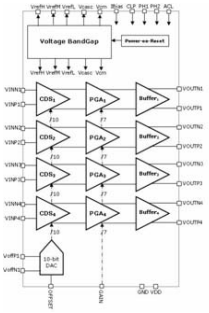


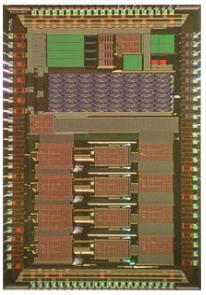


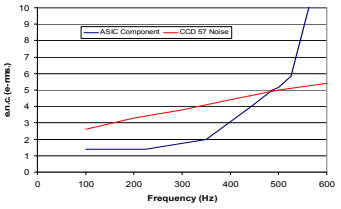
Multi-channel CDS for High Throughput

- 2 generations of analogue ASIC, 2nd with a linear CDS cell
- CDS cell could be replicated for multi-channel systems
- Suitable for either 4 channel CCD, or mosaic of 4 CCDs
- Compatible with direct wire bonding from CCD to ASIC
- Hybrid module with CCD57 also built using 1st gen. CDS ASIC
- CCD noise dominated up to 400kHz





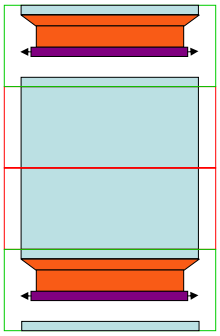


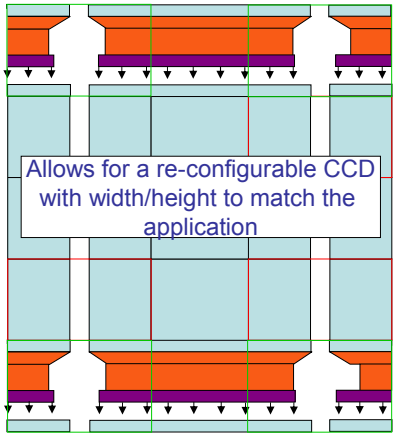


CCLRC Rutherford Appleton Laboratory

XEUS CCD Format

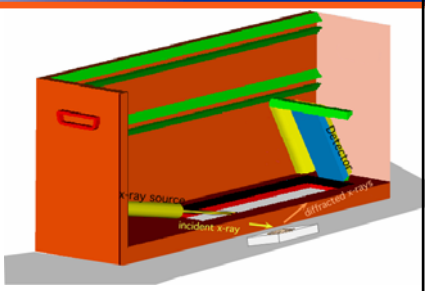
- XMM EPIC CCDs fabricated using 1-D photolithographic stitching
- 2-D stitching now a possibility
- Whole-wafer CCD capability
- Move to 6” wafers

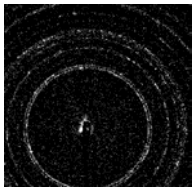


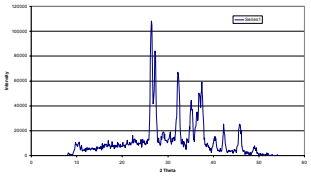


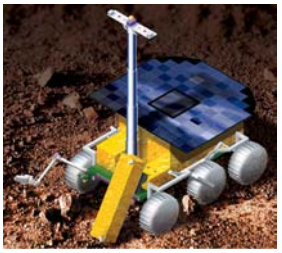
Mars-XRD

- Instrument concept for Mars Rover
- Performs simultaneous XRD and XRF on rock samples on Mars
- Tiled array of CCDs sampling diffraction to provide mineralogy
- XRF to provide elemental composition
- Total instrument mass 800g
- Similar concept to Nasa Chemin instrument
- Poster by Amir Intisar



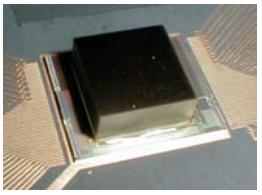






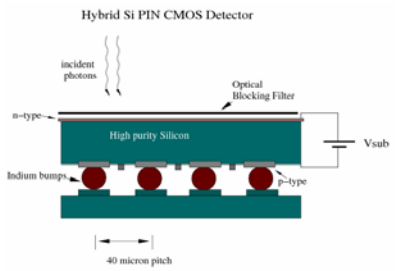
CMOS Imagers

- Developments underway to develop “science grade” sensors
- On-chip intelligence, thresholding, cluster detection
- “Camera on a chip”
- Following development path of CCDs in the 80’s-90’s
- Low noise (e.n.c. <10 electrons rms.)
- Improved detection efficiency
  - Back-illumination, 100% fill factor, >80% QE
  - Detection of EUV and soft electrons (few keV)
  - “Thick-epi” for direct X-ray detection + indirect
- Large arrays using photolithographic stitching
- Buttable arrays
- UK MI3 consortium
- CCLRC/e2v 12Mpix BI sensor
  - N. Waltham – talk

