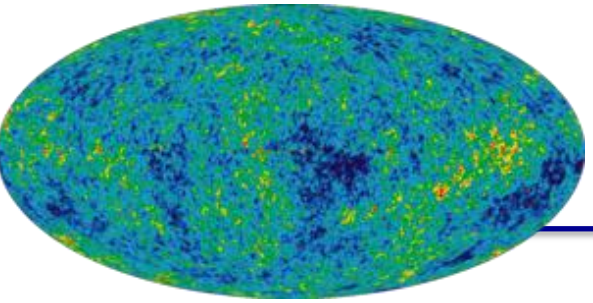
High Energy Astrophysics and Cosmology Technology Investment across NASA Astrophysics

Ann Hornschemeier

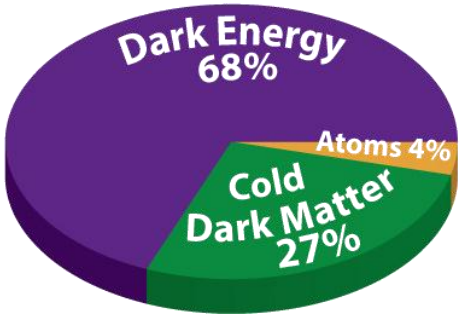
Physics of the Cosmos (PCOS) Program, Chief Scientist

pcos.gsfc.nasa.gov

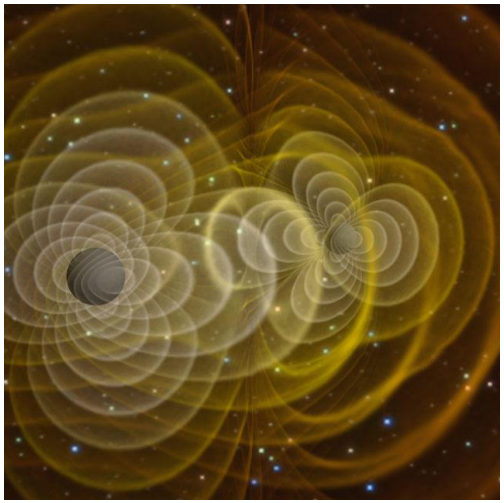


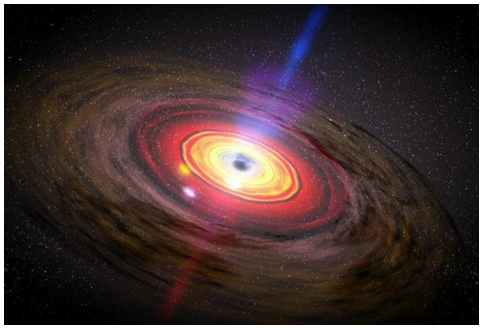
Physics of the Cosmos

Science Objectives



- Expand our knowledge of dark energy
- Precisely measure the cosmological parameters governing the evolution of the universe and test the inflation hypothesis of the Big Bang
- Test the validity of Einstein's General Theory of Relativity and investigate the nature of spacetime
- Understand the formation and growth of massive black holes and their role in the evolution of galaxies



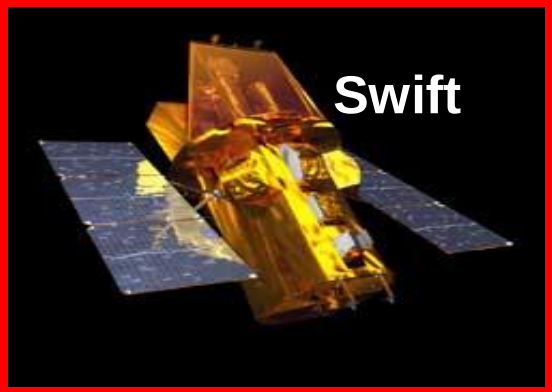


- Explore the behavior of matter and energy in its most extreme environments

PCOS MISSIONS

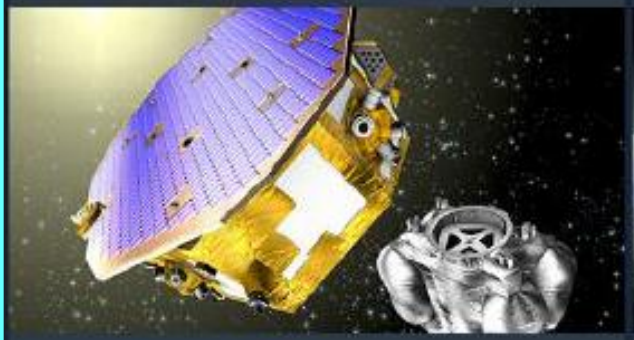
OPERATING

RELATED



Astrophysics Missions in Development

LISA Pathfinder 9/2015
ESA-led Mission



NASA supplied the ST7/Disturbance Reduction System (DRS)

ASTRO-H 11/2015
JAXA-led Mission

NASA supplied the Soft X-ray Spectrometer (SXS) instrument

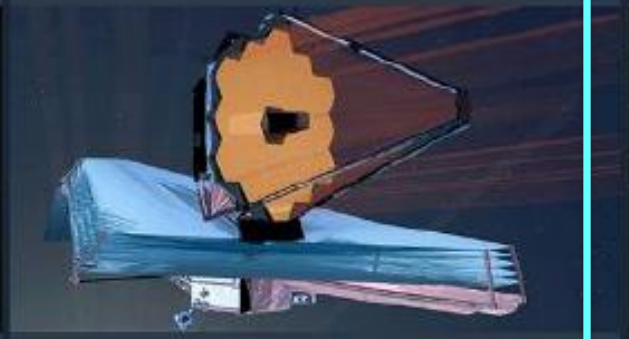
NICER 8/2016
NASA Mission

Neutron Star Interior Composition Explorer

TESS 8/2017
NASA Mission

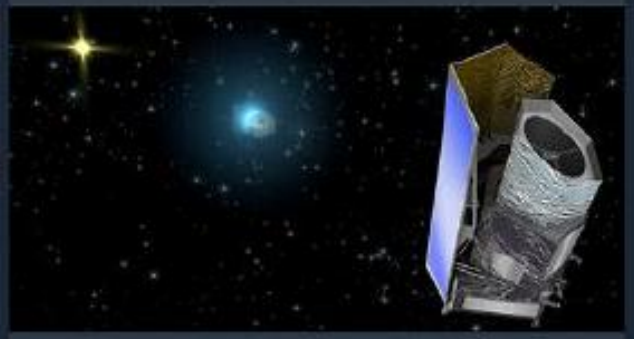
Transiting Exoplanet Survey Satellite

JWST 10/2018
NASA Mission



James Webb Space Telescope

Euclid 2020
ESA-led Mission



NASA is supplying the NISP Sensor Chip System (SCS)

Physics of the Cosmos (PCOS): Scientific and Technical Stewardship for future missions

- **Provide scientific and technical stewardship for decadal-survey recommended missions:**
  - Of the six highly-ranked medium and large-scale space-based priorities in NWNH, three fall within the PCOS science program:
    - LISA (Gravitational Waves)
    - IXO (X-ray)
    - Inflation Probe (medium-scale)
  - NOTE: Although dark energy SCIENCE is within PCOS program, WFIRST is located within the Exoplanet Program

ROSES 2014, Priorities for the PCOS Strategic Astrophysics Technology (SAT):

The following technological areas are identified as of particular interest for the TPCOS Program:

- **Technologies for X-ray Astrophysics**, including, but not limited to, high-resolution microcalorimeter arrays, lightweight replicated optics and precision structures, high-resolution gratings (both transmission and reflection).
- **Technologies for Gravitational Wave Astrophysics**, including, but not limited to: dimensionally stable, optical telescopes; frequency-stabilized metrology lasers; high-resolution phasemeters; low-noise microthrusters; ultra-quiet inertial references; and long-distance, laser metrology techniques.
- **Technologies for CMB Polarization Measurements**, including, but not limited to, high-throughput cold mm-wave telescopes and large low-background multiplexed arrays of detectors.

Technology development within the PCOS portfolio

- **For a summary each year, please read the PCOS Program Annual Technology Report (PATR)**
- **Includes:**
  - Progress report on all funded PCOS SAT activities
  - Technology priorities for PCOS

PCOS Program Office Leadership

- ** Program Manager: Mansoor Ahmed (a.k.a. Mooni)
- ** Deputy PM: Tom Griffin
- Chief Scientist: Ann Hornschemeier
- Deputy Chief Scientist: Peter Bertone
- **Chief Technologist: Bernard Seery
- **Technology Development Manager: Thai Pham

**** = Shared with COR, Cosmic Origins**

The Strategic Astrophysics Technology (SAT) program

- **In 2009, the Astrophysics Division launched the Strategic Astrophysics Technology (SAT) program to support the maturation of technologies of mid-range TRL already developed and tested in the laboratory (TRL~3) to a point where they can be incorporated into a flight mission with an acceptable level of risk (typically TRL 5 or 6).**
- **The SAT program does not support:**
  - basic research of new technologies (TRL< 3)
  - Flight qualification of mature technologies (TRL 7-9).
- **SAT fills the so-called "Mid-TRL Gap" of technologies that have potential but are not sufficiently mature for adoption in flight programs**

Five years of Strategic Astrophysics Technology (SAT) SELECTIONS

SAT Element	2009	2010	2011	2012	2013*	2014
TDEM	7 (20%)	9 (40%)	…	3 (18%)	4 (40%)	Pending
TCOR	…	3 (21%)	5 (21%)	3 (23%)	…	Pending
TPCOS	…	5 (23%)	5 (19%)	3 (30%)	6 (75%)	Pending
TOTAL:	**7**	**17**	**10**	**9**	**10**	**Pending**

71 PCOS SAT proposals to date, 19/65 funded (29%)

*X-ray solicitation only, potential technologies that might be contributed to ESA'S Athena mission

PCOS SAT Funding

Fiscal Year	TOTAL PCOS SAT
FY12	$2,351K
FY13	$8,328K
FY14	$7,837K
FY15	$6,012K
FY16	Pending

Currently-funded PCOS SAT projects

- **14 currently-funded PCOS SAT projects:**
  - 7 finish this fiscal year
  - By topical area:
    - Gravitational waves: 5 (4 finish this FY)
    - X-ray: 8 (2 finish this FY)
    - Inflation Probe: 1 (finishing this FY)

