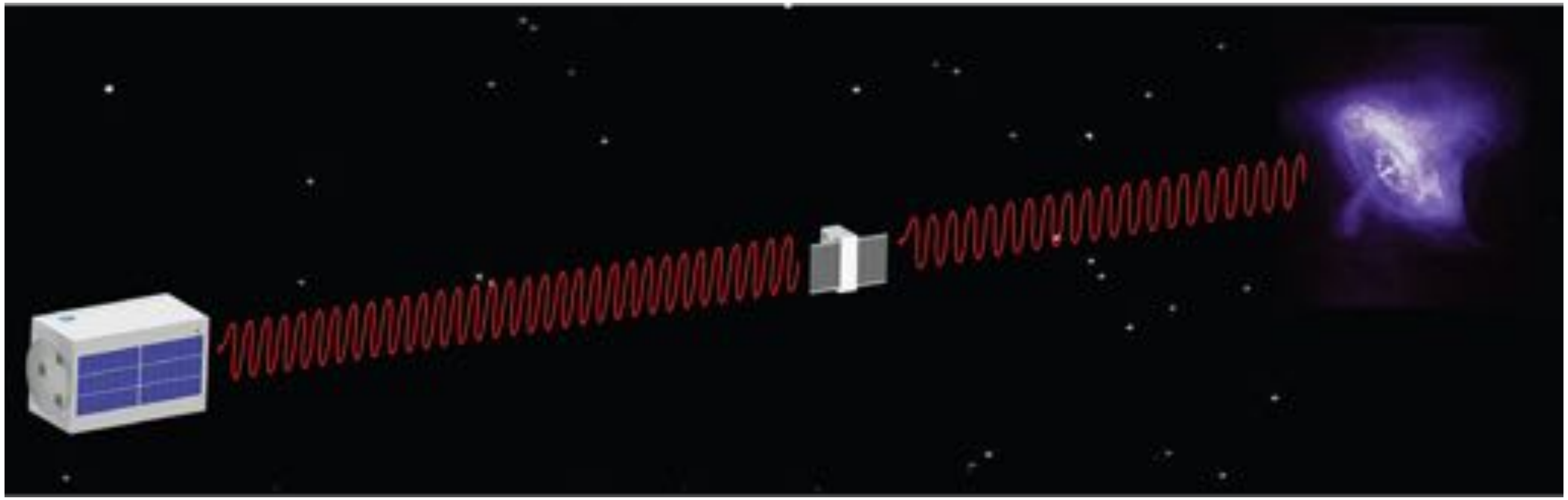
Virtual Telescope for X-ray Observations

VTXO

NASA Partner

John Krizmanic (UMBC/NASA/GSFC/CRESST) for the VTXO team



VTXO Mission Synopsis: VTXO development funded under NASA RA NNH18ZDA001N-AS3

- 3 cm diameter Phase Fresnel Lenses (PFLs) and formation-flying SmallSats form a Virtual X-ray Telescope with **1 km focal length** and **55 milli-arcsecond (mas)** imaging of bright X-ray sources.
- **6U OpticsSat** (PFL optics & beacons) and **EPSA-class DetectorSat** (H2RG HyViSI/ACADIA readout X-ray camera and NISTEx-II precision star/beacon tracker) form the virtual telescope.
- GN&C studies have shown that a highly elliptical, Super Synchronous orbit, (90,000 km altitude apogee and 600 km altitude perigee altitudes), **can hold the formation for 10 hours per each 32.5 hour** orbit around apogee with modest Δv requirements yielding **~260 day mission lifetime**.

VTXO Collaboration

VTXO

Principle Investigator: John Krizmanic[1]

Science Team: Mike Corcoran[2], Alice Harding[3], Chris Shrader[2]

Engineering Team: Neerav Shah[3], Steven Stochaj[4], Phil Calhoun[3], Lloyd Purves[3], Cassandra Webster[3], Kyle Rankin[4], Daniel Smith[4], Asal Nasari[5], Laura Boucheron[4], Krishna Kota[4], Hyeongun Park[4]

1 CRESST/NASA/GSFC/University of Maryland, Baltimore County
2 CRESST/NASA/GSFC/Catholic University of America
3 NASA/Goddard Space Flight Center
4 New Mexico State University
5 Space Dynamics Laboratory

SmallSat2020 Related Paper:

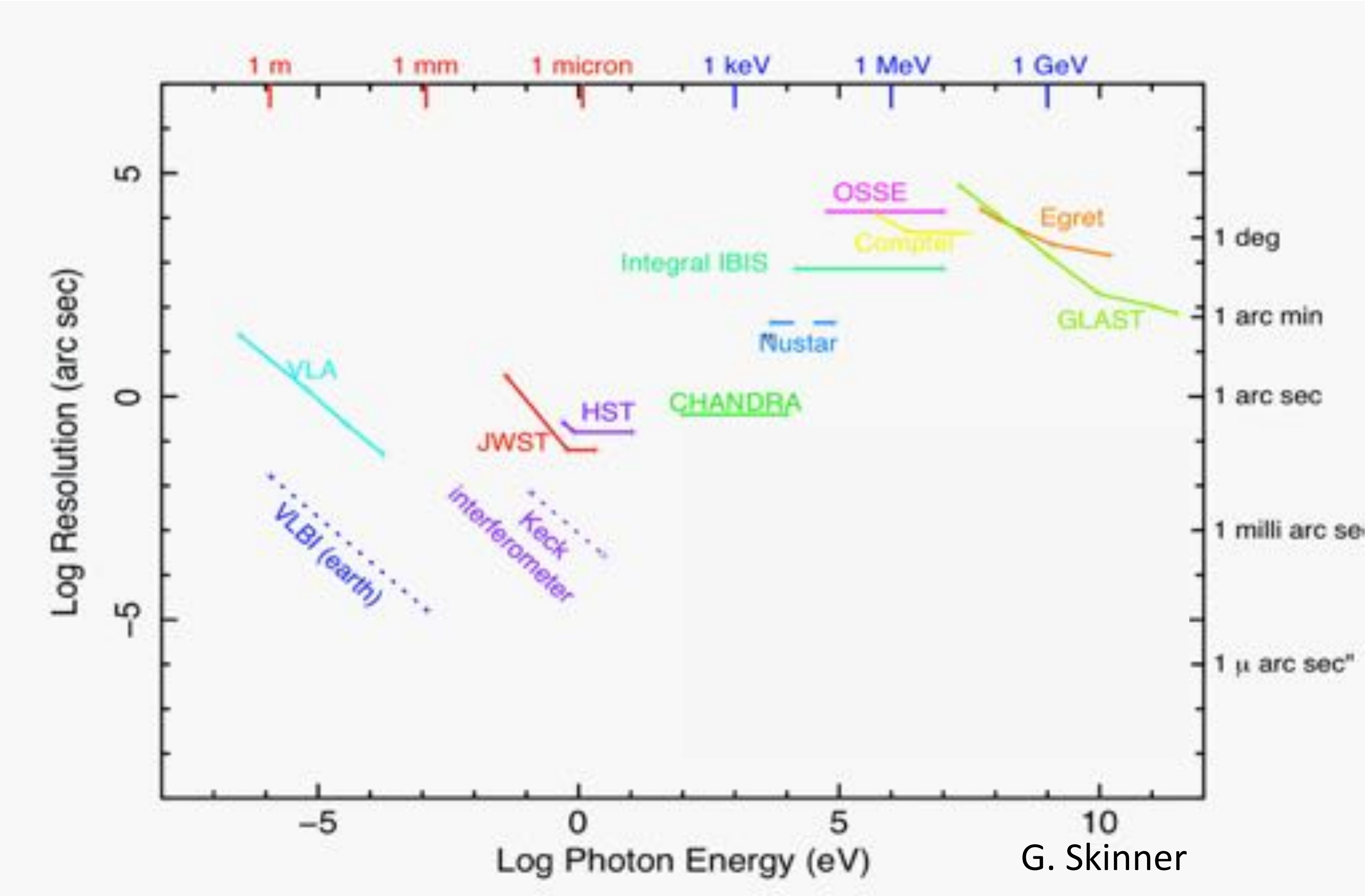
SSC20-WP2-28: *Trajectory Optimization for Virtual Telescope for X-ray Observations* – Kyle Rankin, Hyeongun Park, John Krizmanic, Neerav Shah, Steven Stochaj, Asal Nasari