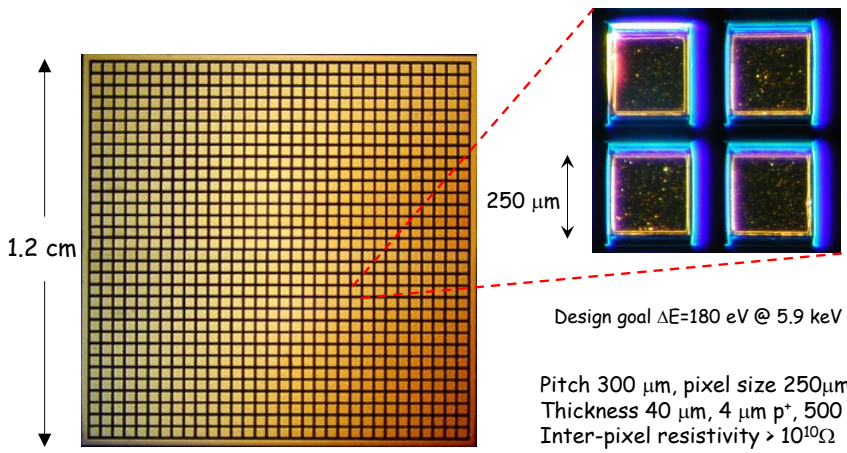


Hybrid Pixel Arrays

- De-couple the Detection from the readout functions
- Developed for IR sensors (Talk by Colin Cunningham)
- Detection layer can be Si, GaAs, CZT, CdTe, TlB ….
- Extends detection to visible, soft and hard X-ray
- For X-ray, both photon counting and Integrating systems



ESA - GaAs 32 x 32 array



Design goal ΔE=180 eV @ 5.9 keV

Pitch 300 μm, pixel size 250μm
Thickness 40 μm, 4 μm p^+, 500 μm n^+
Inter-pixel resistivity > $10^{10}\Omega$

GaAs prototype 32 x 32 array - first results

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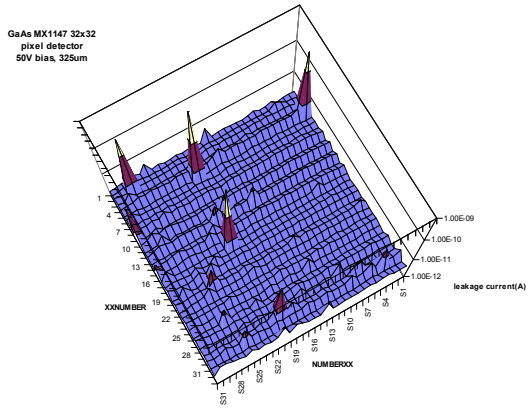
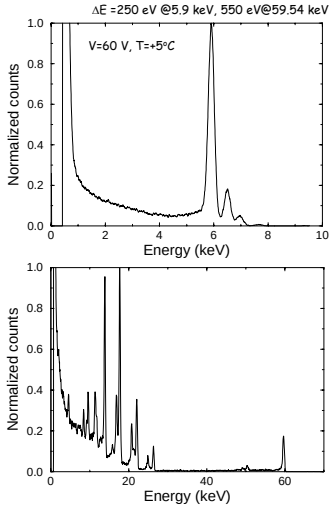
Leakage current map at RT