Current PCOS Technology Development Portfolio

Funding Source	Technology Development Title	PI	Organization	Current TRL	Start Year and Duration	Science Area
SAT2010	Directly-Deposited Blocking Filters for Imaging X-ray Detectors	M. Bautz	MIT	5	FY12, 4 years	X-ray
SAT2011	Demonstrating Enabling Technologies for the High-Resolution Imaging Spectrometer of the Next NASA X-ray Astronomy Mission	C. Kilbourne	GSFC	4	FY13, 3 years	X-ray
SAT2011	Colloid Microthruster Propellant Feed System for Gravitational-Wave Astrophysics Missions	J. Ziemer	JPL	4	FY13, 2 years	GW
SAT2011	Telescope for a Space-based Gravitational-Wave Mission	J. Livas	GSFC	3	FY13, 3 years	GW
SAT2011	Advanced Laser Frequency Stabilization Using Molecular Gases (co-funded with STMD)	J. Lipa	Stanford	3	FY13, 3 years	GW
SAT2012	Antenna-Coupled Superconducting Detectors for Cosmic Microwave Background Polarimetry	J. Bock	JPL	3	FY14, 2 years	Inflation
SAT2012	Demonstration of a TRL 5 Laser System for eLISA	J. Camp	GSFC	3	FY14, 2 years	GW
SAT2012	Phase Measurement System Development for Interferometric Gravitational-Wave Detectors	W. Klipstein	JPL	4	FY14, 3 years	GW
SAT2013 & SAT2010	Advanced Packaging for Critical Angle X-ray Transmission Gratings	M. Schattenburg	MIT	3	FY15, 2 years	X-ray
SAT2013 & APRA2011	Development of 0.5 Arc-second Adjustable Grazing Incidence X-ray Mirrors for the SMART-X Mission Concept	P. Reid	SAO	3	FY15, 3 years	X-ray
SAT2013 & SAT2010	Reflection Grating Modules: Alignment and Testing	R. McEntaffer	U. of Iowa	4	FY15, 2 years	X-ray
SAT2013 & SAT2011	Affordable and Lightweight High-Resolution Astronomical X-Ray Optics	W. Zhang	GSFC	4	FY15, 2 years	X-ray
SAT2013	Fast Event Recognition for the ATHENA Wide Field Imager	D. Burrows	PSU	3	FY15, 2 years	X-ray
SAT2013	Technology Development for an AC-Multiplexed Calorimeter for ATHENA	J. Ullom	NIST	3	FY15, 2 years	X-ray

Colloid Microthruster Propellant Feed System

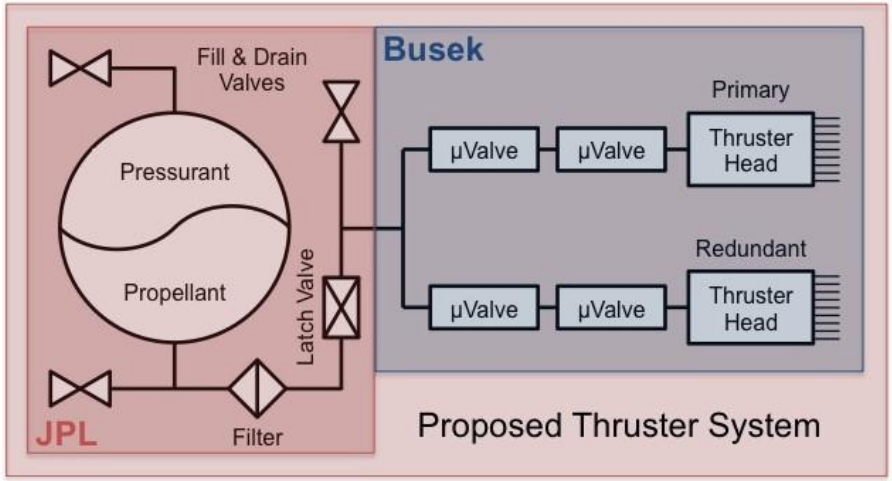
PI: John Ziemer/JPL

Objectives and Key Challenges:

- Replace the heavy (up to 15 kg) spring-loaded bellows design from ST7 with a light-weight pressurized diaphragm tank (≤1 kg)
  - O1: Design tank and feed system with full redundancy
  - O2: Design, fabricate, and test stainless steel diaphragm tank
- Use the new Busek Microvalve (Phase II SBIR and Phase IIe) to reduce complexity while providing redundancy
  - O3: Design, fabricate, and test new Busek Microvalves
  - O4: Integrate and test feed system components to TRL 5

Significance of Work:

- A new, flight-like, fully redundant, higher capacity colloid thruster feed system at TRL 5 can support any gravity wave observatory concept
- A clear path to TRL 6 once the mission and system are defined



Approach:

- Teaming arrangement between flight tank vendor Keystone, Busek for the Microvalve, and JPL to manage, perform I&T
- Use standard liquid-fed propulsion flight design guidelines and practices – the new technology is in the assembled pieces working together, not the propulsion engineering approach
- Four tasks related to each objective, plus a management task, each with a JPL expert lead
- Hold peer reviews at each meaningful milestone: requirements definition, design, and test

Key Collaborators:

- Busek Co., Inc. on Microvalve and systems engineering
- Keystone Engineering on flight-like tank manufacture and test
- JPL electric / chemical propulsion and flight propulsion groups

Current Funded Period of Performance:

- Jan 2013 – Jan 2015

Recent Accomplishments:

- Tank fabrication and TRL 5 tests are complete
- Microvalve fabrication and environmental tests are complete
- Redundant Microvalve subassembly including accumulator and volume compensator has been fabricated and tested for TRL 5
- Tank and supportive feed system components are all at JPL, ready for integration; data system complete

Next Milestones:

- Receive Busek Microvalve subassembly and test full feed system assembly to TRL 5

Application:

- Drag-free gravity wave observatories
- Remove reaction wheels - precision pointing of exo-planet observatory and next generation space telescopes
- Small spacecraft main propulsion

TRLin = 3-4 ***TRLcurrent = 4*** ***TRLtarget = 5***

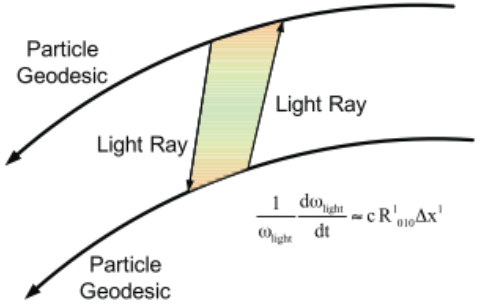
Other PCOS and PCOS-related technology activities

LISA Pathfinder, IR arrays for dark energy, and some “PCOS APRA highlights”

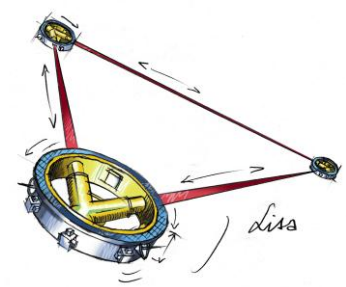
LISA Pathfinder

Goal: Demonstrate measurement concept an key technologies for a future space-based gravitational-wave observatory.

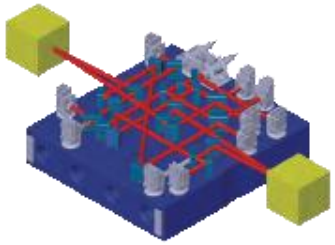
Textbook GW detector



LISA Mission Concept



Technology Demonstrator

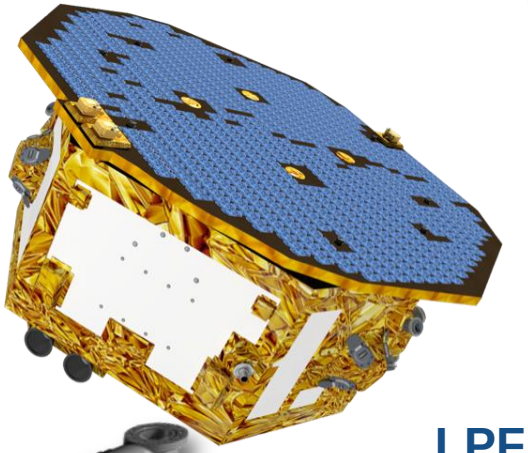


Measurement Concept:

- Interferometric ranging between two free-falling test masses.
- Replicates single “arm” of a LISA constellation in one spacecraft.
- Not sensitive to gravitational waves but very similar instrument noise

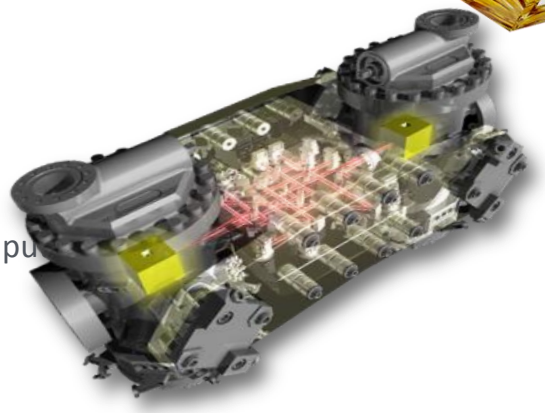
Key Components

- **Spacecraft**
  - Provided by ESA
  - Industrial Prime Contractor: Airbus Defense & Space
  - Spacecraft also includes the drag free control software and micro-Newton thrusters



LPF

- **Payloads**
  - The LISA Technology Package (LTP)
    - Provided by European member states and ESA
    - inertial sensors, interferometric readout, payload compu and diagnostic subsystem
  - The Disturbance Reduction System (DRS)
    - Provided by NASA (JPL lead, GSFC participation)
    - processor running drag-free control software and micro-Newton thrusters
    - Utilizes LTP sensors/actuators



LTP Core Assembly

ST7-DRS

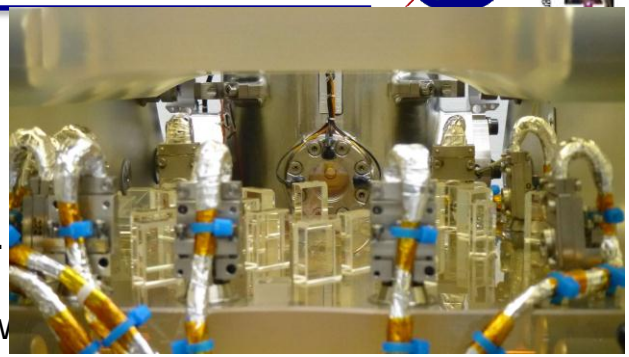
LISA Pathfinder Current Status

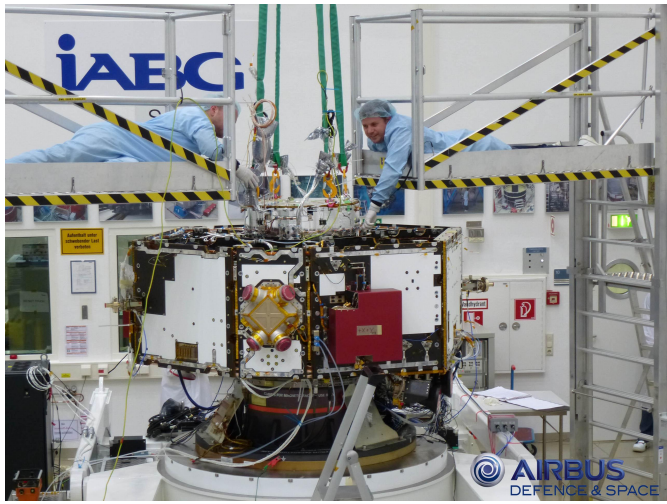
- **Spacecraft/Payload**
  - ST7 delivered and accepted in 2011
  - LTP delivered and accepted in June 2015
  - Both payloads integrated with spacecraft in June 2015
  - Final SC testing underway
  - Shipment Readiness: Sept. 2015

- **Operations**
  - Infrastructure complete and tested
  - Data analysis infrastructure nearing completion

- **Launcher (VEGA)**
  - 5 successful launches so far, LPF will be number 6
  - LPF's eastward trajectory requires modification of launch profile.
  - Launcher readiness currently driving launch date estimated as November 2015.