VTXO started as an EPCoR-funded proposal at NMSU with GSFC as partner. VTXO development benefited from multiple student internships: including Kyle Rankin (initial work on GN&C for elliptical orbits) and Daniel Smith (source target list and orbit radiation environment).

The **concept of using PFLs and formation-flying spacecraft** to form **virtual telescopes with milli-arcsecond to micro-arcsecond X-ray/γ-ray imaging** performance is based on **papers by Gerry Skinner** (A&A 375, 691-700 (2001) and A&A 383, 352-359 (2002) and beyond).

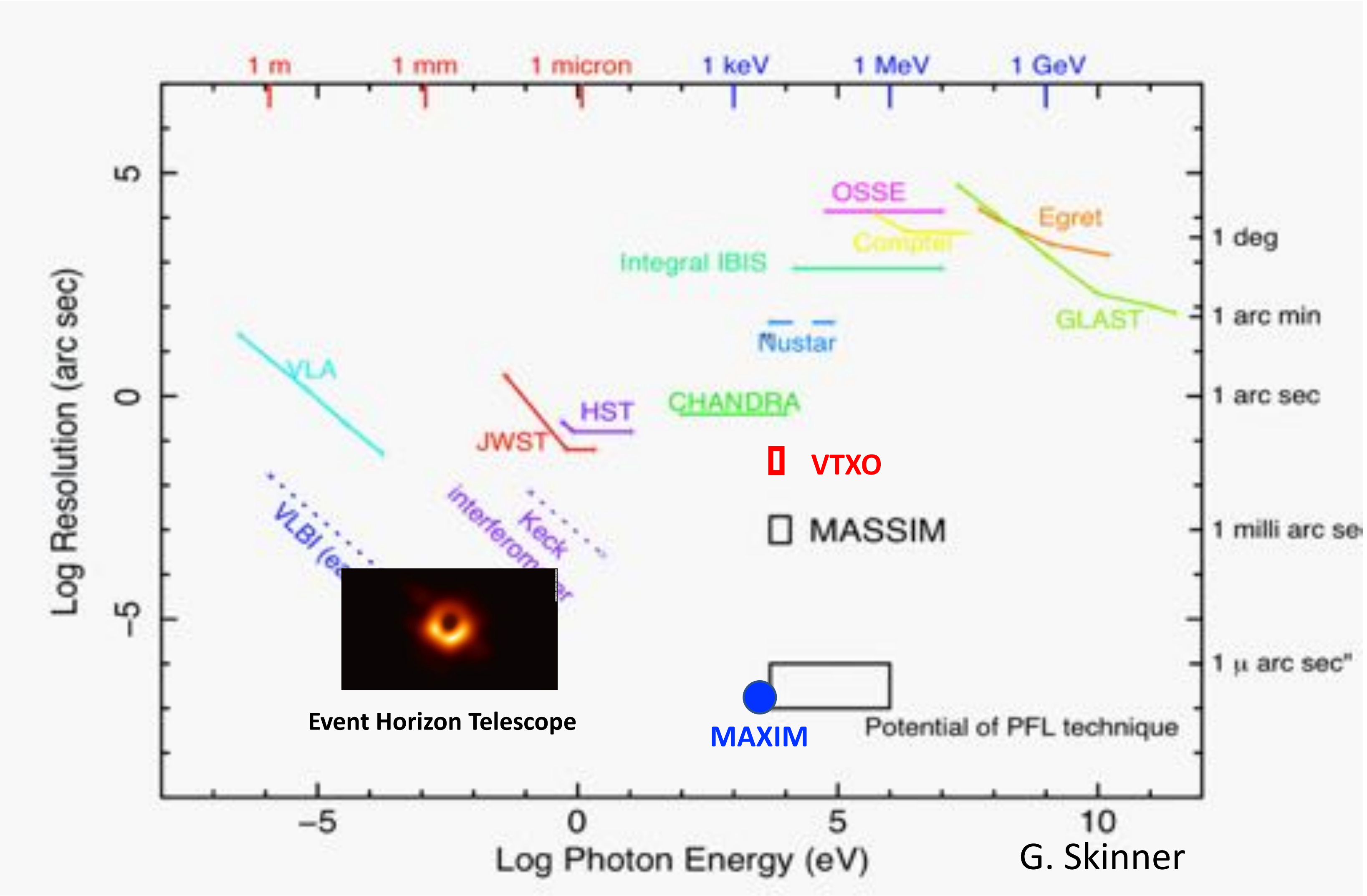
Angular Resolution Performance vs Wavelength

VTXO



G. Skinner

Angular Resolution Performance vs Wavelength



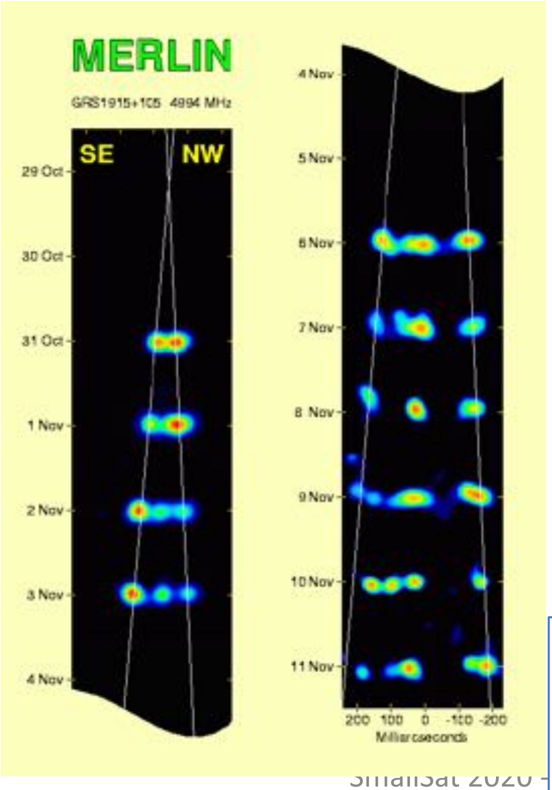
VTXO Science Objectives

Image environments ×10 closer to compact X-ray sources

- Sco X-1: X-ray telescope PSF calibration.
- Cyg X-1 & GRS 1915+105: jet structure in X-ray Novae:
  - MERLIN radio results show structure ~ 100 mas scale.
- Cyg X-3, GX 5-1, Cen X-3: dust scattering halos.
- Crab PWN: structure in accelerator termination shock.

