TOWARDS PRACTICAL AUTONOMOUS DEEP SPACE NAVIGATION USING X-RAY PULSAR TIMING: INSTRUMENTATION ASPECTS

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XNAV instrumentation

- Similar to what is needed for existing science concepts
  - Detect Pulsar signals
  - Minimise error sources (e.g. sky background, internal background, pointing stability, …)
  - Determine position of spacecraft
- BUT – needs low resources!
- Technical Requirements
  - High time resolution (<1μs, goal <300ns)
  - High collecting area (~50cm^2 @1keV for imager)
  - Energy range ~0.5-8keV
  - Low background
  - Maintain accurate OBT standard

How to minimise resources

- Collimators vs Imaging
  - Collimators restrict FoV to reduce sky background
    - $A_{detector} = A_{collimator}$ → high non-sky background
  - Imagers concentrate flux onto smaller detector (large reduction in background)
    - $A_{detector} = A_{collecting}$ → reduced background

- Most timing missions to-date use collimated instrumentation and are a *dedicated payload*
  - i.e. are designed for science return not optimised as a satellite sub-system

- Optimised subsystem = minimum mass/size for maximum performance

  → Current focus in the literature on concentrators and imaging

Examples

- RXTE PCA
  - 1^{o} FoV, 4.4μs timing, needed 10 clock calibrations per day
- USA
  - 1.2×1.2^{o} FoV collimated GPC
  - 2μs timing, 2000 cm^2 detector
- NICER
  - the first attempt to use the imaging advantage to optimise XNAV performance
  - Mass:165kg, Volume: 0.8 m^3, Power: ~ 80-110W.

→ Not optimised for deep space application

Overview of our study

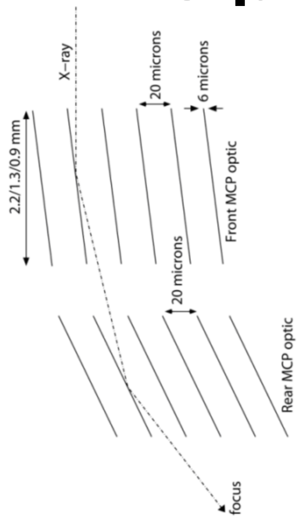
- Strong focus on imaging
  - Maturing low mass optics
  - Capable small detectors (low mass / power / background / …)
  - Offers mechanism to reduce the mass of instrumentation and provide high S:N

    → viable deep-space implementation?
- Note:
  - Considering collimated solutions in principle valid - possible to generate larger areas
  - very difficult to overcome the imaging advantage within scope of a realistic deep space payload