Demonstrated resolution of
ΔF=270 eV @ 5.9 keV at RT



esa

Science Payload and Advanced Concepts

Medipix 1 ASIC

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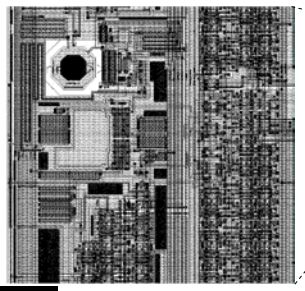
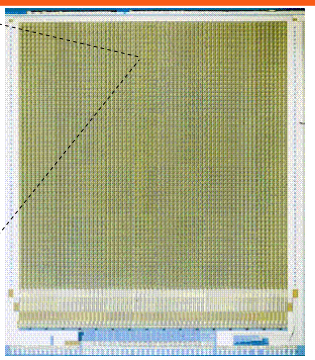
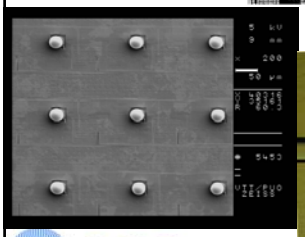
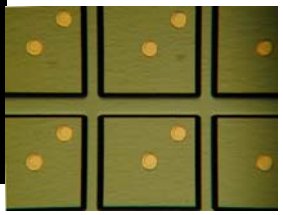








Medipix1 (1998)

4096 pixels 170 x 170 μm²

1.2 cm² sensitive area

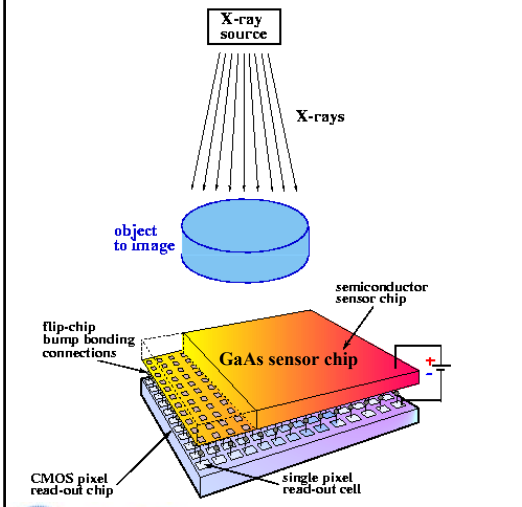
1.6 x 10⁶ transistors

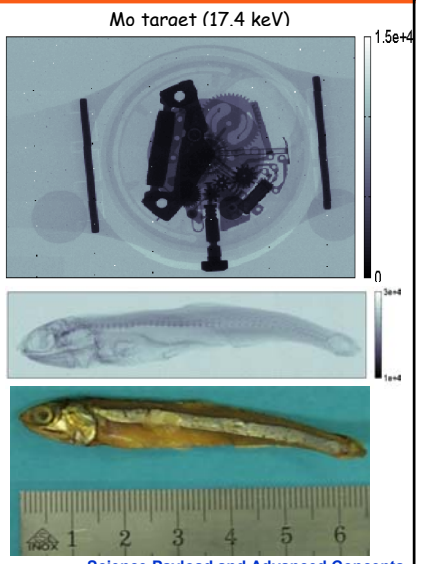
Visschers 2002

esa

Science Payload and Advanced Concepts

ESA X-ray test set-up and results

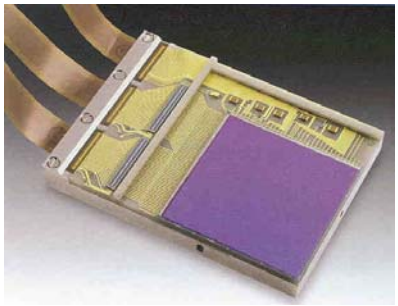




Science Payload and Advanced Concepts

IR Focal Plane Arrays

- JWST is driving the development of large area focal plane hybrid arrays
- Some spin-off into optical and X-ray domains with the Rockwell HyVisi technology
- Rockwell HyVisi arrays use silicon detector for visible applications
- Hyvisi works in X-ray domain
- Development of CZT-version using PICNIC ROIC in collaboration with Surrey and Rockwell.

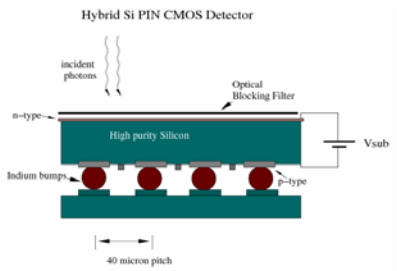


Raytheon 2k x 2k

Orion InSb array

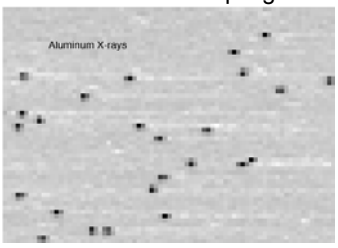
Rockwell HyVisi Range

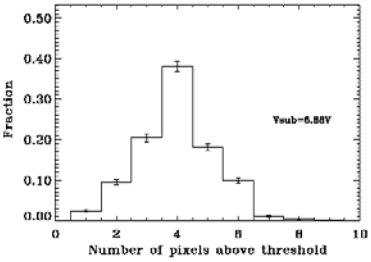
- Picnic ROIC - 256x265 pixel imager, 40 μm pixels
- Hawaii I and II with 1024^2 and 2048^2 pixels
- Si-detection layer bonded to CMOS readout
- Designed for optical imaging
- Non-destructive read capability “Fowler Sampling”
- Tested for X-rays at SAO, Harvard