X-ray Sources in Reach:

- Exoplanet Space Weather, Proxima B 40 mas away from Proxima Cen.
- Eta Carinae: colliding wind accelerator, 20 mas apartron orbital separation.
- γ Cassiopeiae: 10 mas needed to test X-ray emission companion hypothesis.



MERLIN radio observations of the X-ray binary GRS 1915+105 during the Oct/Nov 1997 outburst (astro-ph/9812150):

Observation time for 1000 VTXO counts in the energy band 4.5 +/- 0.075 keV		
Source	Flux (mCrabs)	Obs Time (hr)
Sco X-1	8000	0.2
GX 5-1	1260	1.5
GRS 1915+105	450	4.2
Cyg X-3	390	4.9
Cyg X-1	350	5.4
Crab Pulsar	100	19
Cen X-3	90	21
γCas	13	146
Eta Carinae	4.2	452

Flux Ref: PRAXyS and VTXO Science team (ave estimates)
Crab: 2.4 × 10^{-8} ergs/cm^2/s in 2 – 10 keV band

3 cm diameter PFL with 30% efficiency
2.1 cm^2 Effective Area/PFL

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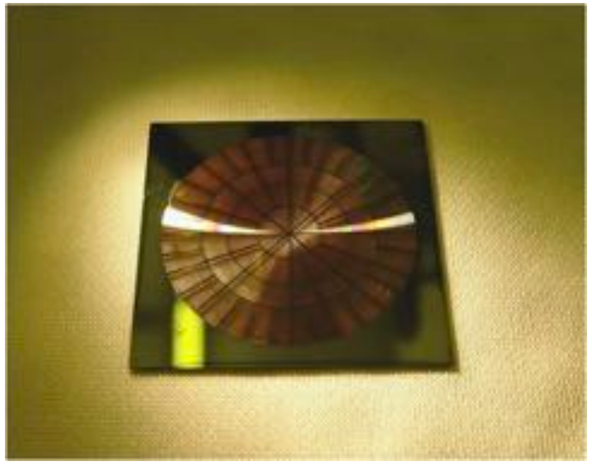
Phase Fresnel Lenses: imaging using diffraction

VTXO

3 cm diameter, 8.2 μm thick

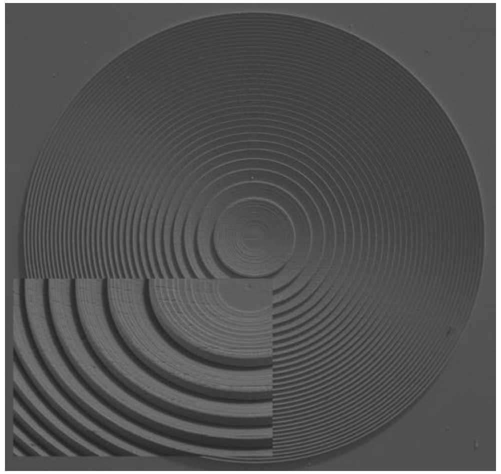


Photograph of a 3-cm diameter 5.4 keV silicon PZP fabricated GSFC. Ref: Dennis et al., Solar Phys (2012) 279:573–588

1st order Efficiency:
(no absorption loss)
$\varepsilon = [n/\pi \sin(\pi/n)]^2$
n=2 : 41%
n=4 : 81%

Fabricated $p_{Min} \approx 2$ - 10 μm
focal length = 110.4 m

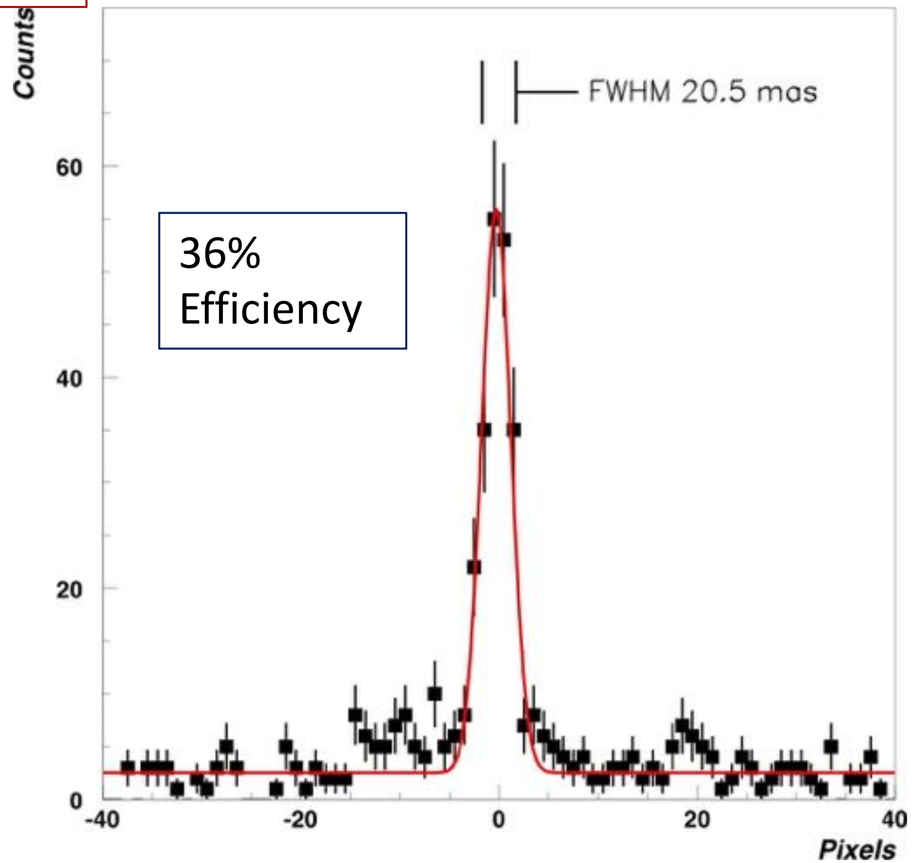
3 cm dia, 41 μm thick (4π PFL)



SEM of a 8 keV PFL fabricated at UMCP

$$t_{2\pi} = \lambda/\delta \Rightarrow 2.55 \left(\frac{\mu m}{keV}\right) E\,(\mathrm{keV}) \quad (\text{for silicon, } E > 2\ \mathrm{keV})$$

$$f = p_{Min} d/2\lambda = 4.033 \left[\frac{p_{Min}}{1\ \mu m}\right]\left[\frac{d}{1\ cm}\right]\left[\frac{E_\gamma}{1\ keV}\right] m$$



Projection of the image of a 5 μm slit formed in Cu Ka X-rays (8.041 keV) with a 3 mm diameter PFL. 15.9 milli-arcseconds (mas) which includes slit magnification and detector resolution effects.
Ref: Krizmanic et al., Proceed 31st ICRC (2009).