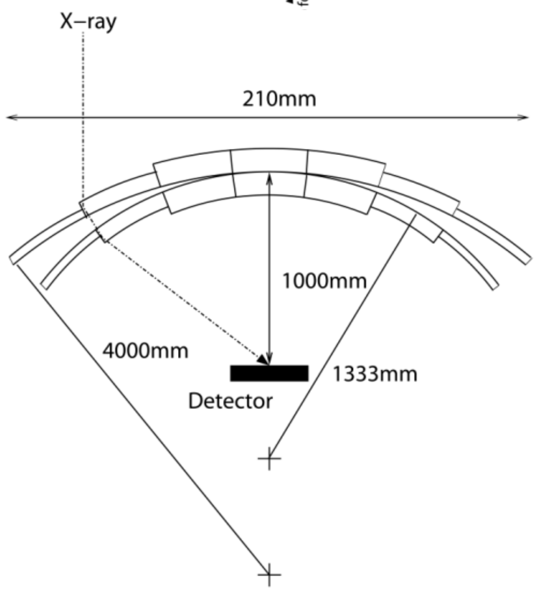
Optics

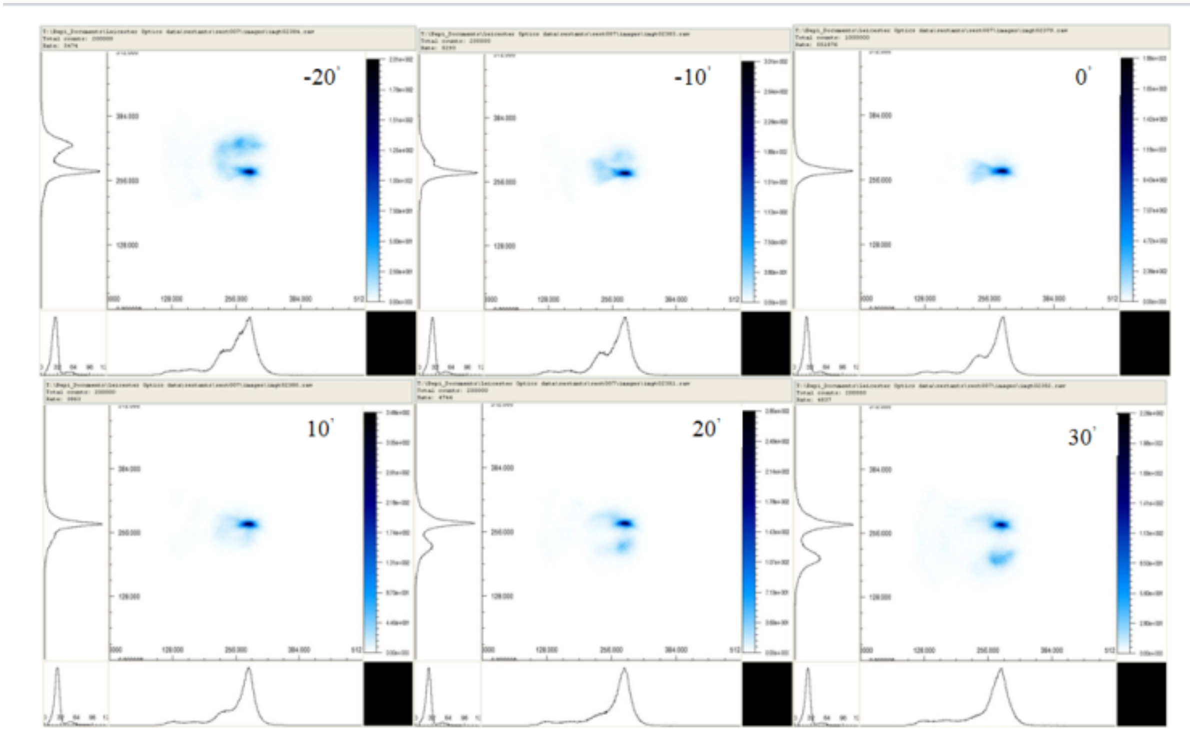
- Existing optics technologies
  - Foil shells, Slumped glass, Silicon pore optics
    - See talk by RW
  - MCP optics (most promising - mass)
    - MCPs are glass plates with millions of microscopic pores etched in manufacture
    - square pores → reflecting surfaces
    - Manufactured by Phtonis SAS (Brive, France)
