The Warm-Hot Intergalactic Medium Explorer (WHIMex) – A Response to the Concepts for the Next NASA X-ray Astronomy Missions RFI, Solicitation: NNH11ZDA018L

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Northrop Grumman supported the Whimex mission concept development effort and established that this mission could be realistically performed within the $200M cost and schedule envelope of the Explorer 2011 AO. We believe that high resolution X-ray Spectroscopy missions are possible at modest cost without IXO. We attach the following publically released paper to show how this can be done, and would be happy to present our mission concept at a workshop.

ABSTRACT

The WHIMex X-ray observatory will provide an order of magnitude improvement in sensitivity and spectroscopic resolution, ushering in a new era in astrophysics. With a resolution ≥ 4,000 and collecting area ≥250 cm^2 in the 0.2-0.8 keV band, WHIMex will greatly extend the spectroscopic discoveries of Chandra and XMM with a low-cost, highly-productive Explorer mission. WHIMex's spectra will provide a wealth of new information on the physical conditions of baryonic matter from the local regions of our Galaxy out to the Cosmic Web and the large-scale structures of the Universe. WHIMex achieves its high level of performance in a single-instrument, affordable package using X-ray optical technologies developed for IXO and NuSTAR by academic, industrial and government research centers. The technology readiness levels of all the components are high. We propose building an optical test module and raise the optical system readiness to TRL 6.

1. INTRODUCTION

The Warm Hot Intergalactic Medium Explorer (WHIMex) was proposed as an Explorer 2011 mission which, if selected for development, would have launched in 2017 into a low Earth orbit to obtain high resolution X-ray observations of highly ionized material in Active Galactic Nuclei, Galactic Sources, and the filamentary structure of the Cosmic Web (Figure 1). The WHIMex payload consists of a grazing incidence X-ray telescope with a 7-m focal length, off-plane reflection gratings and a CCD detector. The spacecraft bus avionics are mounted on panels attached to the telescope structure. Two solar arrays provide 632 W of power for the 655 kg observatory. Mission Operations for WHIMex will be provided by the Laboratory for Atmospheric and Space Physics at the University of Colorado and Science Operations will be provided by the nearby Center for Astrophysics and Space Astronomy. WHIMex builds on recent advancements in X-ray mirror and gratings technology to provide an order of magnitude improvement in spectroscopic performance over existing missions. It will demonstrate technologies planned for the International X-ray Observatory (IXO) and achieve an important subset of IXO science objectives, a decade earlier at 10% of the cost.

2. SCIENCE INVESTIGATION

2.1 Science Goals

The bulk of the baryonic (regular) matter in the Universe resides in the vast, empty stretches between the galaxies. However, due to the extremely low density of this matter its existence has only been inferred; rather than observed. This baryonic matter is thought to result from the gravitational collapse of moderately over-dense, dark-matter filaments of the Cosmic Web. The chemical enrichment of the Cosmic Web, in turn, appears to arise from galactic super winds and early generations of massive stars.

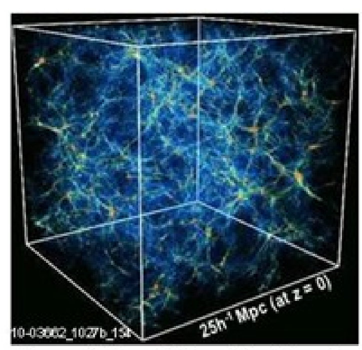


Figure 1. Simulation of the Cosmic Web. WHIMex will detect absorption lines in the high-density filaments of the Cosmic Web.

The goals of the WHIMex mission are to: Understand the cycles of matter on a cosmological scale; Detect the thin primordial gas from which modern galaxies were formed; Find the "missing" low-redshift baryons that may reside in a warm-hot intergalactic medium (WHIM); Constrain models of evolution of structure in the Universe; Understand the behavior of giant black holes, the accretion disks that feed them, the formation of relativistic jets, and the feedback of matter from the central engine into the interstellar medium (ISM) and intergalactic medium (IGM); and Explore high-energy phenomena in a fascinating array of energetic Galactic sources. Study high-temperature processes including gravitational compaction, shock-heating of plasmas, and the role of magnetic fields.

These goals are made achievable by an order of magnitude improvement in both spectral sensitivity and spectral resolution. At the WHIMex resolution of $R \equiv \lambda/\Delta\lambda = 4000$, absorption lines in the spectra of distant X-ray sources are resolved down to their thermal width, providing the temperature and velocity information needed to attack astrophysical problems. To study the Cosmic Web, we will measure absorption lines from species such as O VII and O VIII, the primary tracers of 400,000 to 3,000,000 K gas. These lines, which are too weak and narrow to confidently study with existing instruments, become accessible with the high sensitivity of WHIMex.

2.2 WHIMex Performance Compared to other Missions

X-ray spectroscopy has evolved over the last 50 years, from the first missions to broad-band observatories covering the energy band from 0.2 keV to 20 keV. For technological reasons, the spectral resolving power of X-ray spectrographs has lagged far behind the optical, infrared, and ultraviolet. The Chandra and XMM gratings achieved R = 400 (750 km/s resolution), which is well short of the 75 km/s needed to see the intrinsic thermal widths of the lines. The next major advance in X-ray astrophysics requires spectroscopy with resolution elements V < 100 km/s (R > 3000), enabling far more sensitive surveys of absorbers in the WHIM and other hot plasmas, opening up a new set of diagnostics of the physical state of over 90% of the baryons in the universe. The WHIMex gratings are designed to provide R = 4000 (75 km/s) resolution (Figure 2), comparable to the planned performance of the IXO gratings and micro calorimeters. The longer exposure times allowed in a dedicated Explorer mission more than make up for the somewhat lower effective area of WHIMex compared to IXO. WHIMex will thus offer, for the first time, both high-resolution and high-SNR on a significant number of X-ray targets throughout the Galaxy, in external galaxies and quasars, and in the hot IGM.