VTXO PFL Imaging Performance at 1 km focal length

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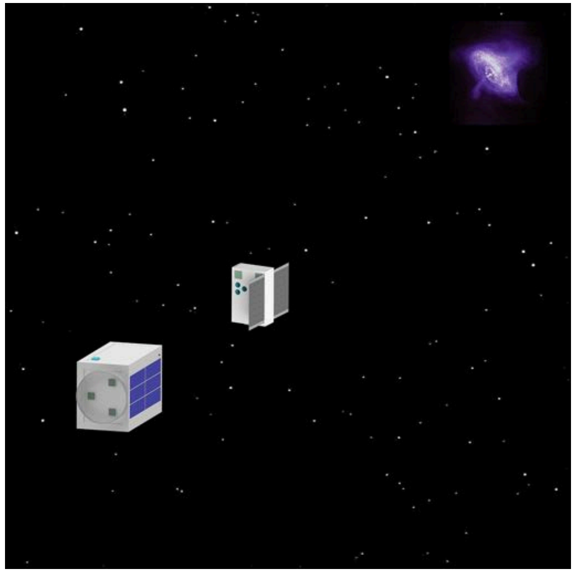
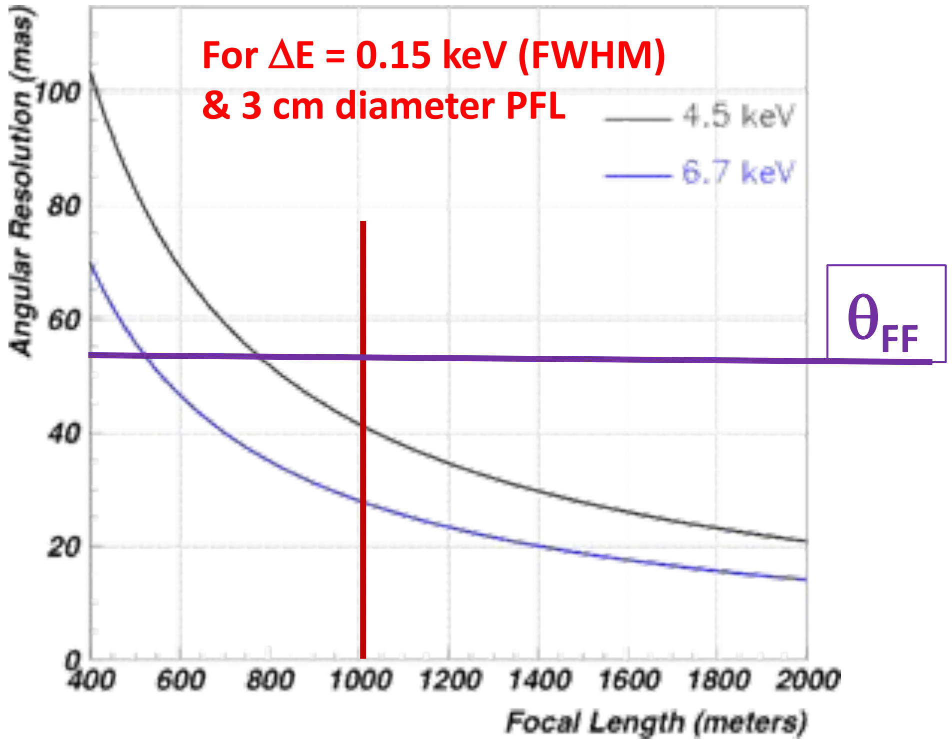
Angular Resolution Terms:

- Diff Limit: $\theta_{Diff}=1.22\lambda/d$
- Finite Pixel Size: $\theta_{PXL}=\Delta x/f$
- Chromatic Aberration: $\theta_{CA}=0.2\ \Delta E/E\ d/f$

$$f = p_{Min} d / 2\lambda = 4.033 \left[\frac{p_{Min}}{1\ \mu m}\right]\left[\frac{d}{1\ cm}\right]\left[\frac{E_\gamma}{1\ keV}\right] m$$



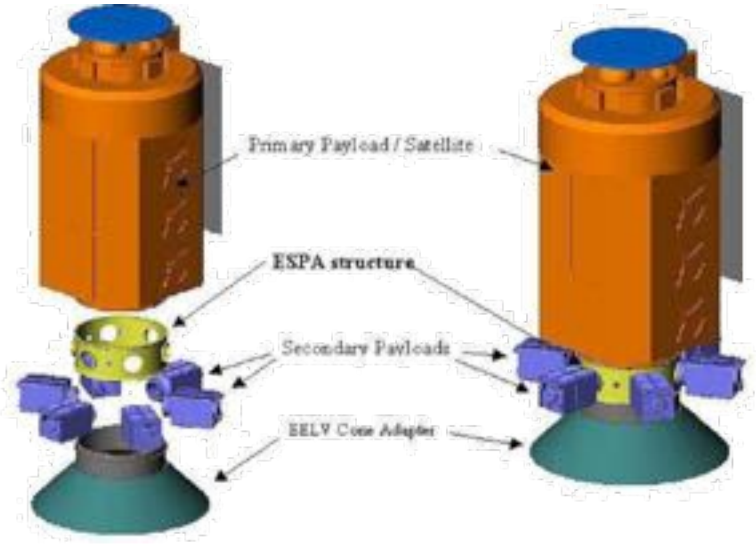


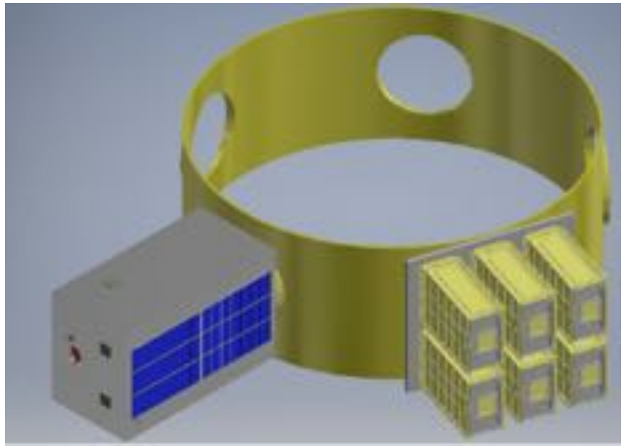
- Requires 0.15 keV (FWHM) energy resolution of X-ray camera sensor, and thus requires cooling using TEC:
  - 250 K for H2RG HyViSI X-ray Camera
- **3 cm diameter PFL and 1 km focal length sets PSF ≲ 50 mas for E_γ ≳ 4 keV.**
- **From VTXO study, formation-flying pointing error: $\theta_{FF} \approx 53$ mas (FWHM)**

Launch/Rideshare/ESPA Ring Deployment

VTXO

Source: Wikipedia (via Mike Deep for NSF/L2)





SpaceX FH2 Launch April 11, 2019

- SuperSynchronous GTO
- Apogee Altitude: 90,000 km
- Perigee Altitude: 200 km

VTXO SmallSats would deploy from an ESPA ring, go online, then boost perigee to 600 km (Δv=20 m/s).