LTP integration showing optical bench and gravitational reference sensor. (ESA, Airbus, CGS, U. Glasgow





LTP being lowered into LPF spacecraft (ESA, Airbus)

VEGA launch of Sentinel 2A on June 22nd, 2015


iABG
Aufenthalt unter schwebender Last verboten
Wandhydrant
AIRBUS
DEFENCE & SPACE

Euclid

A visible and near-infrared telescope to explore cosmic evolution

- **ESA Cosmic Vision 2015-2025 Mission**, M-Class with NASA participation.
- 1.2-m mirror, visible & near-IR images, spectra
- **Launch Date**: Mar 2020
- **Science Objectives**:
  - Euclid will look back 10 billion years into cosmic history.
  - Probe the history of cosmic expansion
  - Probe dark matter along the line of sight to galaxies via gravitational lensing, probing large scale structure.
  - Measure galaxy clustering

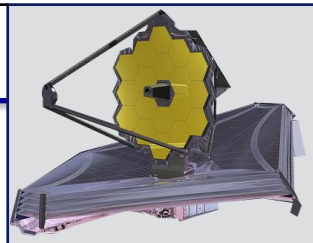
CURRENT STATUS:

- **Currently in implementation phase.**
- **~50 U.S. scientists are members of the Euclid Science Team that will analyze the data, and make maps of the sky.**
- **NASA is providing the sensor assembly for the NISP instrument.**
  - First experimental manufacturing run for the Euclid near-infrared detectors was completed in FY 2014 (ESA) and are currently being evaluated and characterized.
  - NASA has initiated purchase of the flight infrared detectors. First lot is complete, second lot underway. NASA will test and characterize the near-IR flight detectors.
  - Final proposal for detector contract received from Teledyne in February 2015.
- **NASA is funding the ENSCI (Euclid NASA Science Center at IPAC):**
  - Support all segments of US community on Euclid to enhance science utilization
  - Integrate into Euclid Science Ground System provided by the Euclid consortium to gain/contribute expertise in pipelines

IR arrays for Dark Energy: H2RGs, H4RGs

- The Teledyne H2RG is a 2048x2048 pixel sensor chip assembly (SCA) developed for JWST (PI: Prof. Don Hall, University of –Hawaii-). The H2 = "Hawaii-2" was an existing legacy detector, "R" = reference pixels, and "G" = built in "guide window". The material is mercury-cadmium-telluride (HgCdTe)
- The Teledyne H4RG-10 is a 4096x4096 pixel SCA that has 10 µm pixels. An optical version exists (TRL-6) and WFIRST is supporting development of an IR version of the H4RG.

Today's Near-IR Focal Plane Technology for Astrophysics

	 **JWST**	 **Euclid**	 **WFIRST-AFTA** (preformulation, 6/2015)	 **Ground Based Astronomy (GBA)**
SCA	**H2RG** • 15 Flight SCAs - 8 with 2.5 µm cutoff HgCdTe - 7 with 5 µm cutoff HgCdTe • T ~ 40 K • Moly package, TRL-8	**H2RG** • 16 Flight SCAs • 2.3 µm cutoff HgCdTe • T ~ 100 K • Moly package, TRL-7	**H4RG-10 (and others)** • 18 Flight H4RG-10s for wide field imager • Smaller format (legacy) HxRGs for IFU • 2.5 µm cutoff HgCdTe in H4RG-10s • T ~ 100 K	**Various** **(this list is incomplete)** • Raytheon - 4Kx4K pixel HgCdTe arrays in development - 2Kx2K HgCdTe VISTA arrays in use • Selex Galileo - HgCdTe APD arrays used for wavefront sensing and guiding • Teledyne - 4Kx4K H4RG-15 in development - 2Kx2K H2RG widely used
SCE	**SIDECAR** • 15 flight SIDECARs (1 per SCA) • T ~ 40 K • TRL-8	**SIDECAR** • 16 flight SIDECARs • T ~ 125 K • TRL-6/7	**SIDECAR** • One SIDECAR per flight SCA • T ~ 175 K	**Various** • Custom, observatory-specific controllers often used • Commercial "Leach" controllers popular • SIDECAR sometimes used, but GBA does not face the same packaging and power constraints as space

Credit: Bernie Rauscher, Ed Cheng, Neil Gehrels, Bob Hill

ASTROPHYSICS RESEARCH AND ANALYSIS PROGRAM (APRA)

Five broad categories:

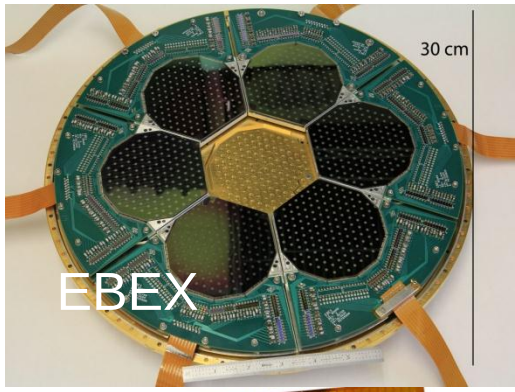
1. Suborbital/Suborbital-class Investigations ($5-6M per year)
2. Detector Development ($1-3M per year)
3. Supporting Technology ($2-4M per year)
4. Laboratory Astrophysics ($0.6-2M per year)
5. Ground-Based Observations ($30-60K some years).

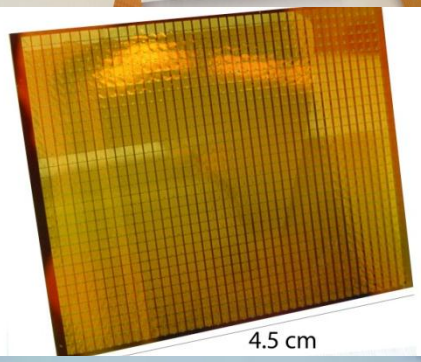
- **Covers technology development from TRL1→ TRL9**

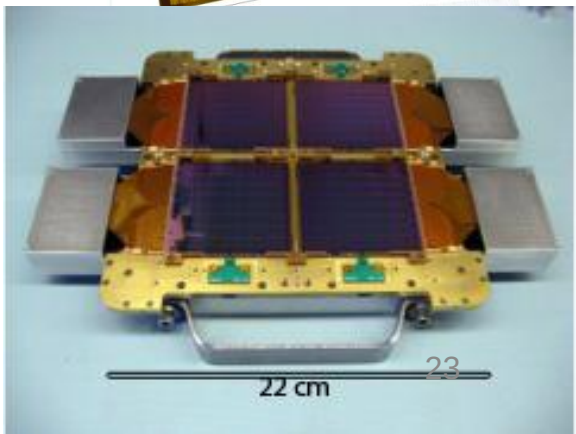
- **Note also that ROSES also has a solicitation for XRP – Exoplanet Research Program – proposals outside of APRA.**

CMB Polarization from Space, Balloons

- **Note: APRA balloon experiments are "outside PCOS" programmatically.**
- **Currently NASA supports three balloon-borne experiments that probe the polarization properties of the CMB covering 90-600 GHz with Transition-Edge (TES) bolometers with different polarimetric approaches :**
  - EBEX2012: (2012-2015): Flight in Jan 2013, E and B experiment (EBEX; P.I. Hanany), intermediate ell, analysis underway and paper anticipated by end of 2015
  - SPIDER: (2012-2016): Recent flight in 2014 Dec-Jan: Suborbital Polarimeter for Inflation Dust and the Epoch of Reionization (P.I. Bill Jones)
  - PIPER Phase 3 (2015-2019): Primordial Inflation Polarization Explorer Phase 3 (P.I. Al Kogut)







Most recent suborbital APRA selections (APRA-2013)

- There were 8 payloads selected last year, 5 of these are PCOS-related**:

- SuperTIGER-2: A Very-Large-Area, High-Resolution Trans-Iron Cosmic Ray Investigation **(Walter Binns)**
- A Balloon-Borne, Advanced Scintillator Compton Telescope with Silicon Photomultiplier Readout **(Peter Bloser)**
- Diffuse X-rays from the Local galaxy (DXL) **(Massimilliano Galeazzi)**
- Primordial Inflation Polarization Explorer (Phase 3) **(Al Kogut)**
- Ultra-high Energy Particle Astrophysics with ANITA-4 **(Peter Gorham)**