    - Many geometries can be mimicked with square pore MCPs
    - Simplicity & compactness key for XNAV

Optic Geometries - Wolter I



MCPs use conical approximation to Wolter I





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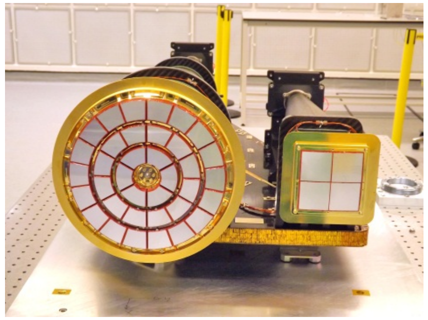
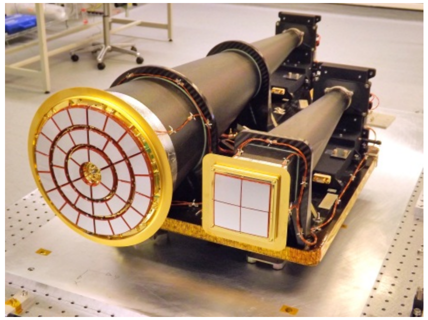
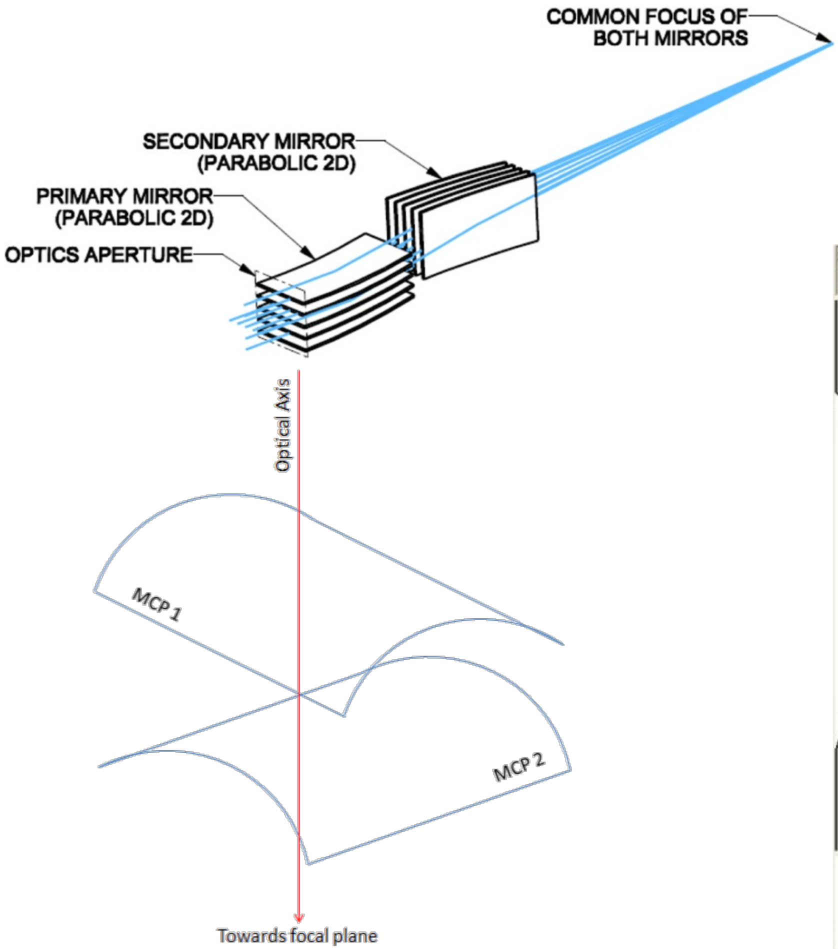
Example: MIXS