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VTXO Concept of Operation

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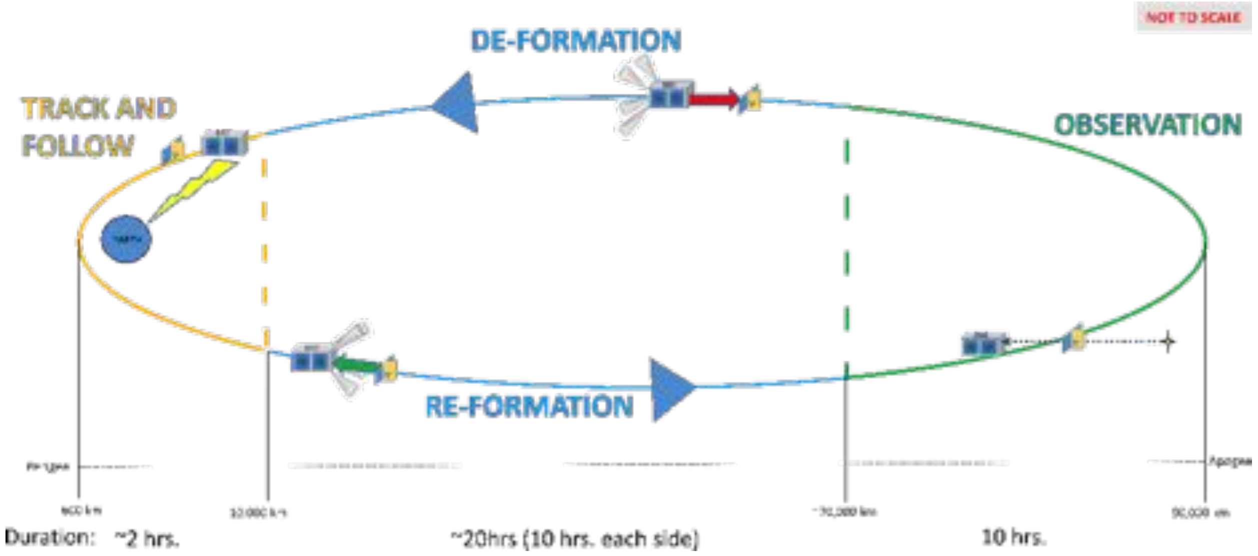

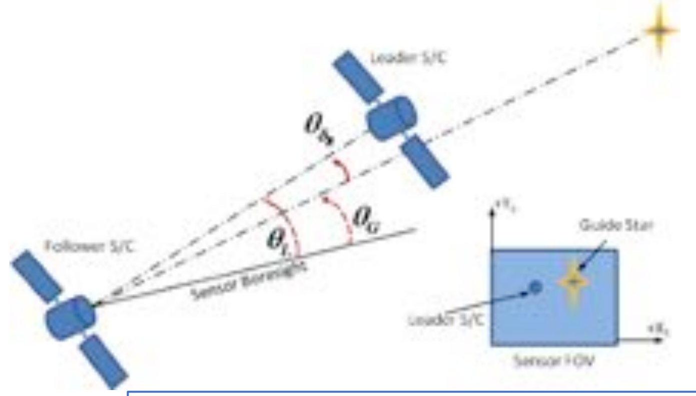

Schematic of the star tracker relative navigation scheme: Source M. Malajner, P.Planinsic, & G.Dusan (2015)
VTXO augments this with radio ranging and OpticsSat Nav data vis radio interSat link.

- Science Formation relaxes and re-forms every orbit to align OpticsSat and DetectorSat
- Loose formation (20 m separation) leaves perigee.
- **Science formation (1 km separation)** forms in ~10 hr to 1 km focal length at 5 hr before apogee:
  - Thrusters keep image on X-ray camera within ± 5 mm for **±5 hr around apogee during science observation**.
  - Navigation filter uses **NISTEx-II star tracker (41 mas pointing resolution)** also imaging beacons on OpticsSat & radio ranging & Nav sensors (via interSat link) to obtain 53 mas (95% CL ellipse) telescope pointing resolution.
- Formation relaxes (to 20 m separation) moving to perigee.
- Ground com occurs before perigee at an altitude ~10,000 km.
- Process repeats.

VTXO Formation Flying Performance based on GN&C simulations

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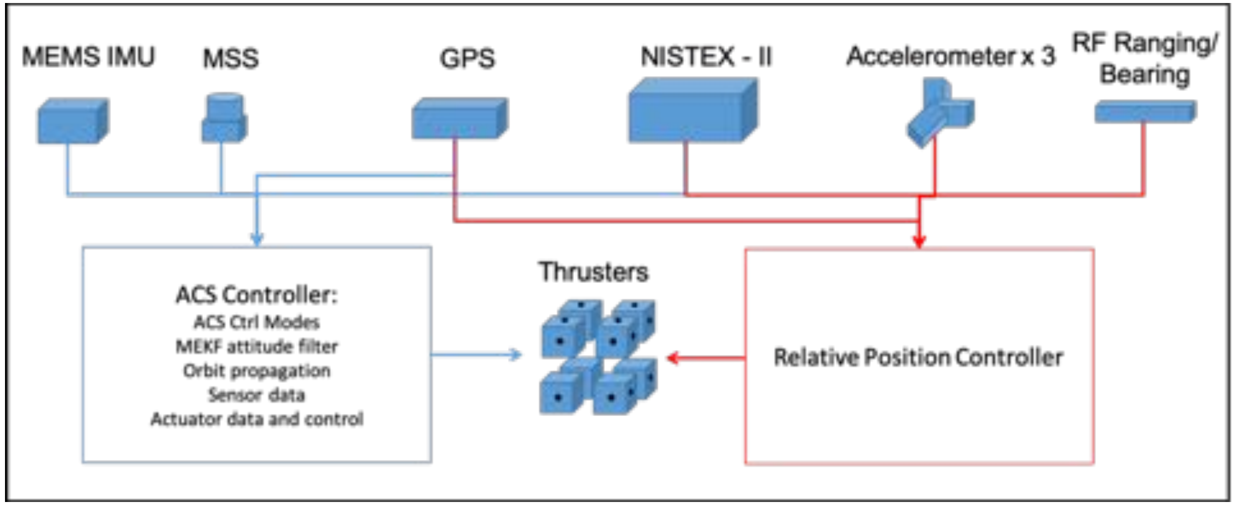
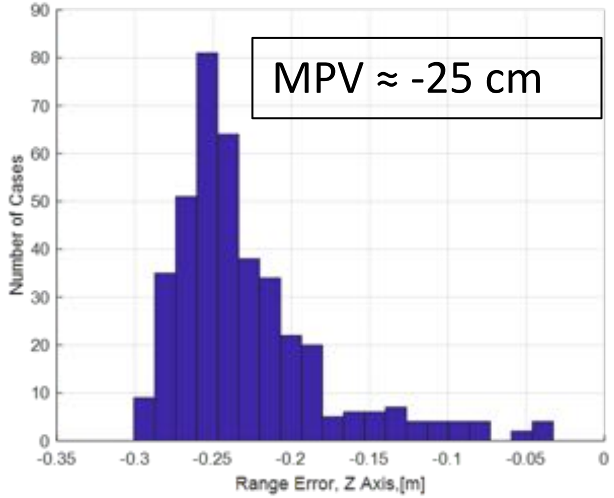
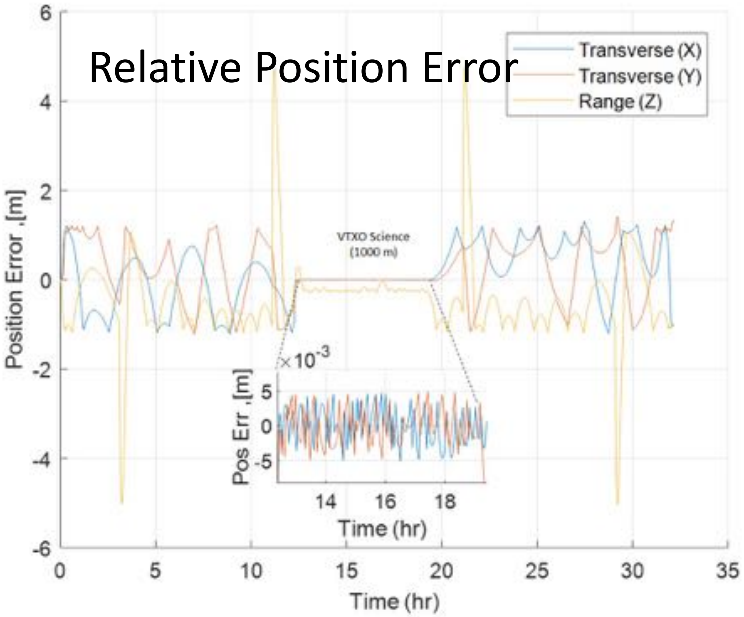
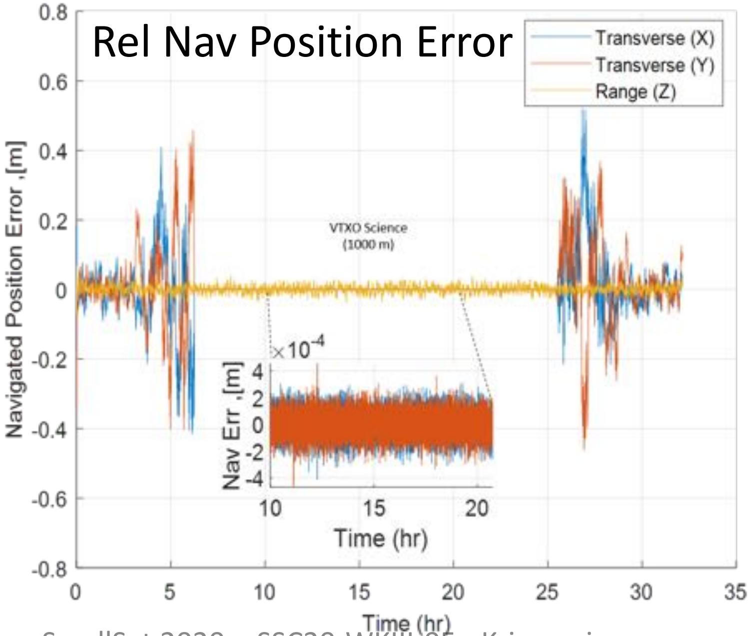
Requirement:
- Focal Length: 1 km ± 1 m
- Lateral Control: ± 5 mm
- Pointing Know.: 50 mas
- S/C Pointing Control: 0.5°