***** = PCOS science, APRA does not sort by program!**

ANITA (Antarctic Impulsive Transient Antenna) Long-Duration Balloon Payload

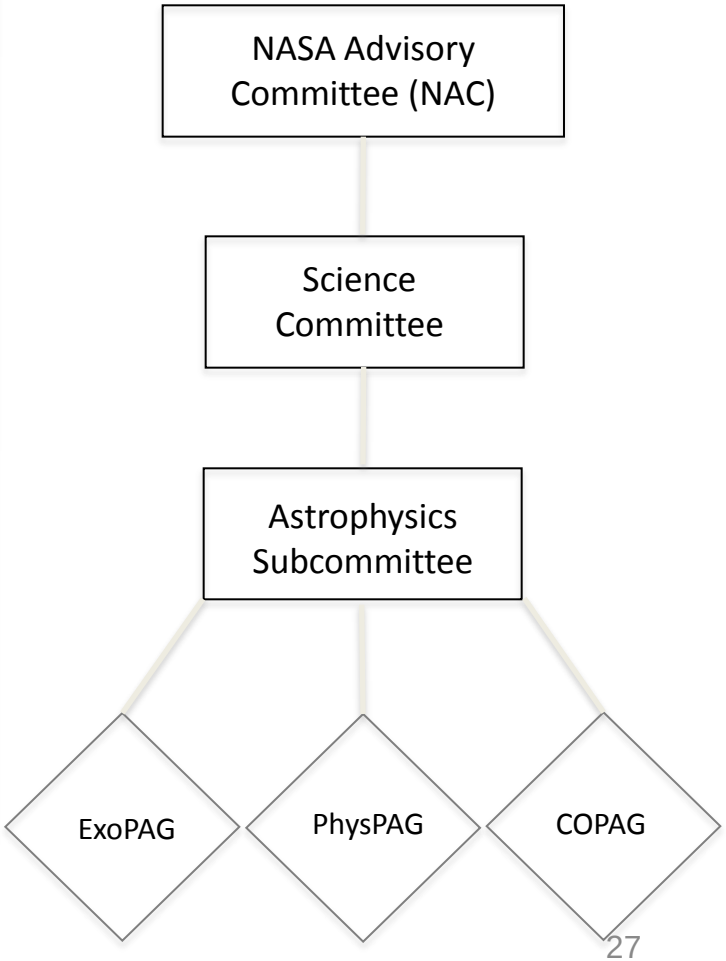
- **Most sensitive neutrino observatory in the world at 1-100 EeV energies (1 EeV = 1e9 GeV = 1000 PeV)**
- **Complements the "low energy" IceCube experiment**
- **Detects UHECRs via radio synchrotron from air showers**
- **Detects UHE neutrinos by recording broadband radio pulses from particle showers produced by neutrino interactions in Antarctic ice**
- **P.I., Gorham, University of Hawaii at Manoa**
- **Co-Is:**
  - James Beatty/Ohio State University
  - Dave Besson/University of Kansas
  - Walter Binns/Washington University in St. Louis
  - John Clem/University of Delaware
  - Andrew Romero-Wolf/Jet Propulsion Laboratory

How can you interact with NASA’s Physics of the Cosmos program?

Communicating with NASA Astrophysics via the Program Analysis Groups (PAGs)

- The Physics of the Cosmos Program Analysis Group (PhysPAG) serves as a forum for soliciting and coordinating input and analysis from the scientific community in support of the PCOS program objectives.
- The Program Analysis Groups (PAGs) include all members of the community interested in providing input to NASA on issues of strategic importance via analysis studies
- PAGs hold regular public meetings.
- PAGs identify specific, well-defined topics for further detailed studies assigned to Study Analysis Groups (SAGs) as well as longer-standing, discipline-centered analysis groups – Science Interest Groups (SIGs). All are task forces of volunteers.

Advisory Committees



PhysPAG SIG Leaders

- **Six Science Interest Groups:** Cosmic Structure, Inflation Probe, Gamma Rays, Cosmic Rays, Gravitational Waves, X-Rays, Cosmic Structure (NEW! March 2015)
- **PhysPAG Executive Committee membership:**
  - **J. Bock, Chair, California Institute of Technology**
  - **M. Bautz, Vice-Chair, MIT, X-rays**
  - **R. Bean, Cornell University, Cosmic Structure**
  - **J. Bookbinder, SAO, X-Rays**
  - **J. Conklin, University of Florida, Gravitational Waves**
  - **N. Cornish, Montana State, Gravitational Waves**
  - **O. Doré, NASA Jet Propulsion Laboratory, Cosmic Structure**
  - **H. Krawczynski, Washington University St. Louis, Gamma Rays**
  - **M. McConnell, University New Hampshire, Gamma Rays**
  - **A. Miller, Columbia University, Inflation**
  - **J. Nousek, Penn State, X-Rays**
  - **A. Olinto, University of Chicago, Cosmic Rays**
  - **Eun-Suk Seo, University of Maryland, Cosmic Rays**
  - **E. Wollack, NASA Goddard Space Flight Center, Inflation**
- Rotating off in Dec 2015, Call for applications in Fall 2015

Technology gaps for the PCOS program: informing the rankings in the PCOS PATR

- **2014:**
  - The PCOS Program Office (PO) received 21 gaps for consideration by the 2014 TMB, and forwarded all of these to the PCOS Technology Management Board
  - The TMB folded seven of the gaps into others, leaving 14 for prioritization.
- **2015:**
  - The PCOS Program Office (PO) received 37 gaps for consideration by the 2015 TMB
  - These were forwarded to the PhysPAG EC for consolidation, underway NOW

THANK YOU

Ann.Hornschemeier@nasa.gov

pcos.gsfc.nasa.gov

(Sign up for email list at "PCOS News and Announcements tab)

BACK-UP CHARTS

Five years of Strategic Astrophysics Technology (SAT) Proposals

SAT Element	2009	2010	2011	2012	2013*	2014
TDEM	34	22	…	17	10	7
TCOR	…	14	24	13	…	15
TPCOS	…	21	26	10	8	6
TOTAL:	**34**	**57**	**50**	**40**	**18**	**28**

*X-ray solicitation only, potential technologies that might be contributed to ESA'S Athena mission

APRA Funding and Proposals
Source: ROSES 2015 – APRA AO

APRA Category	Total allocated to new selections [$M]				Number of New Selections (including Co-I proposals)			
	A-09	A-10	A-11	A-12	A-09	A-10	A-11	A-12
	FY11	FY12	FY13	FY14	FY11	FY12	FY13	FY14
Suborbital Investigations	5.6	8.9	5.0	6.1	10	12	8	15
Detector Development	1.9	1.3	2.7	3.1	6	4	10	7
Supporting Tech.	4.3	2.8	3.1	1.9	15	12	13	6
Lab. Astro.	1.0	1.8	0.9	0.6	8	8	8	5
Ground-based Obs.	0.03	0.06	0	0	1	1	0	0

LISA Pathfinder Status
(including JPL project ST7)

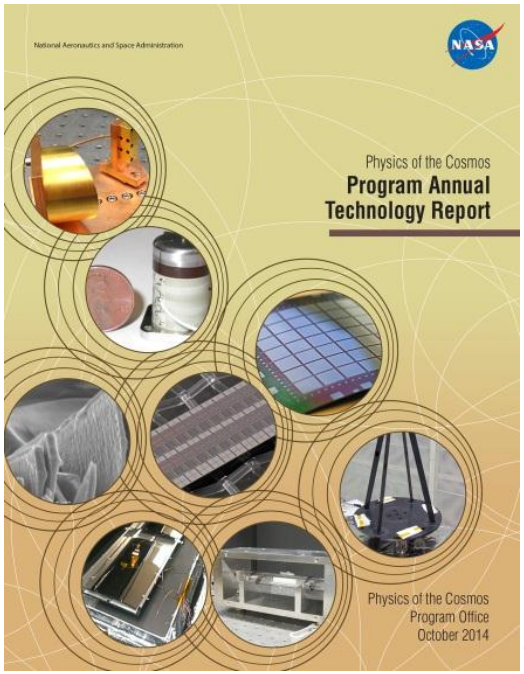
- **LPF Current Status: Late stages of integration with *launch expected in October 2015*.**
  - Preparations for mission and science operations underway with numerous exercises/test campaigns planned for the coming year

ESA
Transfer Orbit
Thermal Test

PCOS community activities

- Encourage your finishing students and early-career postdocs to apply for the Einstein fellows' program
  - Einstein Fellows hold their appointments at a Host Institution in the U.S. for research that is broadly related to the science goals of the NASA Physics of the Cosmos program.
- The PhysPAG provides input on technology needs to the PCOS program office that are fed into the PCOS Annual Technology Report (PATR) each year. (Thanks for sending in 21 technology gaps during summer 2014!)

Laura Blecha, 2012 Fellow



Keeping up with PCOS

- **Sign up for email announcements, or for a Science Interest Group**
- **pcos.gsfc.nasa.gov**

National Aeronautics and Space Administration

Physics of the Cosmos Newsletter

August 2014 Vol. 4 No. 2

Summer 2014 PCOS Update

Mansoor Ahmed, *PCOS Program Manager*
Ann Hornschemeier, *PCOS Program Chief Scientist*

Since February 2014, progress has continued on a number of fronts in the PCOS portfolio. Chief among these are the next steps in defining a U.S. role in the European Space Agency (ESA) L2 and L3 opportunities. Following the June 2014 announcement by ESA of the selection of the L2 mission Athena we are now referring to this mission by name and are pleased to have selected, via an open community call in early July 2014, a U.S. representative to the Athena Science Study Team (SST).

Please read Robert Petre's article on Athena which includes the full list of members of the ESA-selected SST. Conversations with ESA concerning L3 are at a much earlier stage and we ex-

(continued on page 2)

Contents

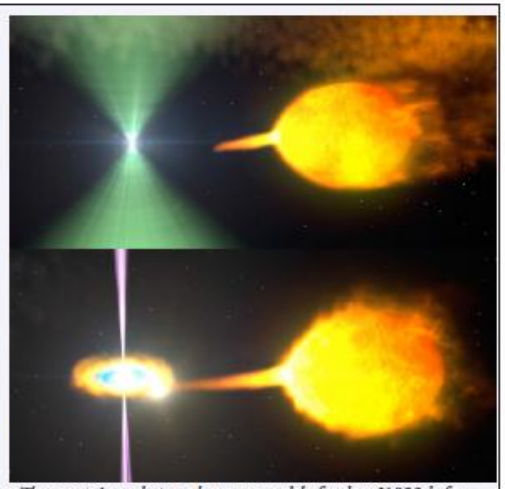
NASA's Fermi Finds A "Transformer" Pulsar

In late June 2013, an exceptional binary containing a rapidly spinning neutron star underwent a dramatic change in behavior never before observed. The pulsar's radio beacon vanished, while at the same time the system brightened fivefold in gamma rays, the most powerful form of light, according to measurements by NASA's Fermi Gamma-ray Space Telescope.

The binary pairs a 1.7-millisecond pulsar named PSR J1023+0038—J1023 for short—with a star containing about one-fifth the mass of the sun. The stars complete an orbit in only 4.8 hours, which places them so close together that the pulsar will gradually evaporate its companion.

For J1023, the dramatic changes seem to reflect an erratic interaction with its companion star, according to a recent study by an international team led by Ben Stappers at the University of Manchester in England.