- One of 11 instruments on ESA/JAXA BepiColombo mission to Mercury
- Light Weight X-ray telescope (MIXS-T) could be a pathfinder for XNAV
  - Deep space implementation of Wolter I imaging X-ray optic.
  - Total Mass of telescope = 3.2kg
    (optic, tube, electron diverter, detector FEE)
- Gives ~$50cm^2$ (ideal) effective area @1keV
- DEPFET active pixel sensor detector
- Designed for planetary science goals but indicates a roadmap for XNAV and could be used commercially e.g. asteroid composition

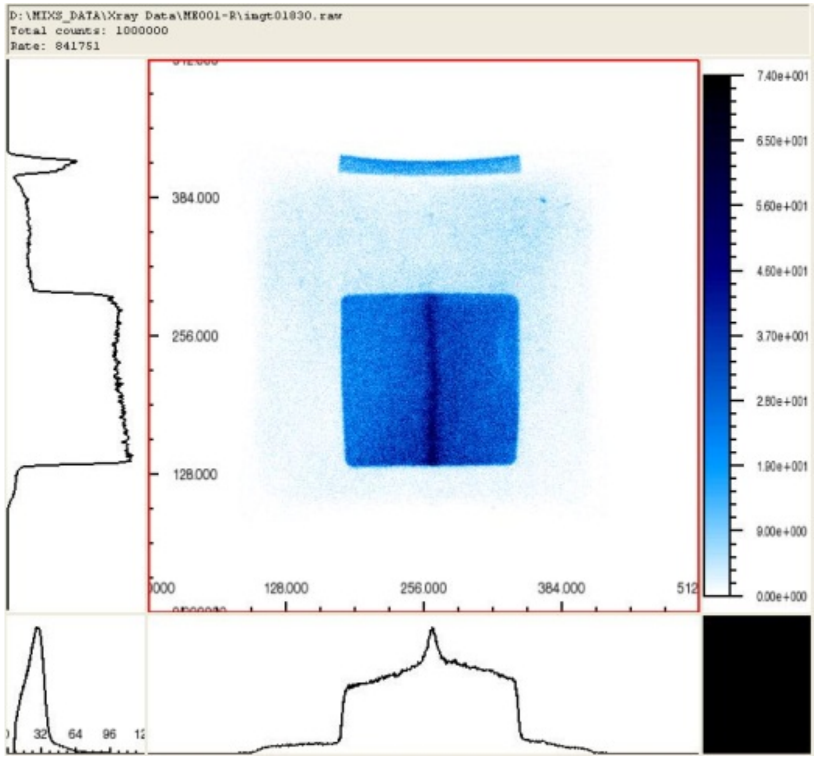




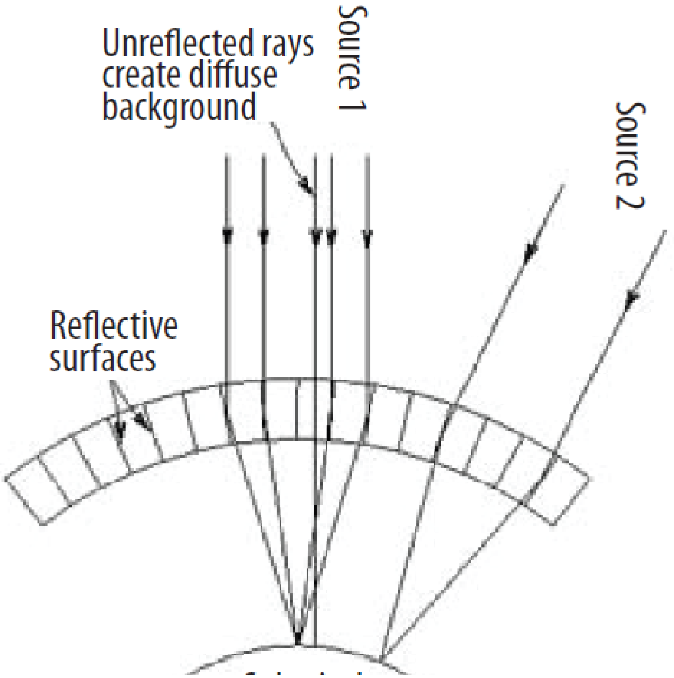
Optic Geometries - Kirkpatric Baez



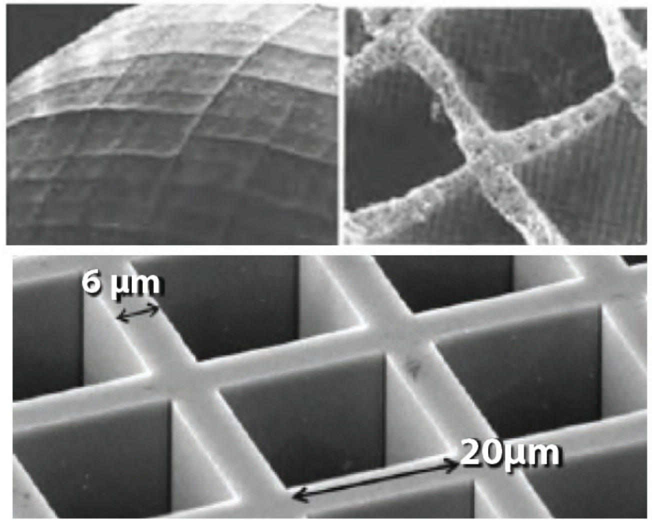
MCPs use planar approximation

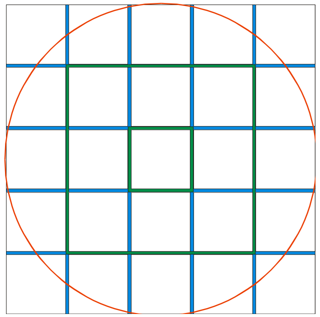


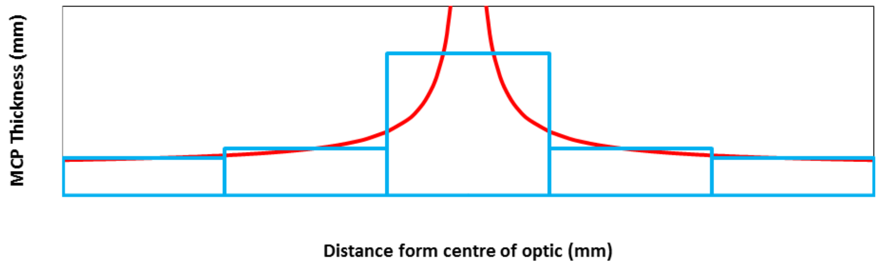
Optic Geometries



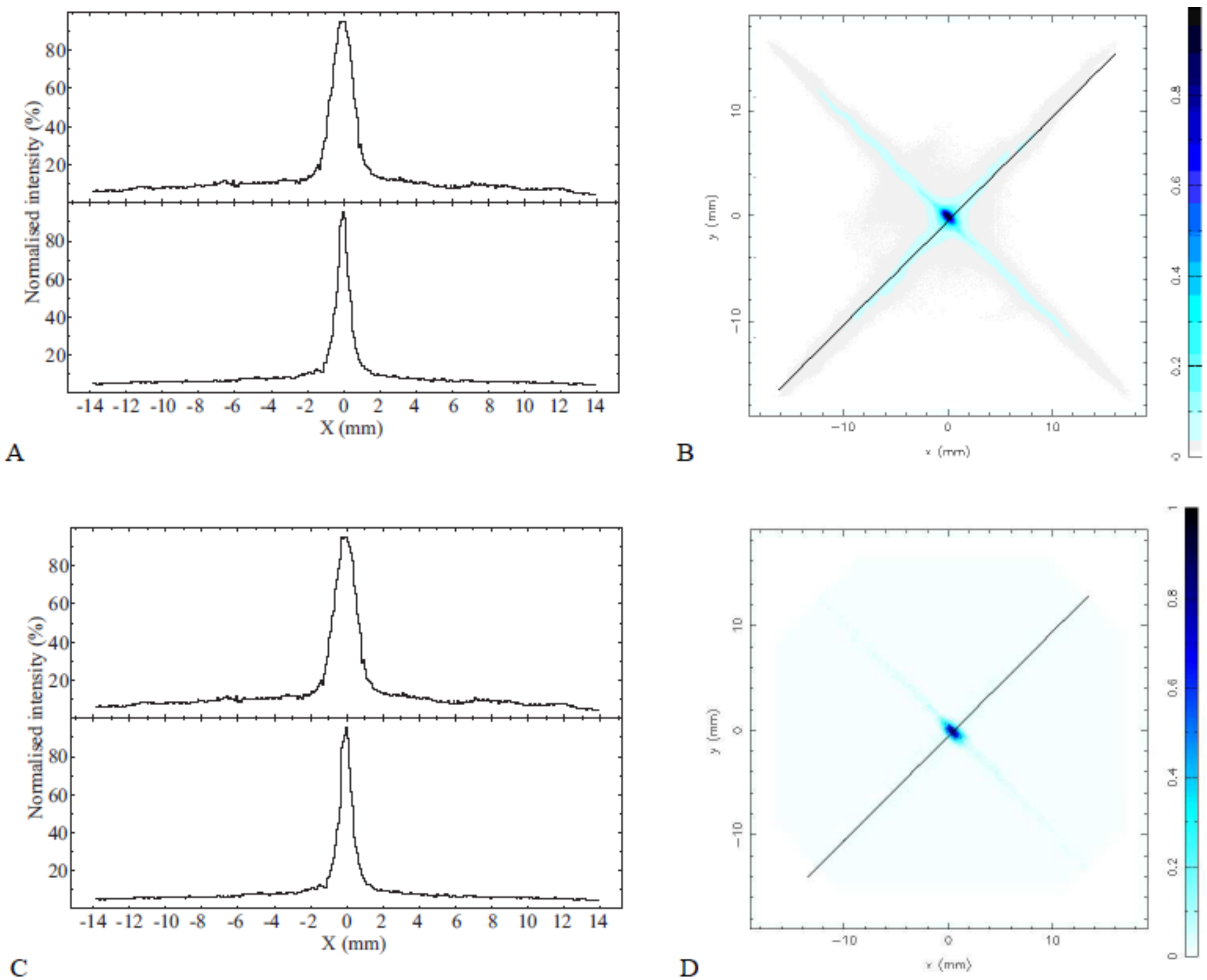
Lobster eye geometry (can be optimised for small FoV)