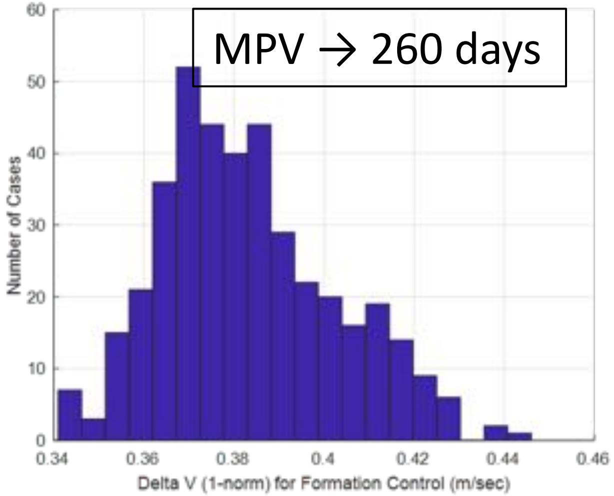


400 MC runs with variations









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VTXO SpaceCraft and Instruments

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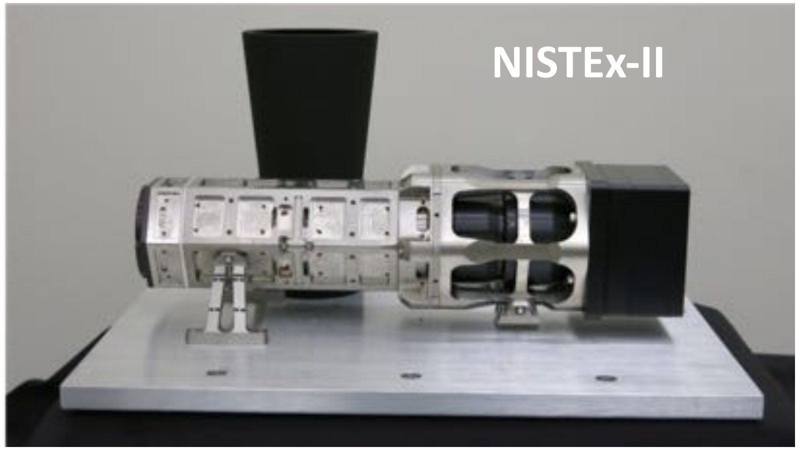


NISTEx-II interferometric star tracker (Optical Physics Corp w/US Navy and NASA/GSFC): 41 mas pointing resolution, currently operating on STP-H6 on ISS. Source: NASA.

Instruments:

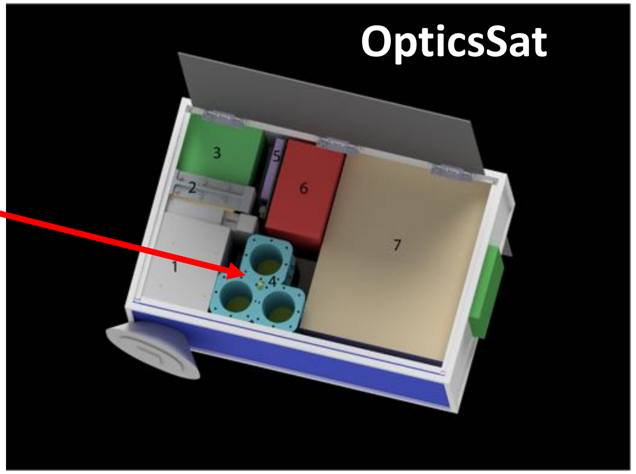
1. PFL Optics: 4.5 keV, 6.7 keV, PFL-achromat
2. X-ray Camera: TEC-cooled H2RG HyViSI with ACADIA readout (developed by WFIRST).
3. Small charged particle counter to measure radiation environment.

1 VACCO 3-nozzle cold gas thruster; 2 SWIFT SLX radio; 3 Batteries; 4 Avionics bus/shielding; 5 NISTEx-II interferometric start tracker; 6 X-ray camera assembly; 7 Instrument electronics/shielding; 8 VACCO cold gas generator; 9 X-ray camera/star tracker viewing ports.

DetectorSat: 50 × 40 × 80 cm^3

- H2RG X-ray camera and NISTEx-II star tracker on optical bench
- Charged particle counter
- Avionics
- VACCO cold gas propulsion (Δv = 100 m/s)
- S-band radio for ground com and interSat radio ranging and com link
- GPS
- Power System

Beacons



1 BCT XACT-50 (star camera FoV shown by cone); 2 GPS receiver; 3 SWIFT SLX radio; 4 PFL assembly and laser beacon; 5 EPS unit; 6 Batteries; 7 VACCO cold gas MiPS

OpticsSat: 6U

- 3 PFL ports
- Beacons for Nav alignment
- Avionics
- VACCO cold gas propulsion (Δv = 40 m/s)
- S-band radio for ground com and interSat radio ranging and com link
- GPS
- Power System