The stars are close enough that a stream of gas flows from the sun-like star toward the pulsar. The pulsar's rapid rotation and intense magnetic field are responsible for both the radio beam and a powerful outflow of high-energy particles. When the radio beam is detectable, the pulsar wind blows back the companion's gas stream, preventing it from approaching too closely. But when the flow from the companion surges, the gas is able to reach toward the pulsar and establish an accretion disk.



These artist's renderings show one model of pulsar J1023 before (top) and after (bottom) its radio beacon (green) vanished. Normally, the pulsar's wind staves off the companion's gas stream. When the stream surges, an accretion disk forms and gamma-ray particle jets (magenta) obscure the radio beam. Image Credit: NASA's Goddard Space Flight Center

Gas in the disk becomes compressed and heated, reaching temperatures hot enough to emit X-rays. Next, material along the inner edge of the disk quickly loses orbital energy and descends toward the pulsar. When it falls to an altitude of about 50 miles (80 km), processes involved in creating the radio beam are either shut down or, more likely, obscured.

Read the full article at **http://www.nasa.gov/content/goddard/nasas-fermi-finds-a-transformer-pulsar/** and published paper **Stappers et al. ApJ, Vol. 790, p. 39** at **http://adsabs.harvard.edu/abs/2014ApJ...790...39S**

Technology Readiness Levels (TRL)

- **Taken from ROSES-2014 SAT call (proposals due March 2015)**

Table D.8.1. Technology Readiness Levels Summary. This table has been updated December 16, 2015 with Amendment 47	
TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof-of- concept
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 5	Component and/or breadboard validation in relevant environment
TRL 6	System/sub-system model or prototype demonstration in a relevant environment
TRL 7	System prototype demonstration in an operational environment
TRL 8	Actual system completed and "flight qualified" through test and demonstration
TRL 9	Actual system flight proven through successful mission operations

Programs within Astrophysics@NASA
Prioritization from Astro2010 Decadal Report

Astro2010 science themes map to the Astrophysics Division themes:

New Worlds	Exoplanet Exploration
Cosmic Dawn	Cosmic Origins
Physics of the Universe →	Physics of the Cosmos

The highest priority science for Physics of the Universe are captured in the PCOS Science Objectives:

Dark Energy: Probe the nature of dark energy by studying the expansion rate of the universe and the growth of structure

Theory of Inflation: Test the theory of inflation by measuring the polarization of the Cosmic Microwave Background.

Black Holes & General Relativity: Probe the properties of black holes and testing General Relativity using x-ray emission and gravitational waves.

ESA's L2 Advanced X-ray Observatory: Athena (Launch: 2028)

- **Mission now in Phase A study in Europe with "Invitation to Tender" issued for industry bids for mission assessment.**
  - First part of mission assessment looked at impact of smaller mirror area, involved many U.S. scientists
- **NASA and ESA are discussing a potential NASA contribution.**
  - ESA Athena Science Study Team: Randall Smith (CfA) is U.S. member. Robert Petre (GSFC) and Michael Garcia (HQ) are ex officio.
  - ESA instrument AO expected mid-2016
- **NASA's budget supports a potential Athena partnership.**
  - NASA will continue investing in technologies likely to be appropriate for an Athena contribution including competed SAT investigations.
  - NASA is budgeting for flight hardware, U.S. participation in the Athena science team, and a U.S. data center and GO program.
- **NASA has suggested the following types of contributions, limited to $100-150M for contributed flight hardware.**
  - Portions of the calorimeter instrument (US & Japan have entered X-IFU consortium)
  - Other possible contributions also under discussion

Future Gravitational Wave Observatory (Launch 2030's)

- **NASA and ESA are discussing a potential NASA contribution to ESA L3 which has the theme "The Gravitational Universe"**
- **NASA is participating in ESA's planned assessments for its L3 gravitational wave observatory via the Gravitational Observatory Advisory Team (GOAT): www.cosmos.esa.int/web/goat**
  - Interim report indicating laser interferometry is the recommended mission approach (per Arvind Parmar, ESA)
- **The partnership likely will be subject to Astro2020 decadal approval**

Deposited Blocking Filters for X-ray Detectors

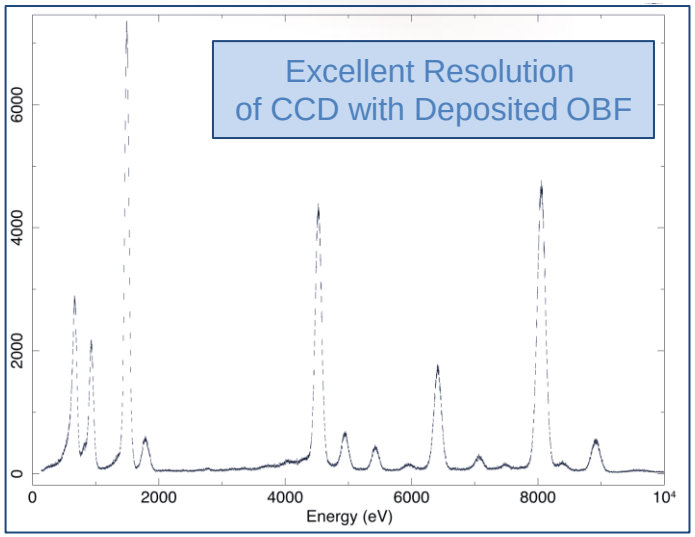
PI: Mark Bautz/MIT MKI

Objectives and Key Challenges:

- Silicon Imaging X-ray detectors require filters to block noise/background from UV and optical light
- Filters must be thin (<300 nm) to transmit X-rays
- State-of-the-art, free-standing filters use fragile, thin substrates
- Objective: deposit blocking filter directly on CCD X-ray detector, eliminating substrate

Significance of Work:

- Filter deposited on detector requires no fragile substrate
- Allows cheaper, more robust sensors (no vacuum housing!)
- Improves QE & makes larger focal planes practical
- Challenges:
- Deposit filter directly without compromising CCD performance
- Deposit sufficiently thin, uniform filters



Approach:

- Exploit existing stocks of (engineering grade/flight spare) X-ray CCD detectors at MIT Lincoln Laboratory
- Screen, thin, passivate, package & apply filters to detectors
- Filter is Al with AlO_2 cap
- Start thick (220 nm Al), get progressively thinner
- Use existing MIT facilities for X-ray characterization
- Use existing & upgraded facilities for optical characterization

Key Collaborators:

- MIT Kavli Institute (Bautz, Kissel et al.)
- MIT Lincoln Laboratory (Suntharalingam, Ryu, Burke, O'Brien)

Current Funded Period of Performance:

Jul 1, 2012 – Dec 31, 2015

Recent Accomplishments:

- Tested devices with alternative back side treatment (10nm MBE vs. 20nm MBE of previous) and 70nm & 100nm thick Al OBF. Optical blocking as expected; OD7 pinhole fraction 0.5%; X-ray performance similar to 20nm MBE devices
- Identified leakage paths through CCD support wafer at long ($\lambda \gtrsim 1000$nm) wavelength, with detection efficiency ~2.5%
  - Significant for REXIS (large visible-light flux)
- Developed underside coating as countermeasures for leakage:
  - Aluminum or 'Z307' paint; REXIS will fly 1 of these

Next Milestones:

- Support tests of REXIS flight CCDs/OBFs, achieve TRL-6

Application:

Every X-ray imaging or grating spectroscopy mission

- Explorers (Lobster, Arcus…)
- "Probes" (AEGIS, N_XGS, AXSIO, WFXT…)
- Flagship (Athena...)

TRLin = 5 ***TRLcurrent = 5*** ***TRLtarget = 5***

Demonstrating Enabling Technologies for the High-Resolution Imaging Spectrometer of the Next NASA X-ray Mission

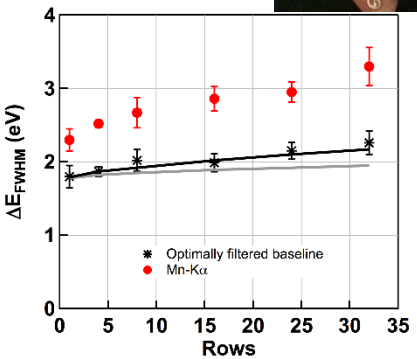
PI: Caroline Kilbourne NASA/GSFC

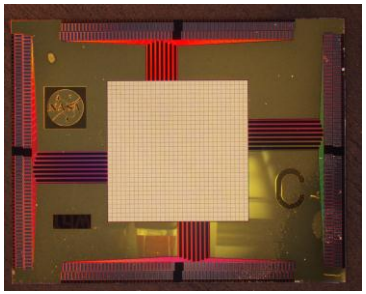
Objectives and Key Challenges:

- Developing large-format arrays of X-ray microcalorimeters & read-out, enabling next generation of high-resolution X-ray imaging spectrometers for astrophysics.
- Advance TRL of the key components of an X-ray microcalorimeter imaging spectrometer from TRL-4 to TRL-5, and to advance a number of important related technologies to at least TRL-4.

Significance of Work:

- Demonstrate multiplexed (3 columns x 32 rows) read-out of 96 different flight-like pixels on a 0.25 mm pitch in a 32x32 (or greater) array with > 95% of pixels achieving better than 3-eV resolution at 6 keV.





Energy resolution at 6 keV in 32 x 32 array with TDM multiplexed read-out of different numbers of rows.

Approach:

- Mo/Au TES thermometers with close-packed Bi/ Au thermalizing x-ray absorbers on a 0.25 mm pitch. Time-division multiplexed read-out.
- For point source array, fine-pitch (0.075 mm) pixels with Au absorbers.

Key Collaborators:

- Joel Ullom, Randy Doriese, Carl Reintsema – NIST
- Kent Irwin – Stanford
- Joseph Adams, Simon Bandler, Richard Kelley, Scott Porter, Stephen Smith - GSFC

Current Funded Period of Performance:

- October 1, 2012 – September 30, 2015
  - Program initially funded as 2-year program, rescheduled as 3-year program due to key participants' involvement with Astro-H

Recent Accomplishments:

- High-resolution spectroscopic capability demonstrated when reading out kilo-pixel array with two multiplexed columns from the array, each of which is multiplexing the read-out of 16 pixels (2/2014).
- Increased speed of read-out amplifier and digital feedback electronics, close to fulfilling the target specifications (12/2014).

Next Milestones:

- Will demonstrate 3x32 multiplexed read-out of standard pixels, and also multiplexed read-out of Hydras and small-pitch pixels (3/2015 – 9/2015).