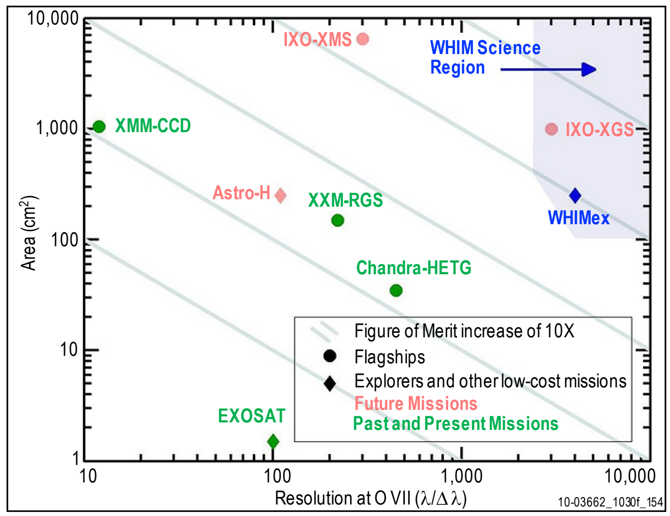


Figure 2. The spectral resolution at 0.57 keV and effective collecting area of WHIMex compared to other missions.

2.3 Baseline Mission

The baseline science mission includes targets that will probe the WHIM, AGN outflow targets, and a variety of other targets of interest (mostly galactic sources). The WHIM target list was selected from several sources, mostly the ROSAT and Swift/ Burst Alert Telescope-detected AGN samples, with a few additional sources from XMM and ASCA studies. Objects with $z < 0.1$ were excluded from the survey as they do not provide a long enough intergalactic path length. For the ~100 most promising objects, we searched archival flux measurements with ROSAT, XMM, ASCA, Suzaku, and Swift. When there were multiple fluxes (0.5-2.5 keV band), we use the flux at the 75% quartile point, reflecting our strategy of observing objects when they are above average brightness. The AGN were sorted by observing time needed, per unit redshift, to detect a 2 mÅ line. From the final list of 50 targets, 26 are given as our observing list. To create an AGN-outflow target list, our first subsample contains the nine best studied warm absorbers. All of these are low-luminosity and low-redshift objects ($z<0.05$) and will require a total of 7.2 Mega seconds (Ms) to observe to SNR>10. The next subsample contains higher-redshift and higher-luminosity objects that were never targeted before with X-ray spectral observations and that can yield the required SNR>10 in 1-2 Ms. We will be able to target six objects with $0.1<z<0.5$ and seven objects with $0.5<z<3.3$, with bolometric luminosities from $10^{45} – 10^{48}$ ergs/s. We conservatively expect to detect ~20 mass-ejection episodes in each sample. Such numbers of well-studied episodes will go a long way towards establishing the contribution of X-ray absorption outflows to a variety of cosmological processes. To create the Galactic target list, we used a set of objects previously observed with Chandra or XMM gratings, for which our understanding could be improved by better spectral or temporal resolution. These include a wide variety of targets including accreting stars, active stars, high-mass stars, white dwarfs, high- and low-mass X-ray binaries, novae, and neutron stars.

3. INSTRUMENTATION

Our Off-Plane Grating Spectrograph (OPGS) is uniquely suited to the study` of the Warm-Hot Intergalactic Medium (WHIM) and Active Galactic Nuclei (AGN), and offers a low cost, low risk approach to addressing our science goals. We chose an off-plane grating architecture because it provides two major advantages over other X-ray spectrograph architectures: 1) off-plane gratings provide very high diffraction efficiency by operating in a full groove illumination geometry; 2) at grazing incidence, errors of figure, alignment and scatter are predominately in the in-plane direction; off-plane gratings disperse perpendicular to that direction, relaxing the optical assembly and figure tolerances for a given resolution. The OPGS concept[1,2,3] has been proven on many suborbital rocket experiments[4,5,6] and can provide the necessary spectral resolution. An overview and performance estimates for the WHIMex OPGS are shown in Figure 3.