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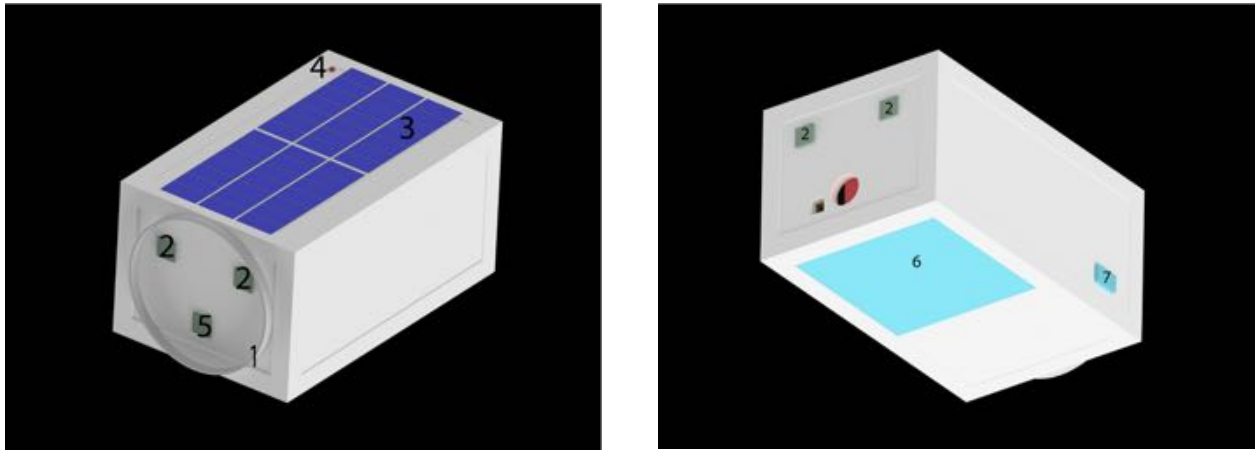
VTXO Spacecraft Exterior Views

VTXO



DetectorSat External Views

1 - RAG PAS 3815
3 - Body Mounted Solar Panel
5 - S-Band Antenna (Ground)
7 - GPS Antenna

2 - S-Band Antenna (Inter-sat)
4 - Course Sun Sensor
6 - Radiator

DetectorSat:
- Dry Mass: 72 kg
- Wet Mass: 109 kg
- Power: 48 W

Telemetry:

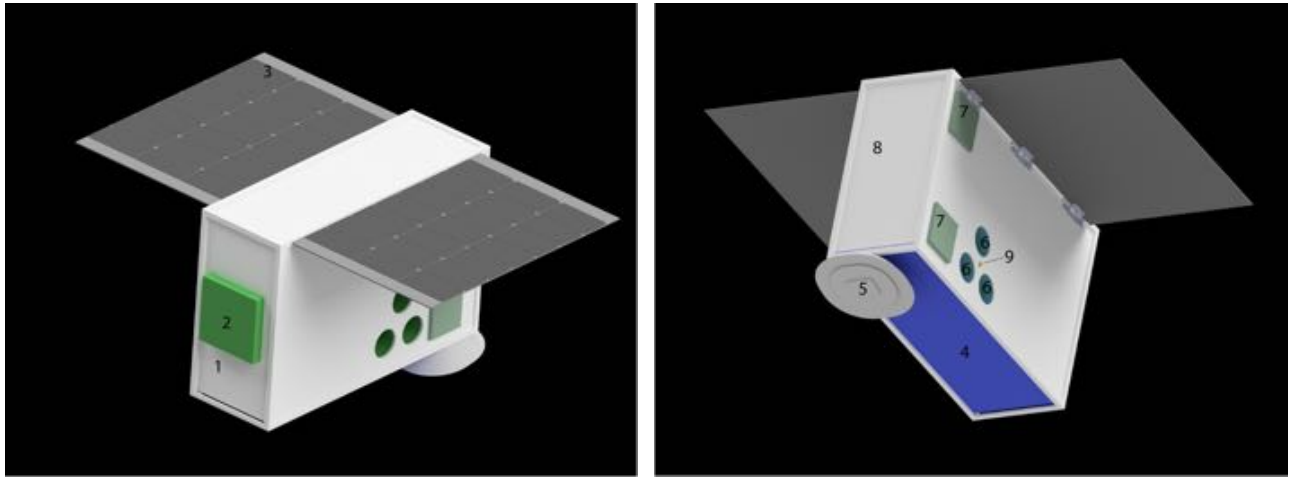
Ground:

$\lesssim$ 200 Mbits/orbit

InterSat:

~ 5 kbps (Nav data)

OpticsSat:
- Dry Mass: 9.7 kg
- Wet Mass: 12 kg
- Power: 24 W



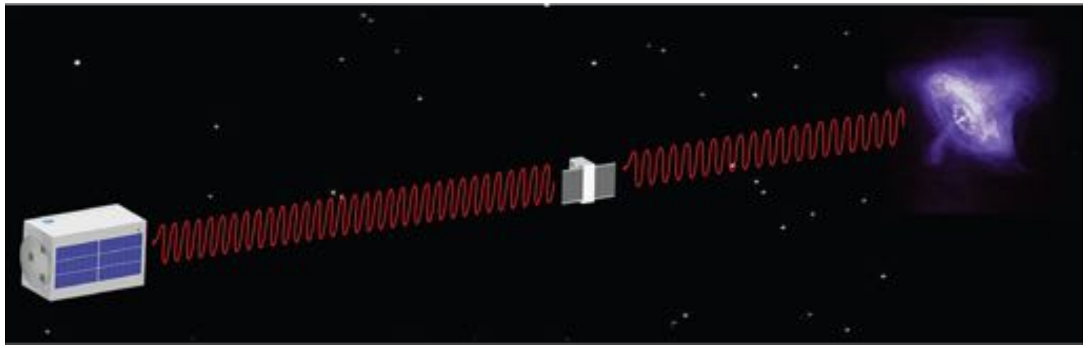
OpticsSat External Views

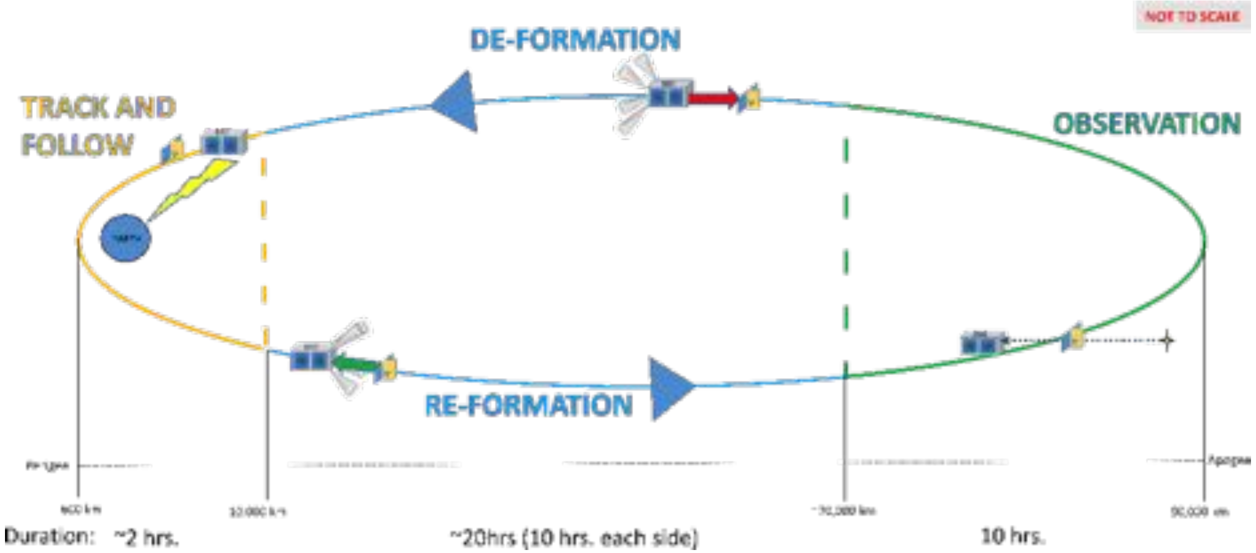
1 - VACCO Cold Gas Thrusters
3 - 6U Deployable Solar Panel Array (2x)
5 - Star Tracker Field of View
7 - S-Band Antenna

2 - S-Band Antenna (Ground)
4 - Radiator
6 - Phase Fresnel Lens Kapton Covers
8 - GPS Antenna

MPL radiation analysis: 5 mm Al needed to keep 1 year TID < 20 kRad.