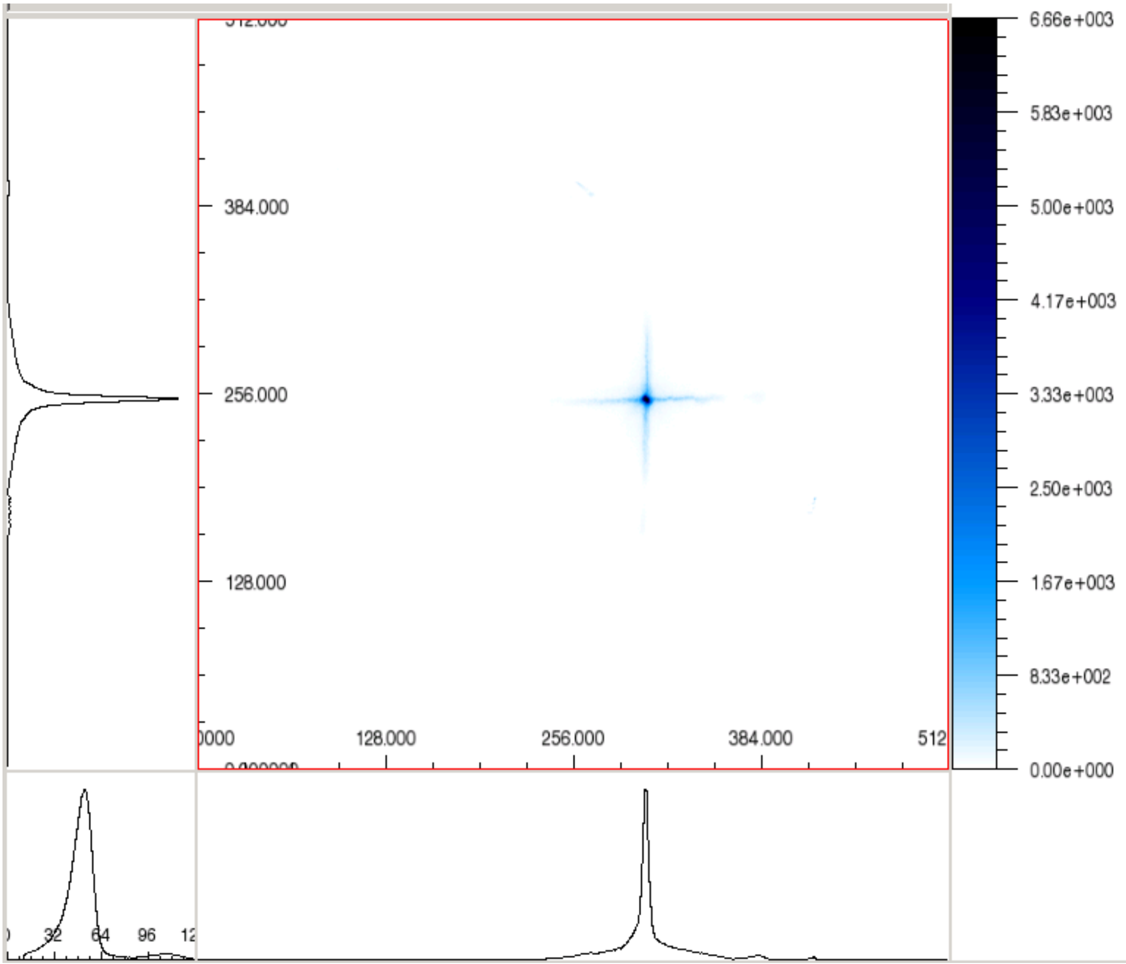




Planar Lobster optic



Slumped lobster optic



Available technology

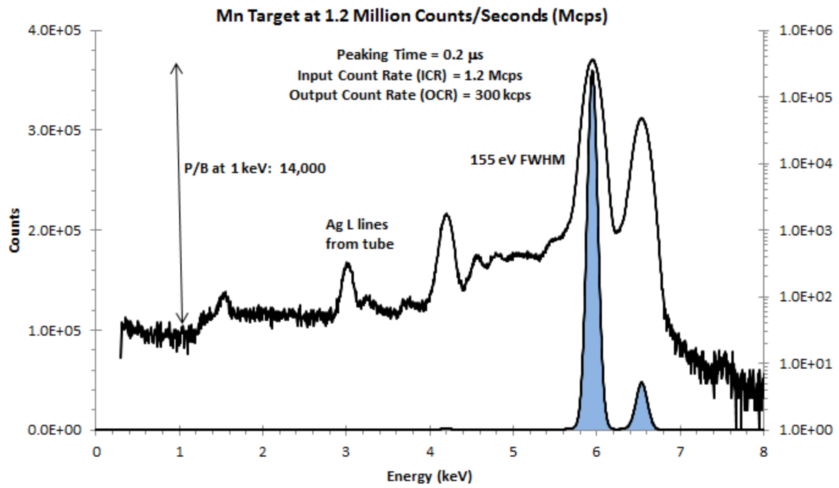
- Optics for lobster/Wolter systems are well proven.
- Resolution
  - ~4-5 arcmin proven for lobster
  - improvement possible – tech. development ~1.5-2 arcmin demonstrated for planar arrays
  - ~8-10 arcmin demonstrated for wolter improvement possible with tech. development.