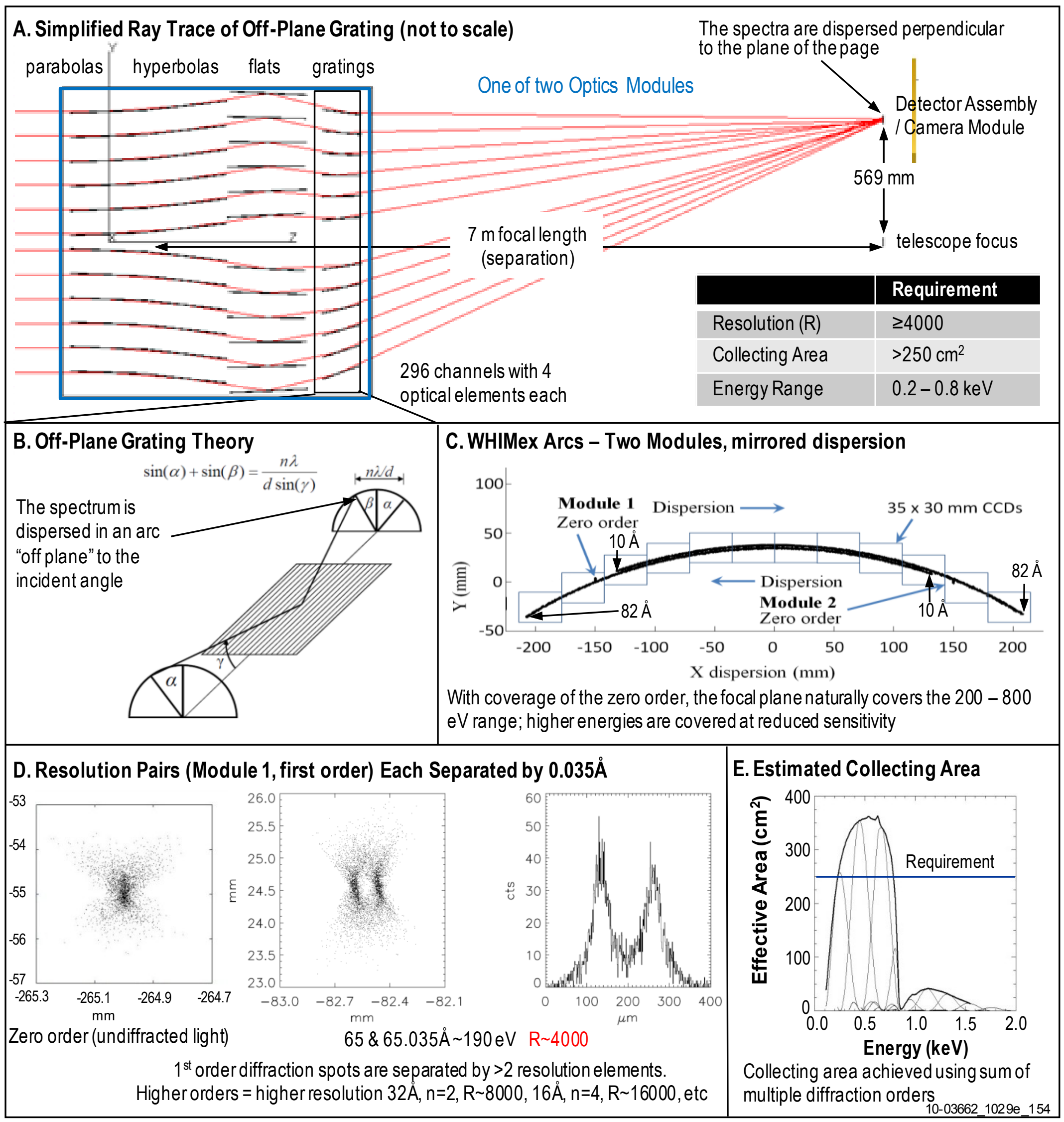


Figure 3. Overview of the Off-Plane Grating Spectrograph Design and Performance. The WHIMex OPGS consists of two nearly identical Optics Modules and a CCD camera to detect the X-ray spectra. High resolution and a large collecting area are achieved in a modest physical package.

In the energy range 0.1–0.9 keV, the Low-Energy Transmission Grating (LETG) instrument on the Chandra observatory achieves R~1000 but has an effective collecting area well under 100 cm^2. The X-ray Multi-Mirror Mission (XMM) Reflection Grating Spectrometer (RGS) (with in-plane reflection gratings) has greater collecting area but only achieves R~200-300 in the energy range 0.35–2.5 keV. Both lack the resolution needed to resolve WHIM features. The OPGS concept is ideal for this purpose, combining high efficiency and resolution with relaxation of figure errors and subaperturing of the beam. With subaperturing, R=4000 can be achieved in the 0.2–2 keV range[2,7] despite the modest half power diameter of ~15 arcsec expected from the thin shell optics.

In our implementation we divide the spectrograph into its principal components. Figure 4 shows an overall view of the instrument (without multi-layer insulation (MLI)) including a TRL estimate for the four primary technologies. Each of the components of the spectrograph is described in detail below. Of these, the Charge Coupled Device (CCD) technologies and deployable bench components are at TRL 6. A technology development program is planned for the optical components, although the mirrors themselves will reach TRL 9 when NuSTAR is launched in 2012. Figure 5shows a block diagram of the payload and its interfaces to the spacecraft. Unlike a traditional payload that is small and bolted to a spacecraft bus, WHIMex is a payload with spacecraft bus components attached to it. Thus the payload design drives the space vehicle configuration.

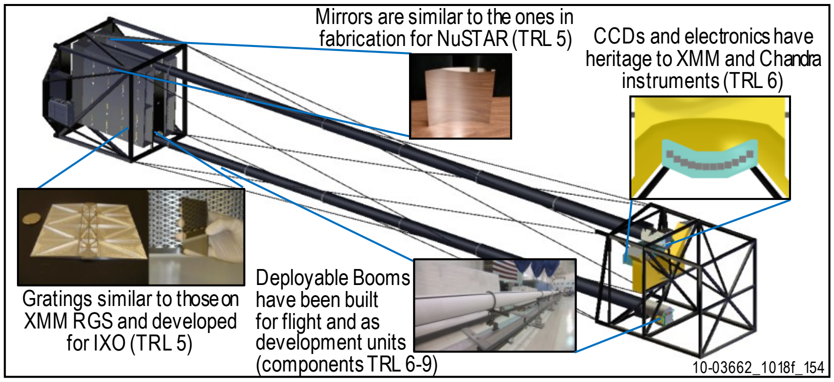


Figure 4. Instrument Overview. The WHIMex spectrograph uses technologies developed under previous efforts to achieve world class science with low cost & low risk.