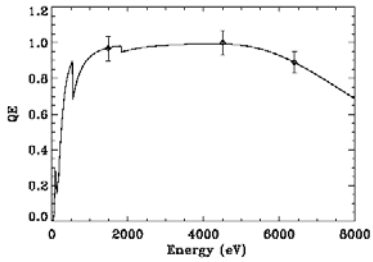


HyVisi X-Ray Testing

- Tested in X-ray photon counting mode
- σ_1=20, σ_{16}=8.8 e- rms.
- Full Depletion for ~10V
- All X-rays split
- Poor spectral resolution
- QE of 88% at 6keV
- Further work on sampling/reset



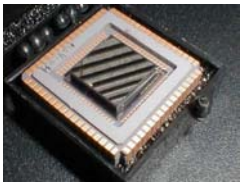


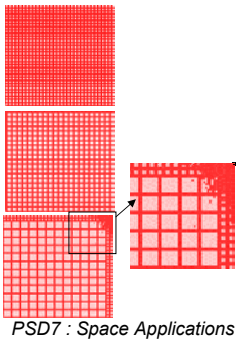


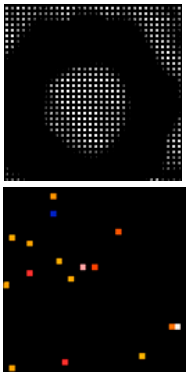
Kenter et al., Proc. SPIE, 5898 (2005)

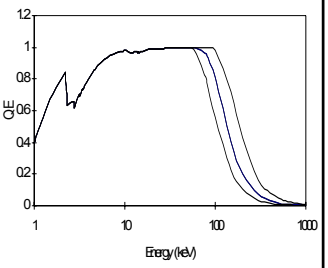
CZT Rockwell Picnic Array

- Developed through a PPARC PIPSS project with P.Sellin (Surrey)
- 2 mm thick CZT detection layer on Picnic array
- Range of detector pixel sizes explored
- Photon counting (60keV) and imaging modes
- Good bond yield



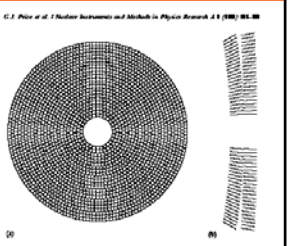


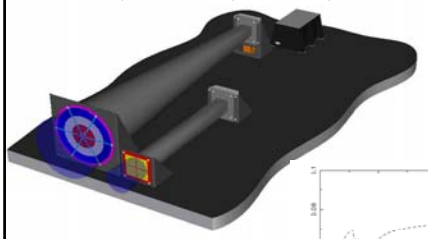


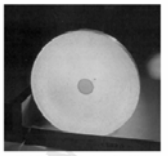


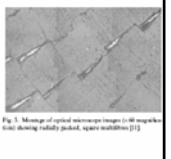
Bepi Columbo - MIXS

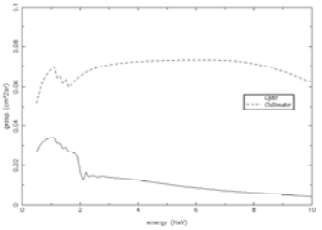
- X-ray fluorescence mapping of Mercury (2013+..)
- Co-aligned collimator (DCIXS) and telescope systems
- X-ray telescope utilising MCP optics and GaAs pixel array
- ESA, Leicester, CCLRC, ..











Conclusions

- CCDs
  - Focal plane arrays getting larger
  - CCDs continue to be workhorse detectors in Astronomy
  - Technology developments are still occurring
- CMOS
  - CMOS APS gaining ground in some applications
  - QE improvement, particularly with back illumination for science apps
- Hybrid Pixel Arrays
  - Hybrid detector technology being extended from IR into optical and X-ray bands
  - Early detectors showing photon counting, energy resolution and imaging
  - Technology still needs development and not routinely accessible