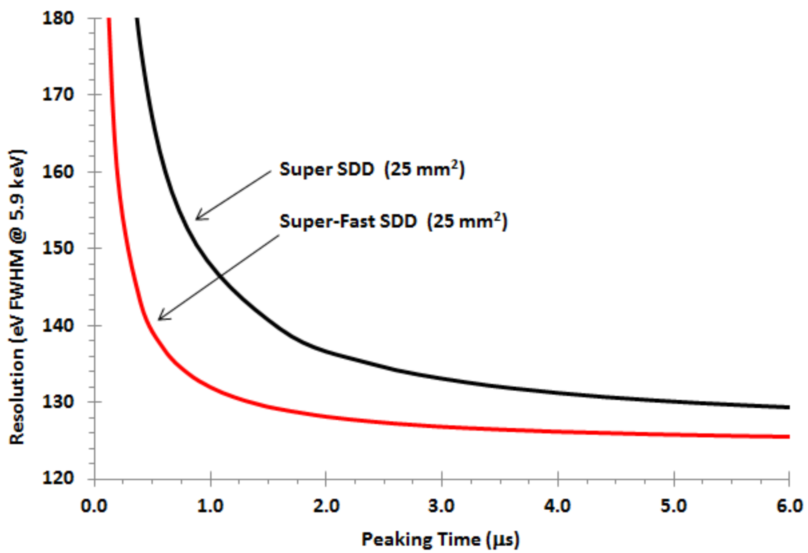
Future technology

- NF lobster
  - Simplest geometry
  - All manufacturing proven
  - Demonstration of array functionality needed
  - Implementation being developed for SVOM MXT
- KB
  - Much simpler than Wolter
  - significantly improved resolution possible
    - Doesn’t suffer some of the error sources
  - Demonstration of tandem pair needed

Detector types

- APDs
  - Gain leads to lower energy resolution but higher readout speed
  - Low E threshold ~0.5keV possible
- SDDs
  - Fast readout demonstrated, good maturity, high performance
  - E.g. "super fast silicon drift detector" from AMPTEK
    - very good energy resolution
    - low energy thresholds of <200eV
    - high quantum efficiency (more efficient filter than the 8 micron Be foil used as standard)
    - Peaking time <1μs
- DePFET detectors possible ideal technology (fast, small pixels, excellent energy resolution)



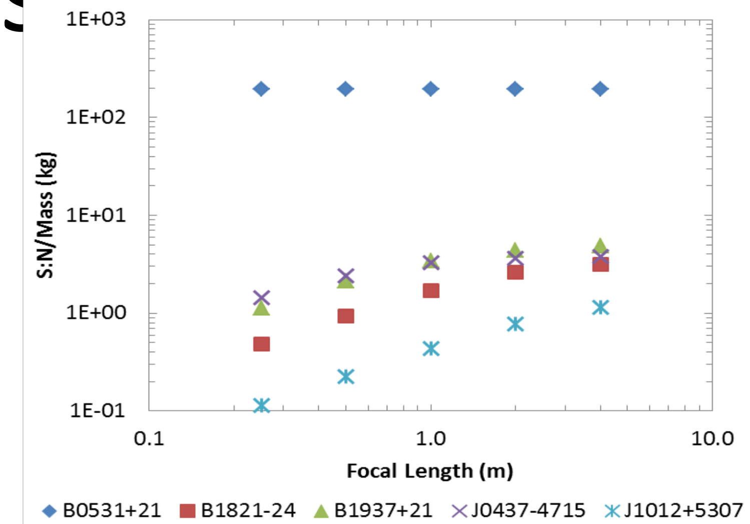


Clock and time transfer

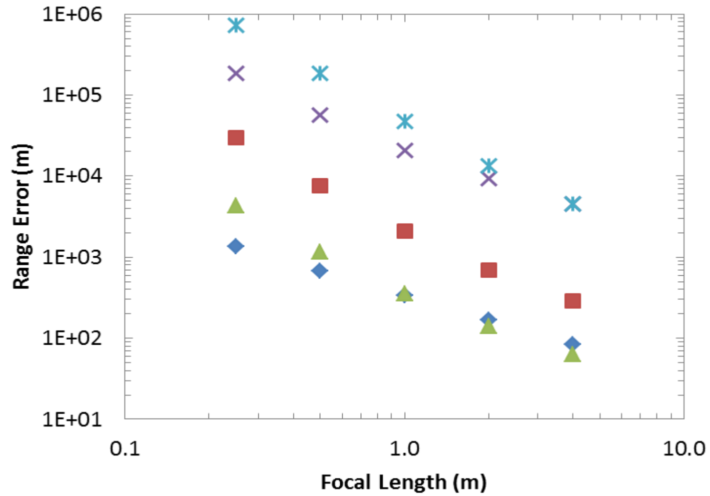
- Time stability
  - During single observations fractional stability ~ 10^{-12} needed & the clocks that flew on Giove-B would offer precision greater than needed
  - However, maintaining accuracy with respect to UTC over deep-space mission timescales is challenging
    - Improved stability of atomic clock needed(~10 years?)
    - NASA developing Mercury ion trap atomic clock that may offer required stability
    - Time transfer link for Earth most likely needed to calibrate relative to terrestrial time standard