Application:

- Potential contribution to the X-ray Integral Field Unit Instrument on ATHENA (Advanced Telescope for High ENergy Astrophysics)
- Japanese mission such as DIOS, or X-ray mission as follow-on to ASTRO-H.

TRLin = 4 ***TRLcurrent est. by PI = 4.5*** ***TRLtarget = 5***

Colloid Microthruster Propellant Feed System

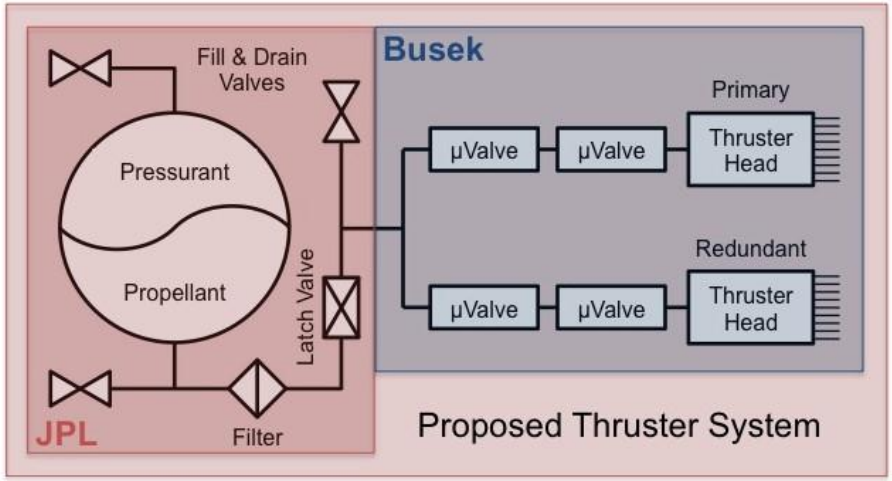
PI: John Ziemer/JPL

Objectives and Key Challenges:

- Replace the heavy (up to 15 kg) spring-loaded bellows design from ST7 with a light-weight pressurized diaphragm tank (≤1 kg)
  - O1: Design tank and feed system with full redundancy
  - O2: Design, fabricate, and test stainless steel diaphragm tank
- Use the new Busek Microvalve (Phase II SBIR and Phase IIe) to reduce complexity while providing redundancy
  - O3: Design, fabricate, and test new Busek Microvalves
  - O4: Integrate and test feed system components to TRL 5

Significance of Work:

- A new, flight-like, fully redundant, higher capacity colloid thruster feed system at TRL 5 can support any gravity wave observatory concept
- A clear path to TRL 6 once the mission and system are defined



Approach:

- Teaming arrangement between flight tank vendor Keystone, Busek for the Microvalve, and JPL to manage, perform I&T
- Use standard liquid-fed propulsion flight design guidelines and practices – the new technology is in the assembled pieces working together, not the propulsion engineering approach
- Four tasks related to each objective, plus a management task, each with a JPL expert lead
- Hold peer reviews at each meaningful milestone: requirements definition, design, and test

Key Collaborators:

- Busek Co., Inc. on Microvalve and systems engineering
- Keystone Engineering on flight-like tank manufacture and test
- JPL electric / chemical propulsion and flight propulsion groups

Current Funded Period of Performance:

- Jan 2013 – Jan 2015

Recent Accomplishments:

- Tank fabrication and TRL 5 tests are complete
- Microvalve fabrication and environmental tests are complete
- Redundant Microvalve subassembly including accumulator and volume compensator has been fabricated and tested for TRL 5
- Tank and supportive feed system components are all at JPL, ready for integration; data system complete

Next Milestones:

- Receive Busek Microvalve subassembly and test full feed system assembly to TRL 5

Application:

- Drag-free gravity wave observatories
- Remove reaction wheels - precision pointing of exo-planet observatory and next generation space telescopes
- Small spacecraft main propulsion

TRLin = 3-4 ***TRLcurrent = 4*** ***TRLtarget = 5***

Telescope for a Space GW Mission

PI: Jeff Livas/GSFC

Objectives and Key Challenges:

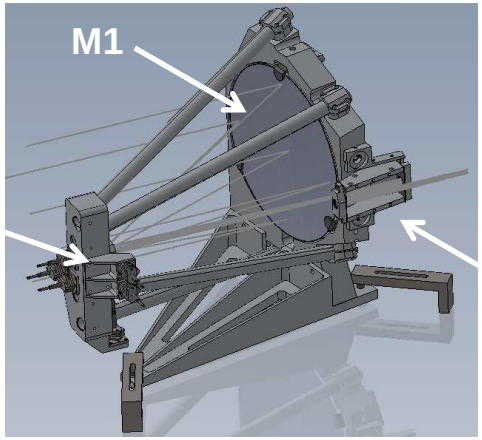
- Establish a complete telescope design meeting optical, mechanical, thermal, and manufacturability NGO requirements for US contribution to L2 mission
- Fabricate and test a prototype

Significance of Work:

Conflicting requirements:

- On-axis design more stable for thermal environment but higher scatter
- Off-axis design lower scatter but more difficult to build (hence expensive)
- Can an on-axis design meet requirements? Or
- Can an off-axis design be manufactured? **YES**

Off-axis Design Prototype in



Approach:

- Use SGO-Mid reference and the ESA eLISA
- "Yellow Book" to generate requirements
- L3/SSG for basic design (off-axis SiC recommended)
- Fabricate a prototype from the design
- Verify for compliance with specifications
- **Concentrate on stray light model validation**

Key Collaborators:

- Code 551: Joe Howard/Garrett West/Peter Blake/Len Seals/Ron Shiri/
- Code 543: John Crow/Justin Ward

Current Funded Period of Performance:

- Oct 2012 – Sept 2014
- Oct 2014 – Sept 2015 no cost extension

Recent Accomplishments and Next Milestones:

- Nov 2013: Telescope RFP terminated: no award
- Dec 2013: Simplified telescope model
- Apr 2014: Telescope mirror specs completed
- Jun 2014: Prototype model contract signed
- Oct 2014: Prototype CDR
- Mar 2014: Prototype Telescope delivery to GSFC
- Apr 2014: Prototype Telescope aligned
- Sep 2015: System-level scattered light model validated

Application:

- Flagship gravitational wave missions (eLISA)
- Laser ranging; precision metrology applications
- Laser communications

TRLin = 3 ***TRLcurrent est. by PI = 3*** ***TRLtarget = 3+***

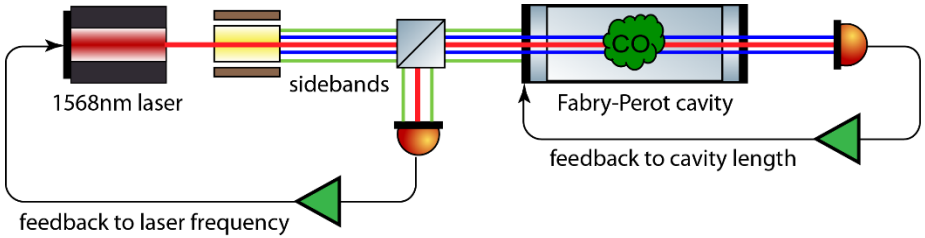
Laser Stabilization with CO

PI: John Lipa/Stanford University

Objectives and Key Challenges:

- Develop a laser operating near 1570 nm with improved noise performance and mid-term frequency stability, for missions that could use a highly coherent light source near the telecom band.
- Performance goals are to achieve substantially lower noise than Iodine-stabilized lasers, the current gold standard for transportable systems. Goal is to achieve an Allan deviation of ~ 2×10^{-15} in a one second measurement time.

Challenge: Noise performance and frequency stability of lasers on short and intermediate time scales: requires dual locking scheme shown on right.



Dual sideband laser locking optics

Significance of Work:

- A highly stable laser simultaneously locked to a cavity and a molecular transition at a Telecom wavelength.

Approach:

- Set up a bench-top model of laser system for CO based on existing system at JILA for C2HD near 1064 nm
- Perform functional tests on system
- Set up a system to allow detailed noise performance measurements
- Upgrade optics and electronics to achieve noise performance goal

Key Collaborators:

- Jan Hall, JILA
- Bob Byer, Sasha Buchman, Stanford
- Shailendhar Saraf, SN&N Electronics, CA

Current Funded Period of Performance:

- Jan 2013 – Dec 2014 (no-cost extension to 6/15)

Recent Accomplishments:

- Laser stabilization system fully functional 6/14
- First ever CO stabilized laser 9/14
- Initial noise measurement 11/14

Next Milestones:

- Noise measurements using frequency comb 1/15
- Noise measurements with reference cavity 3/15
- Documentation of final TRL 5/15

Application:

- Applications would be tests of fundamental physics, gravity wave observation, precision spectroscopy and Doppler, formation flying, trace gas detection.

$TRL_{In} = 3$ $TRL_{PI\text{-}Asserted} = 3+$ $TRL_{Target} = 4$

Planar Antenna-Coupled Superconducting Detectors for CMB Polarimetry

PI: James Bock/JPL

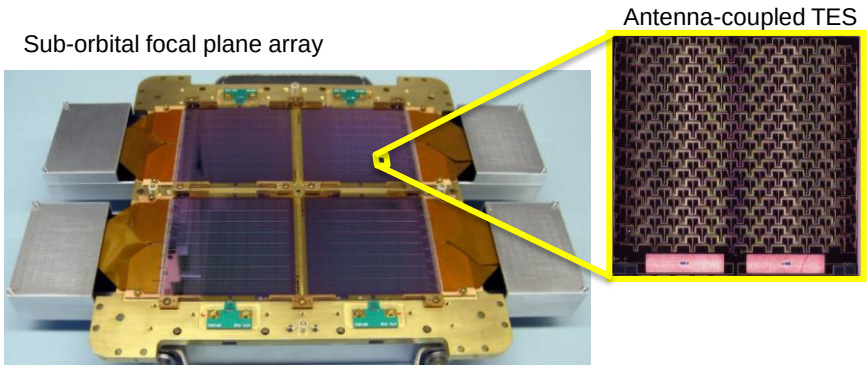
Objectives and Key Challenges:

Advance antenna-coupled superconducting detector technologies for space requirements:

- Antenna design and performance
- Propagation losses
- Develop and test modular focal plane units
- MKIDs for CMB science
- TES stability & cosmic-ray response
- Extended-frequency antennas
- Readout noise stability

Significance of Work:

- RF propagation properties of antennas
- Detector sensitivity, stability, and minimized particle susceptibility



Approach:

- Planar antennas provide entirely lithographed fabrication with no coupling optics
- Design scales to all bands required for Inflation Probe from 30 to 300 GHz
- Detectors provide photon-limited sensitivities in space
- Antennas provide excellent polarization and beam-matching properties
- Modular focal-plane unit for large focal plane arrays

Recent Accomplishments:

✓ Tested sample of far-field beams of tapered antennas
✓ 220 GHz focal planes developed and characterized
✓ Optimized magnetic shielding of 95 GHz focal plane module
✓ Characterized loss and coupling at 250 GHz

Next Milestones:

- Flight of SPIDER for particle response demonstration (Jan 2015)
- Full test of far-field beams of tapered antennas (Mar 2015)
- 40 GHz antenna design (Feb 2015)
- Beam-tests of module in representative optics (April 2015, delayed)

Key Collaborators:

- Koko Megerian, Hien Nguyen, Roger O'Brient, Anthony Turner, Alexis Weber (JPL)
- Jeff Filippini, Sunil Golwala, Howard Hui , Zak Staniszewski (Caltech)
- Chao-Lin Kuo (Stanford)

Applications:

- NASA *Inflation Probe* mission
- Explorer & international CMB missions
- Technology commonalities with Far-IR and X-Ray missions

Current Funded Period of Performance:

- October 2013 – September 2015

TRL_{In} = **3-4** $TRL_{PI\text{-}Asserted}$ = **3-5** TRL_{Target} = **4-6**

Demonstration of a TRL 5 Laser System for eLISA

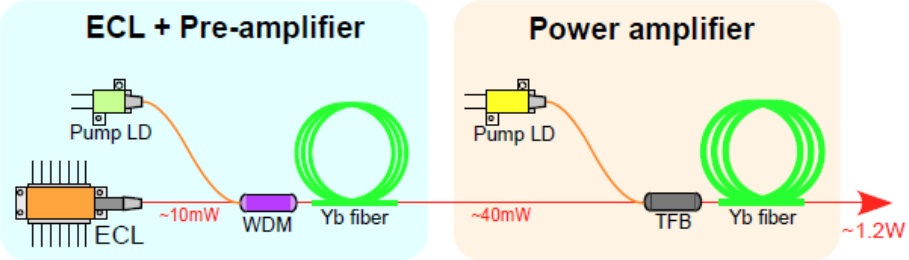
PI: Jordan Camp / GSFC

Objectives and Key Challenges:

- Develop 1.5W light source for the eLISA gravitational wave mission using a Master Oscillator Power Amplifier design with a novel diode laser oscillator (External Cavity Laser, ECL) followed by a 1.5W Yb fiber amplifier, providing a highly stable, compact, and reliable system
- Test the laser system for reliability, and for amplitude and frequency stability, achieving the required noise performance
- Demonstrate system TRL 5

Significance of Work:

- Development, with industrial partner (Redfern Integrated Optics), of space qualified, ultra low-noise oscillator
- Demonstration of low-noise power amplifier with servo controls
- Noise and reliability tests of full laser system



Master Oscillator / Power Amplifier (MOPA) configuration of eLISA laser, including ECL, preamp, and diode pumped Ytterbium (Yb) fiber amplifier

Approach:

- Noise optimization of 1064 nm External Cavity Laser (RIO)
- Reliability study of External Cavity Laser
- Implementation of amplitude and frequency servo controls on full laser system, achieving RIN=10^{-4} at 10^{-3} Hz, frequency noise = 300 Hz / $Hz^{1/2}$ at 10^{-2} Hz, and differential phase noise = 6×10^{-4} rad/$Hz^{1/2}$ at 10^{-2} Hz

Key Collaborators:

- Kenj Numata, Mike Krainak (NASA/GSFC)
- Lew Stolpner (Redfern Integrated Optics)

Current Funded Period of Performance:

- April 2014 – April 2016

Recent Accomplishments and Next Milestones:

- ✓ Developed and constructed 1.5 W laser amplifier
- ✓ Fabricated world's first butterfly package layout 1064 nm ECL
- Rebuild and test 1.5 W laser amplifier (Aug 2014)
- Preliminary laser system test with NPRO (Dec 2014)
- Noise optimization of ECL optical cavity (Dec 2014)
- Preliminary laser system test with ECL (Mar 2015)
- Noise optimization of ECL gain chip (Jun 2015)
- ECL reliability tests (Aug 2015)
- Full laser system noise testing (Jan 2016)
- Full laser system reliability testing (Mar 2016)

Applications:

- Laser source for eLISA Gravitational Wave mission
- Oscillator for ground-based GW LIGO project
- Oscillator for GRACE-II mission

$TRL_{In} = 3$ $TRL_{Current} = 3$ $TRL_{Target} = 5$

Gravitational-Wave Mission Phasemeter Technology Development

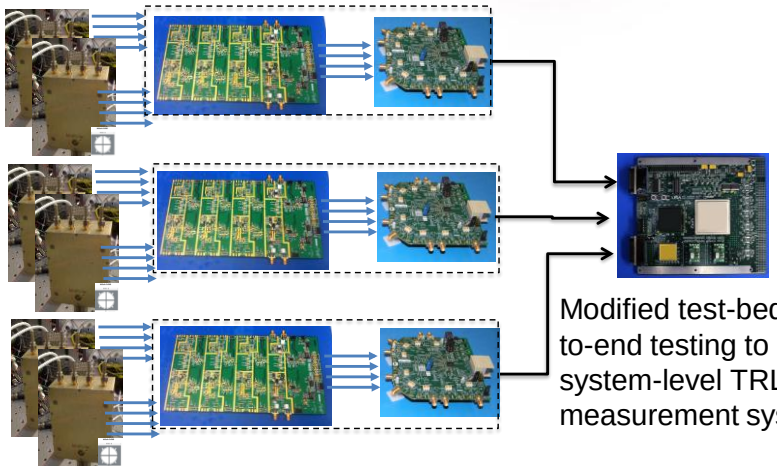
PI: William Klipstein, JPL

Objectives and Key Challenges:

- Advance technology readiness level (TRL) of phase-measurement electronics and demonstrate performance in upgraded interferometer-system-level test-bed providing signals representative of gravitational-wave missions, such as the *Laser Interferometer Space Antenna* (LISA)

Significance of Work:

- High-strain sensitivity requires micro-cycle/Hz$^{1/2}$ precision on a 4-18 MHz beat-note in the presence of laser frequency noise and local clock noise
- We have demonstrated such phase readout in an interferometer test-bed and plan to mature the technology



Modified test-bed for end-to-end testing to advance system-level TRL of phase measurement system

Approach:

- Advance component technologies
  - Advance maturity of analog signal chain
  - Demonstrate wave-front sensing with quadrant photo-receivers
  - Complete design trade for reducing photo-receiver size
- System-level testing
  - Modify interferometer test-bed to include low-light signals
  - Replace COTS components in interferometer test-bed with higher-TRL units and demonstrate performance

Key Collaborators:

- Jeff Dickson, Brent Ware, Bob Spero, Kirk McKenzie, Glenn de Vine, Andrew Sutton (JPL)

Current Funded Period of Performance:

- April 2014 – March 2016

Recent Accomplishments:

- Design 2nd generation analog signal chain (Nov 2014)

Next Milestones:

- Build 2nd generation analog signal chain (Feb 2015)
- Demonstrate wave-front sensing (Sep 2015)
- Implement quadrant photo-receivers in existing test-bed (Dec 2015)

Applications:

- Inter-spacecraft laser interferometry
- Interferometer readout electronics with picometer precision
- Future space mission, e.g., LISA
- Capability supports other interferometry concepts (e.g., exo-planet finding)

$TRL_{In} = 4$ $TRL_{Current} = 4$ $TRL_{Target} = 5$

Development of Fabrication Process for Critical-Angle X-ray Transmission Gratings

PI: Mark Schattenburg/MIT MKI

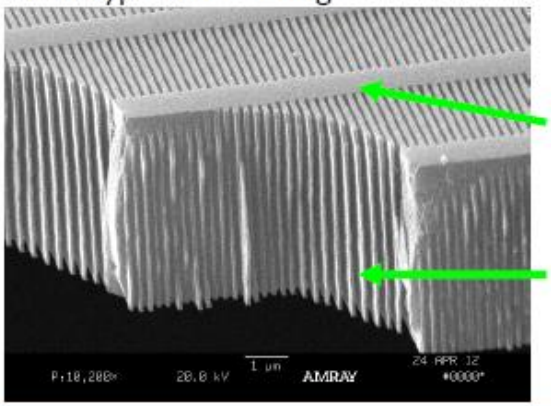
Objectives and Key Challenges:

- Develop key technology to enable a Critical-Angle X-ray Transmission Grating Spectrometer (CATGS), advancing to TRL-6 in preparation for proposed missions or Explorers over the next two decades
- Develop improved grating fabrication processes and procure advanced etching tool and other infrastructure in order to accelerate technology development

Significance of Work:

- Development of nanofabrication technology for the silicon nanomirror grating elements
- Development of microfabrication processes for the integrated grating support mesh

Prototype CAT Grating



Approach:

- Integrated wafer front/back-side fabrication process using silicon-on-insulator (SOI) wafers
- Wafer front side: CAT grating structure + Level 1 support
- Wafer back side: Level 2 support hex-mesh structure
- CAT grating fabricated by deep reactive ion-etching (DRIE) followed by KOH polishing
- Bonded to expansion-matched metal support frame (Level 3 support)
- X-ray testing of prototypes at synchrotrons and MSFC facility

Key Collaborators:

- William Zhang (GSFC)
- Steve O'Dell (MSFC)

Current Funded Period of Performance:

- 1/1/15 – 12/31/16

Recent Accomplishments and Next Milestones:

- Developed improved DRIE process with significantly reduced line bowing. Developed improved backside etch process.
- Demonstrated KOH polish to full 4.0 µm depth following DRIE.
- Demonstrated fully-integrated 31x31 mm^2 grating with KOH polish.
- Developed novel process to produce stress-controlled SOI wafers.
- Acquired and installed new DRIE tool (SPTS Pegasus) in SNL.
- Transferred process to new tool and demonstrated excellent etch profile control.
- Fabricated CAT gratings with record soft x-ray diffraction efficiency.