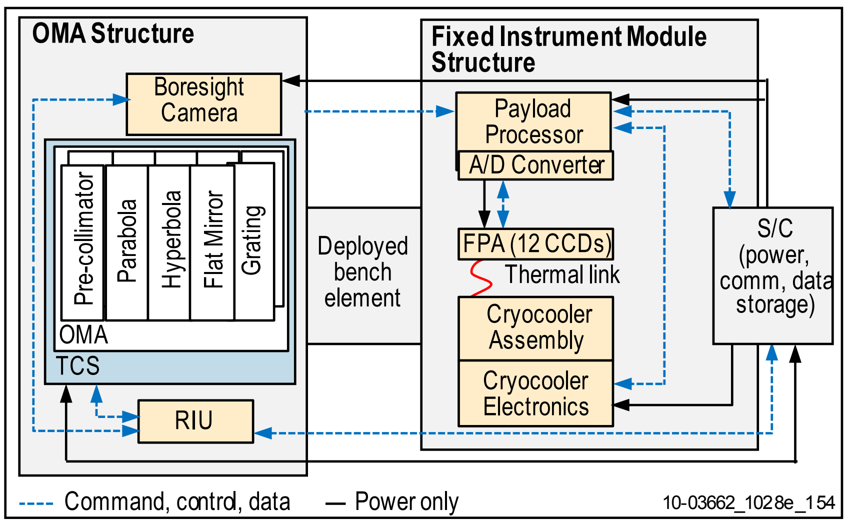


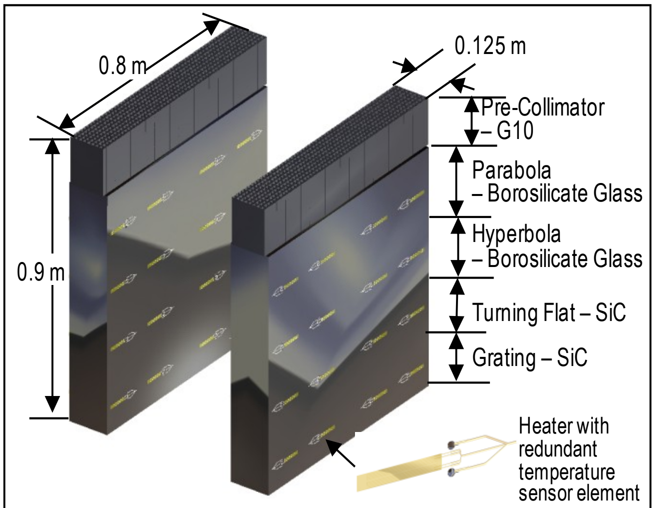
Figure 5. Payload Block Diagram. Simple interfaces to the spacecraft bus provide high reliability and low risk during integration and test.

3.1 Optics Module Assembly

To provide R=4000 spectral resolution and >250 cm^2 collecting area, there are two independent optics modules (OMs). Each covers the spectral range but their spectra are dispersed in opposite directions on the detector and slightly displaced (Figure 3C). This reduces the size of the focal plane array (FPA).

The optical design for WHIMex was developed with Parsec Technology's Interactive Ray Trace (IRT) software which was previously used and verified against numerous flight instruments including those on Chandra, XMM and Beppo-SAX. The key design parameters include the position, graze angle, focal length, and width and height of the paraboloid-hyperboloid (P/H) mirror pairs; the groove density, graze angle, orientation, blaze angle of the gratings; and optical coatings. The effective area of each design was evaluated using University of Colorado proprietary software as verified against IRT.

The final design (Figure 6) provides a good balance of performance and practicality. The heart of each Optics Module (Figure 3A) is a Wolter Type-1 telescope with multiple mirror pairs and a 0.5° graze angle. This telescope is followed by an equal number of flat mirrors and gratings to complete the OM design. The focal length of the optics drives the overall instrument design. For F=7m, there is a good design option using P/H mirrors similar to those being built for the Nuclear Spectroscope Telescope Array (NuSTAR) with an achievable bench design and FPA size. WHIMex nests *identical* P/H pairs (1/12 of a cylinder) which have individual foci. This novel approach allows each of the 296 P/H pairs (per OM) to have the same figure, greatly simplifying the fabrication of the optical elements and ensuring that spares are available during the OM assembly.



Component	Number
Precollimator	2
Parabola/Hyperbola pairs (X-ray mirrors, 0.4 mm thick)	592 pairs, 1184 elements
Turning flats (1 mm thick)	592
Gratings (1 mm thick)	592
Thermal Control Subsystem	64 heaters, 128 sensors
Structure	2

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Figure 6. Optics Module Details. Each OM includes 296 sets of 4 optical elements, plus a Thermal Control System to provide a stable temperature to maintain alignment.

Identical flat mirrors then steer the X-rays to a common focus. Despite the additional reflection the efficiency remains high given the shallow graze angle on all optics. Finally, off-plane gratings disperse the light tangentially to the reflection direction (Figure 3B), with each module producing a complete (offset) spectrum. The gratings are fanned in an array such that each grating is illuminated at the same angle, reducing astigmatism in the resulting spectra. All of the gratings in a single OM are identical, with the same benefits as for the P/H pairs and flats. A grating graze angle of 2.7° is used, with nominal tolerances for fabrication[8].