VTXO Summary





- **VTXO Performance Highlights:**
  - Orbit (after perigee boost) : 90,000 km apogee and 600 km perigee altitudes (>50% orbit outside rad belts)
  - **Mission lifetime: ~260 days, ~200 days science (1900 hours)**
    - DetectorSat has space for larger propulsion tank, could extend mission duration
  - **Target-of-opportunity (ToO) observations can be accomplished with ~ 1 day time lag with minimal propulsion extra Δv costs, assuming adequate target visibility.**
  - Preliminary GPS analysis shows positions and velocities available for entire orbit, resolution reduced above GPS constellation (similar to MMS mission), also have modest (~30 kbps) ground com bandwidth around apogee.
  - Precision formation held for ±5 hours around apogee
  - X-ray Angular Resolution dominated **53 mas** **Image environments ×10 closer to compact X-ray sources**

Angular Resolution Performance vs Wavelength

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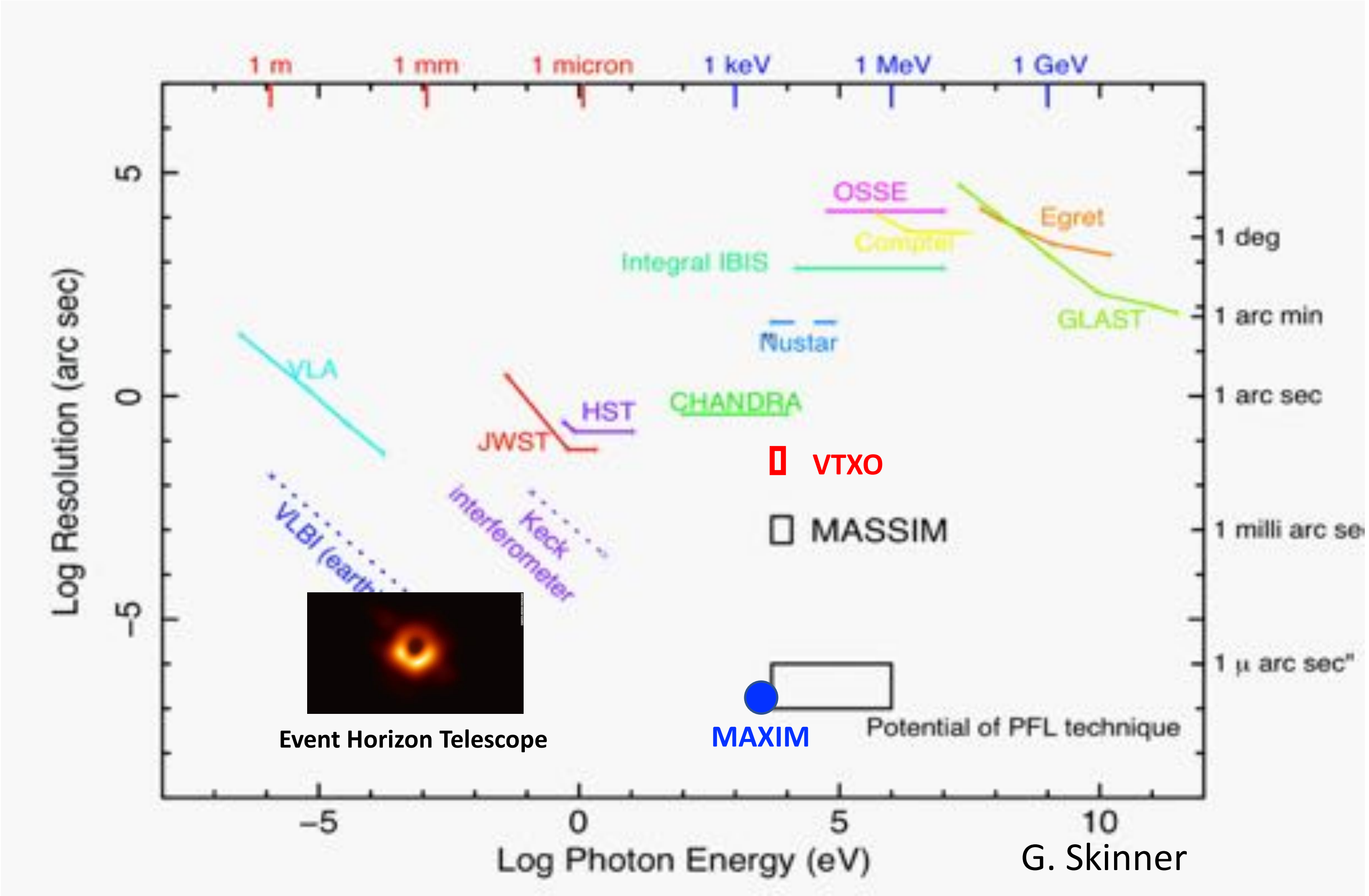
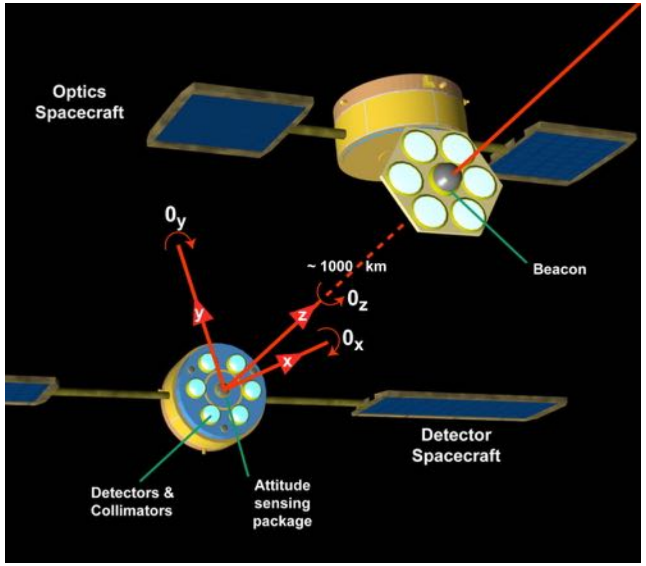
VTXO





MASSIM: G. Skinner et al., SPIE 7011, 70110T (2008)

Table 1 Baseline MASSIM characteristics

Energy Range	4.5-11 keV
Focal length	1000 km
Effective Area	2000-4000 cm^2 (inside 2 milli-arc-sec)
Angular Resolution	0.5 milli-arc-seconds (HEW 6-7 keV)
	0.1 milli-arc-seconds (selected energies)
Field of view	100 milli-arc-secs (1)
Point source sensitivity	8×10^{-15} erg $cm^{-2}s^{-1}$ (2)

(1) Detector limited; 500 × 500 mm assumed + possibility of wider field of view, lower resolution, option.
(2) 5σ in 10^5s, 4.5-11 keV)