System design - parametric analysis

- Signal-to-noise ratio (S:N) per unit mass versus focal length.
  - Signal strength of crab → flat line
  - SN:mass increases for longer F, hence a longer telescope is more mass-efficient than parallel modules (because $Aeff \propto F \uparrow 2$)



- range error as a function of focal length.
  - The different order of the pulsars in the two panels is a result of the relative importance of signal strength, the pulse width and pulse period of the various pulsars.



- Assumes a 10^5s observation.

	Current Technology		Future Technology		
Parameter	Wolter MIXS	Lobster	NF lobster	KB	Comment
Scientific performance					
N	1	4	3	1	Number of modules proposed
Optic effective area (cm^2)	50	24.7 (98.8)	35 (105)	81.5	@ 1keV
Detector active area (cm^2)	0.049	0.049 (0.196)	0.049 (0.147)	0.049	~2.5 mm diameter APD per module
Focal plane scale (arcmin/mm)	3.44	3.44	3.44	3.44	$Tan^{-1}(1/f)$
All up mass estimate (kg)					
Optic mass	1.8	1.5 (6)	1.5 (4.5)	~2.5	per module KB
Detector/housing	2	2 (8)	2 (6)	2	Estimate
DPU	1.5	1.5	1.5	1.5	SSTL OBC750 LEO
PSU	1	1	1	1	Estimate incl. housing
Harness and misc.	1	1 (2)	1 (1.5)	1	Ancillary items
TOTAL (kg)	7.3	7.0 (18.5)	7.0 (14.5)	8.0	Note KB mass estimate higher only because of less mature design – implicit margin
Detector technology	SDD	SDD	SDD	SDD	Small PSF allows use of SDDs
Power consumption estimate (W)	15.9	15.9 (24.7)	15.9 (21.8)	15.9	Including: DPU (10W), detector and FEE (0.25W), analogue electronics (2W), PSU efficiency (70%) Excluding: thermal control (assumed to be a spacecraft radiator)
Volume (mm^3) **Telescope:** **DPU:** **PSU:**	 πx130^2 x 1000 320x170x55 320x170x55	 200x200x1000 (x4) 320x170x55 320x170x55	 200x200x1000 (x3) 320x170x55 320x170x55	 260x260x1000 320x170x55 320x170x55	 PSU estimated as same board area and same box dimensions as DPU

Outstanding questions

- Satellite subsystems - not reviewed in detail
  - Steering mechanism, thermal control (radiator and heat pipes)
  - Steering mechanism may be mass driver,
  - cooling not outside well proven (simple) systems (TEC / radiator) ~ -20^{o}C
  - Onboard Clock & time transfer
  - DPU/PSU parameterised from commercial available units
    - Astrium GDPU or SSTL OBC750 LEO
    - Low mass, proven technology
    - Questions about reliability need to be addressed – are these units designed for instrument operation rather than critical systems? In principle mission critical use in deep space requires more qualification/validation
- Initial position fix needed to limit search area for “cold start” e.g. via a system like DSN or inertial sensors

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Feasibility of an XNAV demonstrator

- Existing technologies could be used to derive a demonstrator
  - "MIXS-like" optic based on MCPs
    - Development program for optics would provide better performance, more mass-optimisation, lower cost
  - NICER-like detector system based on SDDs
    - Development program for detector could yield high time resolution imaging detector
  - Development of electronics and time-tagging algorithms needed
  - High stability clock needed

–Low mass, low risk, limited development, …

Summary

- Current proposed methods of realising XNAV instrumentation are summarised.
  - Existing ideas in the literature are extremely capable but very massive and resource heavy as they are designed for dual-purpose
  - Our study concentrates on what is possible with low resource instrumentation
- Essential technology for a compact, low resource XNAV is available but not well optimised.
- A technology development program is needed
  - A relatively straightforward development path exists for a truly optimised instrument configuration.
  - Development should focus on the following key areas:
    - Realising simpler, optic configuration based on a narrow field Lobster and/or an MCP KB system
    - High speed photon time tagging electronics and software algorithms
    - High stability deep-space qualified atomic clock and/or methodologies for calibrating to UTC via the deep space network