WHIMex exploits the effects of subaperturing in the dispersion direction by using only a small portion of the total annulus. This causes the image of a point source to no longer be mapped into the familiar airy disk, but instead resembles a long, skinny "bowtie" (Figure 3D). This bowtie is longer in the in-plane direction than it is in the off-plane because the scatter and figure errors are primarily in the in-plane direction[2]. Our design has a 100 mm clear aperture for each of the optical elements, which results in the bowtie having a ~10:1 angular resolution aspect ratio of the in-plane to off-plane direction. Routine testing of NuSTAR and IXO developmental P/H channels have produced off-plane profiles of 1.4-arcsecond Full Width at Half Maximum (FWHM). Combined with well known alignment and line of sight (LOS) errors, our current capabilities give an off-plane spectral line width of 2.19 arcsec (3σ), well within the 2.63 arcsec required for $R \geq 4{,}000$. This gives a 1.45 arcsec margin for additional alignment, integration, and LOS errors. To maintain this level of performance, preliminary analysis shows the temperature of the OM must be held at 293±1 K, requiring a thermal control subsystem (TCS) to be implemented for the OM which consists of temperature sensors, heaters, and a control system as shown in Figure 5.

The P/H pairs would be fabricated at NASA Goddard Space Flight Center (GSFC) by slumping 0.4 mm thick borosilicate glass sheets onto precisely figured parabolic and hyperbolic fused quartz mandrels in a process developed and matured for IXO[9]. For WHIMex, all of the P (and H) mandrels are identical. Glass slumping can consistently fabricate P/H pairs which meet the needed optical figure quality. After slumping, the bare glass substrates are coated by an evaporative process with 10 nm Ni to maximize their X-ray reflectivity in the energy band.

The flat mirrors would be fabricated with Silicon Carbide with a chemical vapor deposition SiC top layer polished to a $\lambda/2$ surface figure with ~6Å roughness. The Coefficient of Thermal Expansion (CTE) of SiC is closely matched to the P/H optics. The grating substrates are similar to the flats, with a trapezoidal crossection to minimize edge thickness and mass while maximizing structural rigidity. A master grating will be replicated onto each substrate using nanoimprint lithography and then Ni coated for reflectivity. While many replicas are required, only two masters are needed, one for each OM. By dispersing in opposite directions, spectral redundancy at the FPA avoids the loss of wavelength coverage in case a CCD fails, and provides full spectral coverage for the gaps between CCD chips.

The masters are fabricated with standard processes at HORIBA Jobin-Yvon. The master groove profile will be radial to match the beam convergence of the Wolter Type-1 optics, blazed at an angle of 24°, with a density of 5500 grooves/mm. This groove prescription disperses the peak of the blaze function (70 Å in 1st order) 280 mm away from zero order. The required 70 µm Full Width at Half Maximum (FWHM) spectral line then results in a resolution of R=4000.

All elements will be qualified optically and mechanically at GSFC before being aligned and bonded into module housings. The module housing is made of KOVAR whose CTE is nearly identical to that of the mirror elements, relaxing the required bulk temperature control of the modules to an estimated stability of ±1K, achievable with the TCS. To meet the tight alignment tolerances, the mounting process developed for the IXO is used, slightly modified to allow bonding into the rectangular OMs. At the end of the mounting process, the mirror element is tested again by Hartmann tests to ensure both its alignment and figure; this is repeated for the installation of the flat and grating.

The completed OMs will be fully verified at NASA Marshall Space Flight Center (MSFC) in their X-Ray Calibration Facility and subjected to thermal and dynamic environments, following the pathfinder process validation. They are then integrated into the OMA structure which provides support and an interface to the deployable optical bench. The electronics boxes for the TCS, and a boresight camera (BC) that provides the high angular resolution (0.5arcsec 3σ) pointing knowledge, are also integrated to the OMA. The BC provides the relative pointing knowledge (at 4 Hz) needed to reconstruct the spectra in the presence of low frequency image motion. The BC is a modified version of the spacecraft's Terma star tracker with higher angular resolution over a smaller field of view.

3.2 Detector and Electronics Assembly (DA)

The spectra produced by the OMs are sensed by the detector assembly (Figure 7). The DA includes the Focal Plane Array, control electronics, a cryocooler to provide the necessary FPA cooling, and a baffle to control stray light and minimize the number of charged particles which reach the FPA. Magnetic diverters are included in the design to help deflect low energy electrons from the FPA, reducing the background flux. The baffle also provides a portion of the radiation shielding required for the FPA. The FPA has 12 large format CCDs covering the arc of the spectra, mounted to a large cold plate that provides thermal mass, structural support, and additional radiation shielding. The DA includes the CCD electronics analog/digital converters and the payload processor, which provides the interface to the SC, as well as time tagging, packetizing, and combining the photon and BC data. The CCDs are 35 x 30 mm, back-illuminated, frame transfer devices with a pixel pitch of 15µm. The CCDs include an aluminum light blocking filter on their surface to reduce the effects of optical stray light. To ensure the dark current is <10 e$^-$/s/pixel, the CCDs must be cooled to ~190K. The exact value is not tightly constrained, which allows flexibility to the on-orbit thermal environment, but the temperature must be precisely controlled to better than ±0.5 K to