Application:

- Flagship, Probe and Explorer class x-ray astronomy missions requiring high resolution spectroscopy
- Laboratory x-ray analysis (materials science, energy research)

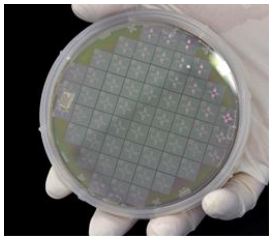
TRLin = 3 ***TRLcurrent = 3*** ***TRLtarget = 6***

Adjustable X-Ray Optics with Sub-Arcsecond Imaging

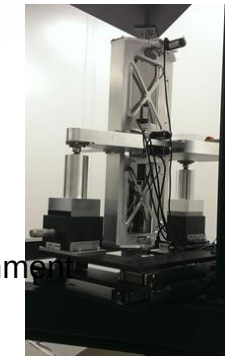
PI: Paul Reid/SAO

Objectives and Key Challenges:

- Develop adjustable light weight x-ray optics with sub arcsecond performance
- Create the enabling optics technology for a large aperture high resolution x-ray mission (SMART-X) for selection at the next Decadal Survey



Adjustable mirror with strain gauges on every cell



Mirror pair during alignment

Significance of Work:

- Sub-arcsecond optics fabricated with traditional methods are too heavy; light, thin replicated optics performance is limited to ~7”
- By coating thin glass optics with piezoelectric material, whose shape can be altered by applying a voltage, we can correct unwanted figure distortions improving performance to <1”

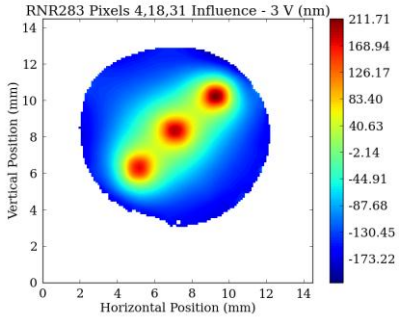


Figure change from three non-adjacent piezo cells energized simultaneously, measured with Shack-Hartmann wavefront sensor

Approach:

- Deposit piezoelectric material (PZT) on conical thermally formed glass
- Mount and align a piezo coated mirror pair
- Correct unwanted figure distortions by adjusting the voltage applied to the piezo material
- Prove out performance using x-ray testing

Key Collaborators:

- Susan Trolier Mckinstry (PSU)
- Brian Ramsey and Stephen O’Dell (MSFC)

Current Funded Period of Performance:

- Feb 2013 – Jan 2016

Recent Accomplishments:

- Demonstrated predicable, repeatable deformations on cylindrical optics that matched values predicted by models
- Completed mounting and aligning of mirror pair using first generation mount; starting mount design improvement phase
- Deposited strain gauges on piezo cells
- Calculated PZT life of > 1000 years from accelerated lifetime test results

Next Milestones:

- Mount / align improved conical optics in TRL-4 mount

Application:

- Large aperture and high resolution x-ray mission for the 2020s (Square Meter Arcsecond Resolution X-ray Telescope, SMART-X)

TRLin = 2 ***TRLcurrent est. by PI = 3*** ***TRLtarget = 4***

Reflection Grating Modules: Alignment and Testing

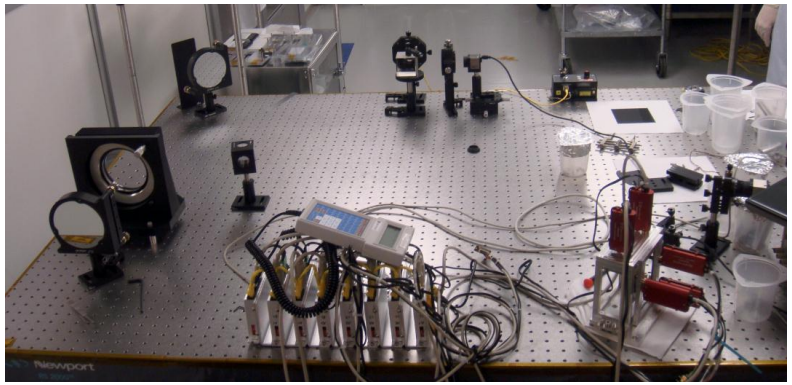
PI: Randall McEntaffer/University of Iowa

Objectives and Key Challenges:

- To increase the TRL of off-plane gratings
- Align multiple gratings into flight-like modules
- Performance test aligned gratings for spectral resolving power
- Environmental test modules with performance verification

Significance of Work:

- Enables future spectrometers to accomplish key soft X-ray science goals that require high sensitivity combined with high spectral resolving power



Upper left: Metrology system for grating alignment,
Lower right: Grating module with pico actuators

Approach:

- Leverage from previous SAT and supporting programs to supply gratings and preliminary designs
- Align gratings into module using proven methods
- Use Stray Light Facility at MSFC for performance and environmental testing

Key Collaborators:

- Jessica Gaskin, MSFC
- Will Zhang, GSFC

Current Funded Period of Performance:

- 01/2015 – 12/2016

Recent Accomplishments:

✓ Initial testing of prototype gratings has been accomplished
✓ Alignment tolerances are known
✓ Initial modules have been fabricated and tested

Next Milestones:

- Test active and passive module mounts (Year 1)
- Increase fidelity of module mount and alignment methodology (Year 1 – Year 2)
- Test flight-like aligned module (Year 2)

Application:

- Suborbital rocket missions - OGRE
- Small Explorers - Arcus

$TRL_{In} = 3$ $TRL_{PI\text{-}Asserted} = 4$ $TRL_{Target} = 6$

Next Generation X-ray Optics: High-Resolution, Lightweight, and Low-Cost

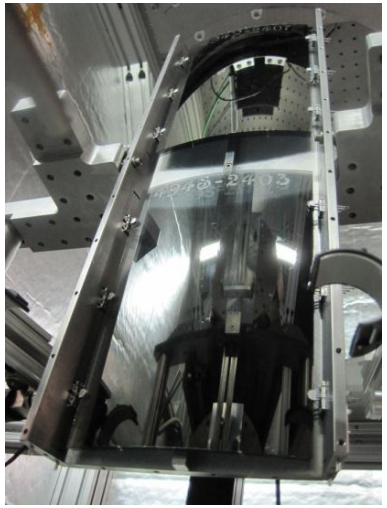
PI: William W. Zhang/GSFC

Objectives and Key Challenges:

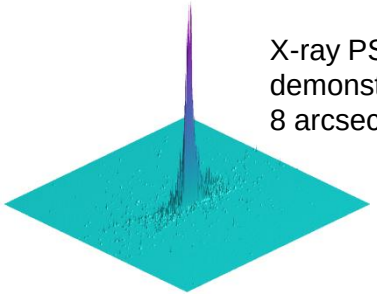
- Develop a lightweight X-ray mirror technology achieving better than 5" HPD angular resolution, advancing it to TRL 5, and readying it to enable missions planned for both 2010's and 2020's
- Mature and perfect this technology to minimize cost and schedule
- Prepare ways to achieve significantly better than 5" resolution while keeping mass and cost at similar levels

Significance of Work:

- Fabrication and metrology of mirror segments
- Alignment and bonding of mirror segments



A Technology Development Module (TDM) containing three pairs of parabolic-hyperbolic mirror segments that has passed both performance and environmental test



X-ray PSF demonstrating 8 arcsec HPD

Approach:

- Make mirror substrates by slumping glass or polishing silicon
- Maximize X-ray reflectance using magnetron sputter or atomic layer deposition
- Measure performance using interferometer, null lens, and interferometric microscope
- Align mirror segments using Hartmann tests
- Develop precision epoxy bonding techniques

Key Collaborators:

- Michael Biskach, Kai-Wing Chan, Ryan McClelland, Timo Saha (NASA/GSFC)
- Stephen O'Dell (NASA/MSFC)

Current Funded Period of Performance:

- October 2014 – September 2016

Recent Accomplishments:

✓ Repeatedly co-aligned and bonded multiple mirror pairs, achieving 8" HPD X-ray Point Spread Function (PSF, see lego plot above)

Next Milestones:

- Transition from using glass substrates to using single crystal silicon substrates by December 2015
- Build and test technology development modules with silicon substrates and achieve 5" HPD by December 2016

Applications:

- Backup technology for ESA's Athena mission
- Flagship and probe-class X-ray missions
- Explorer-type X-ray missions
- Sounding rocket and balloon experiments
- Medical research and diagnosis

$TRL_{In} = 3$ $TRL_{PI\text{-}Asserted} = 4$ $TRL_{Target} = 5$

Fast Event Recognition for the ATHENA Wide Field Imager

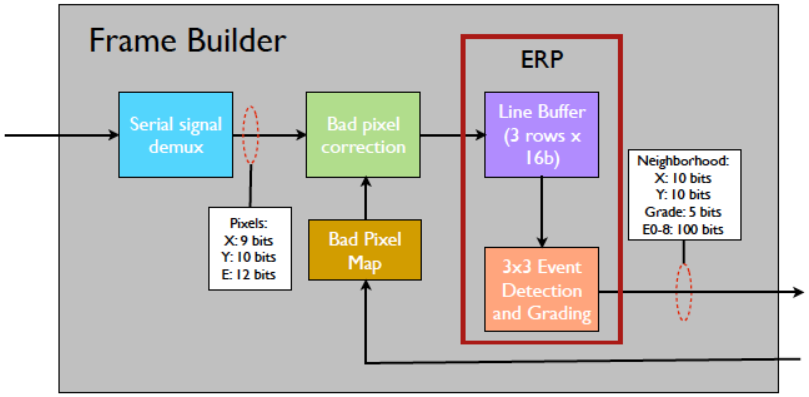
PI: David Burrows / PSU

Objectives and Key Challenges:

- High-speed event recognition and data compression

Significance of Work:

- Required for future proposed X-ray imagers, including *Athena* WFI (ESA L2), *JANUS* XCAT (EX), *XTiDE* XCAT (SMEX), *Arcus* (ISS), *X-ray Surveyor* (Astrophysics Roadmap)



Approach:

- FPGA coding/simulation/testing
- Testing with fixed patterns up to 1GB/s
- Testing with real X-ray data up to 1GB/s

Key Collaborators:

- Dr. Karl Reichard, Eli Hughes (PSU/ARL)
- Dr. Zach Prieskorn, Dr. Tyler Anderson (PSU/ECOS)
- Dr. Mark Bautz (MIT), Dr. Steve Murray (SAO)

Current Funded Period of Performance:

- 1/2015 – 12/2016

Recent Accomplishments:

✓ Initiated internal funding codes, ordered development kit

Next Milestones:

- Design Review, July 2015

Applications:

- Including *Athena* WFI (ESA L2), *JANUS* XCAT (EX), *XTiDE* XCAT (SMEX), *Arcus* (ISS), *X-ray Surveyor* (Astrophysics Roadmap)…

$TRL_{In} = 3$ $TRL_{PI\text{-}Asserted} = 3$ $TRL_{Target} = 4$