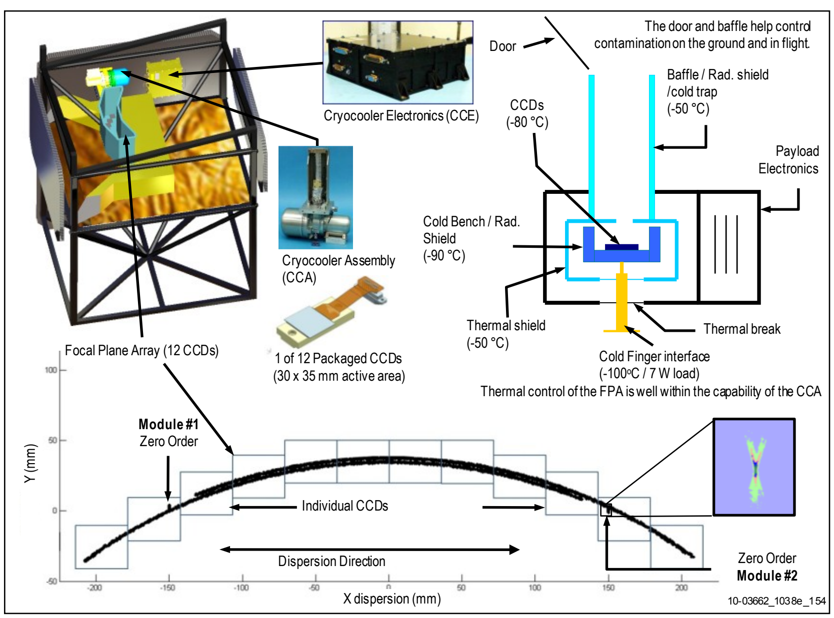

Figure 7. Detector Assembly. The two module Optics Module Assembly is matched to a 12 CCD Focal Plane Array with the modules dispersing their spectra in opposite directions.

maintain uniform response and the ability to accurately subtract the dark current. This is necessary to adequately sort the overlapping spectral orders at each spatial location on the FPA. At these temperatures, the cooling requirement is only marginally within the capability of thermo-electric coolers (TECs) and our LEO orbit makes radiative cooling very restrictive for science operations. Thus we selected a high efficiency pulse-tube cryocooler (HEC) to provide the cooling, at lower power and larger cooling capacity than a TEC. This unit is TRL 9 and has provided decades of on-orbit operation for other missions.

The FPA is controlled by the focal plane electronics, housed in an electronics box in close proximity to the FPA, which reads out the CCDs, provides all the voltages and command signals, and converts the analog output signals into digital data. These data are sent to a payload processor in the same electronics box which strips the X-ray event from the raw image data, reducing them to "event data": location on the FPA (detector #, x, y pixel), signal level, and timestamp. This processor also takes the BC pointing data and incorporates them with the event data before sending the data to the solid state recorder (SSR) on the SC. This processor provides the interface with both the cryocooler (via RS-422) and the SC processor (via MIL-STD-1553). It accepts command sequences from the ground, outputs housekeeping telemetry (e.g., FPA temperatures, cryocooler data), and performs fault management functions for the payload. These functions are standard for payload electronics, using mature technologies, with heritage to Chandra, XMM, and many other missions.

3.3 Deployable Optical Bench (DOB)

High spectral resolution and high collecting efficiency drive our optical design to a moderately large focal length. An F = 7 m system meets our optical design criteria and can be accommodated for launch. While a flagship mission could be launched at this focal length using a fixed optical bench (e.g., Chandra), the launch vehicles available to WHIMex require a deployable system to fit into the available payload fairings. We scaled down the deployment concept NG developed for IXO to achieve the separation required between the OMA and DA after launch. The DOB must provide the positional accuracy between the two units needed to ensure the spectra fall on the CCD array and provide the stability to needed to achieve the spectral resolution required by the science goals.

The DOB (Figure 8) includes the structure supporting the DA, the deployable bench segment, and the OMA fixed structure. We achieve the required separation with NG Astro Aerospace's flight proven technology, using two telescoping Astro Booms, and adjustable tensioning lines to accurately position the OMA and DA and align them with each other. A thermal control tent surrounds the booms and lines to minimize the temperature gradients created by variable sun angles on the deployed system. The details of the deployment mechanisms and thermal control system are discussed in Section 4. The component TRLs are largely 9, with a few elements such as the sections of the boom at TRL 6.

4. MISSION IMPLEMENTATION

We have developed a low-risk approach for meeting our science objectives by using high TRL components and pre-Phase A analyses in key technical areas and leveraging our team's extensive experience building, integrating, and testing X-ray telescopes and operating low-cost missions. The following section describes our mission concept; the flight segment, ground segment, and our plans for launch and mission operations.

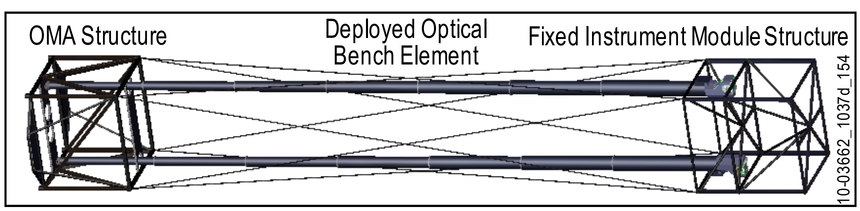

Figure 8. Deployable Optical Bench. The DOB architecture allows it to be accommodated in the smaller fairings of the available launch vehicles.

4.1 Mission Overview

Figure 9 shows the key elements of the WHIMex mission, the mission schedule, our concept for launch and mission operations, and the key characteristics of the observatory.

The observatory has an optical bench that connects the Optics Modules to the Detector Assembly and deploys after launch to provide the required 7-m focal length for the X-ray telescope. The spacecraft avionics are mounted on panels that are attached to the fixed instrument module structure (Figure 8), as are two solar arrays that provide power for the observatory. The spacecraft attitude control system has two star trackers on the avionics panels provide 9 arcsecond (3-sigma) attitude knowledge, and reaction wheels that provide 45 arcsecond (3-σ) attitude control. A bore-sighted star tracker in the OMA provides 0.3 arcsecond line-of-sight knowledge for post-facto data analysis. The Command and Data Handling system collects science and engineering data at an average rate of 3.44 kbps and stores until the next ground contact. The observatory communicates with the ground system at S-band via NASA's Near Earth Network once every three days during normal science operations.

The Mission Operations Center for WHIMex will be located at the Laboratory for Atmospheric Physics on the University of Colorado's East Campus Research Park with capabilities currently utilized for Kepler mission operations. The Science Operations Center will be in the nearby Center for Astrophysics and Space Astronomy. The WHIMex data will be archived and distributed via NASA's High Energy Astrophysics Science Archive Research Center. If an extended mission is funded, a guest observer program for WHIMex could be implemented with support from the Smithsonian Astrophysical Observatory utilizing their experience with the Chandra GO program.

WHIMex would be launched from Vandenberg Air Force Base in March 2017 on a Taurus 3210 or Athena II ELV into a circular 540 km altitude, 40 degree inclination orbit. After a 60 day on-orbit commissioning period, WHIMex would spend the remaining 34 months of its primary mission obtaining observations of the WHIM, AGN and Galactic Sources. WHIMex's lifetime is not limited by consumables and it will have an unmatched capability for high resolution X-ray. We have proposed a 2-year extended mission to observe targets of opportunity and those selected by Guest Observers. The mission operations phase would be followed by decommissioning phase whose duration would depend on the orbit decay rate due to atmosphere drag. We estimate the orbital lifetime of WHIMex will be ~ 10 years.

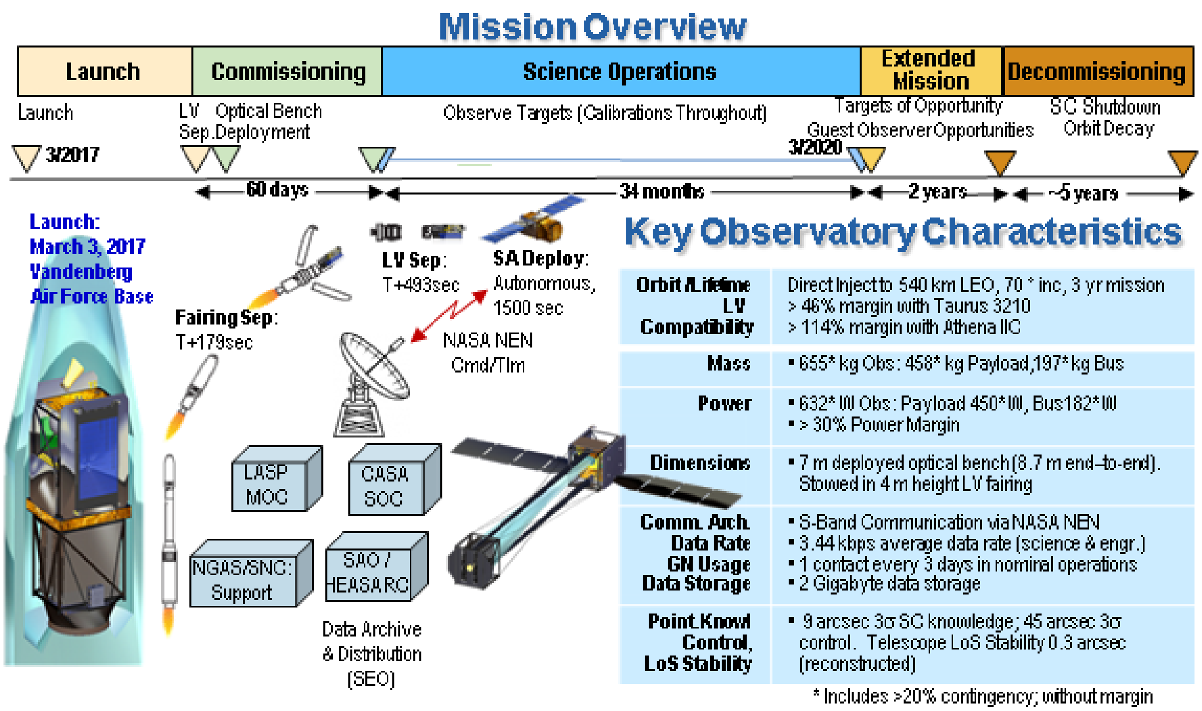

Figure 9. Mission Overview. The key elements of the WHIMex mission, the mission schedule. our concept for launch and mission operations, and the key characteristics of the observatory.

4.2 Spacecraft Configuration

Figure 10 shows the key elements of the WHIMex spacecraft. It is a modular, three-axis stabilized platform that leverages X-ray astronomy observatory design from Chandra and IXO to provide a reliable flight system for the WHIMex mission. A block diagram of the spacecraft is shown in Figure 11.

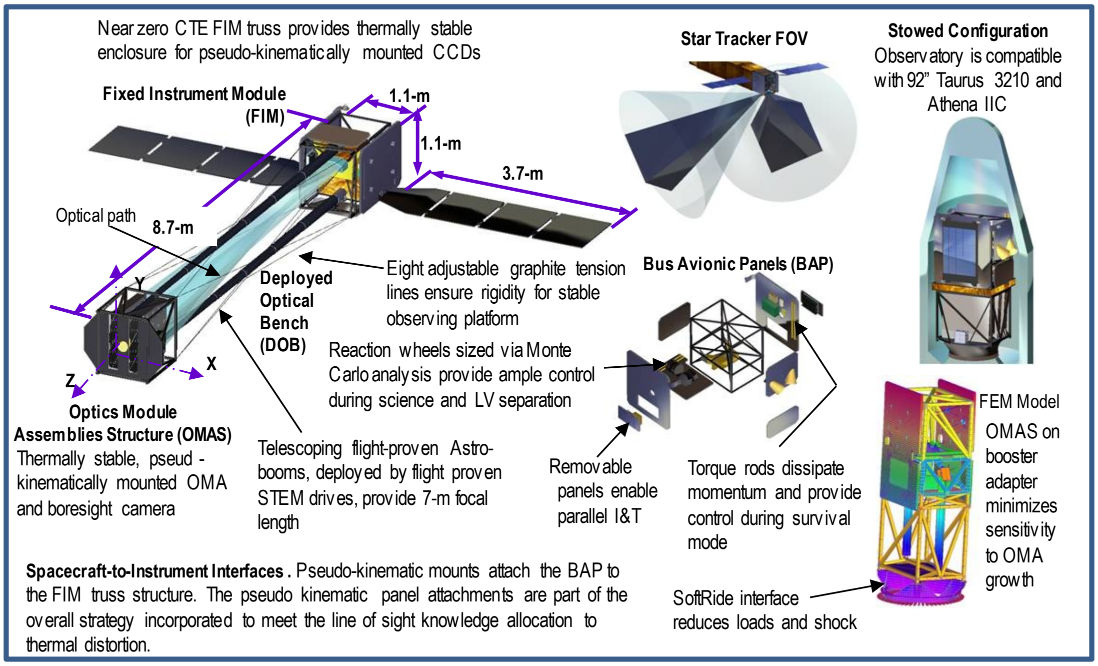

Figure 10. Spacecraft Configuration. WHIMex is a modular, three-axis stabilized platform that leverages X-ray astronomy observatory design from Chandra and IXO to provide a reliable flight system for the WHIMex mission.

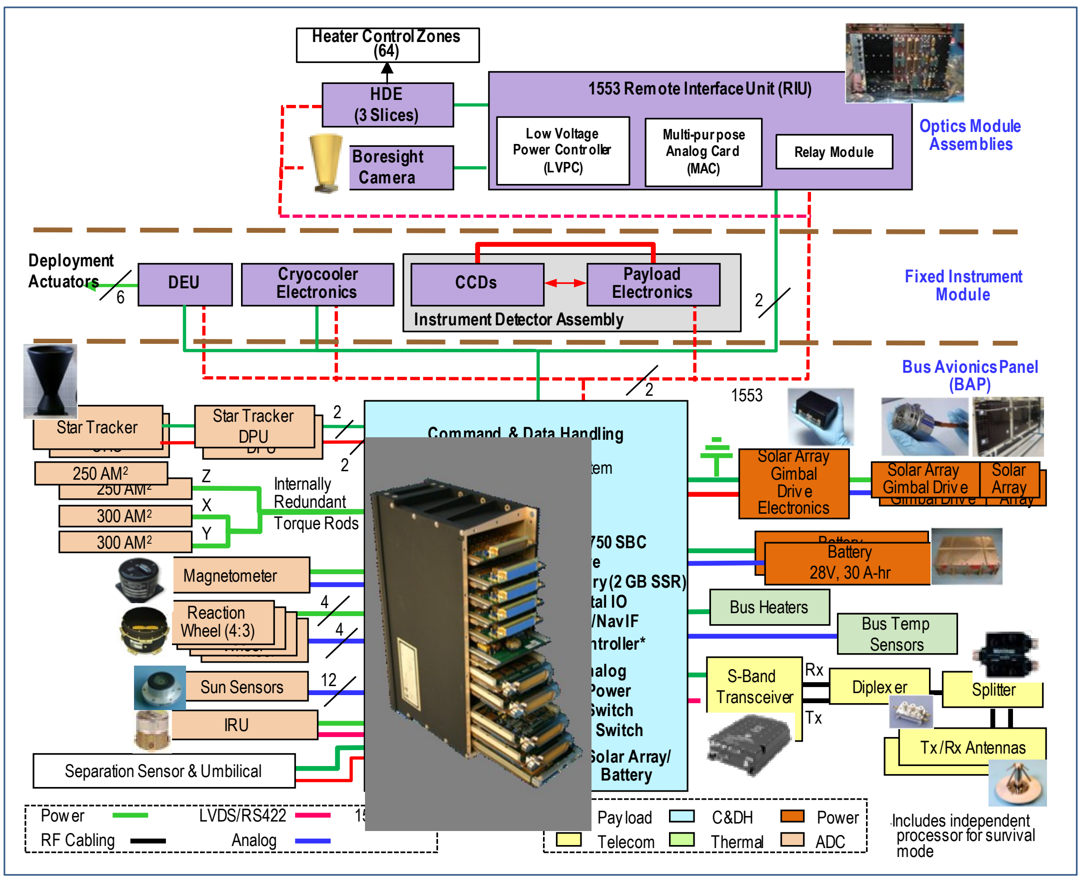

Figure 11. Spacecraft Block Diagram. Simple electrical interface between spacecraft and instrument (1553 and power only) reduce risk and simplify transformation of photons to science data.

5. SUMMARY

The Warm-Hot Intergalactic Medium Explorer (WHIMex) is uniquely suited to addressing the questions of the Warm-Hot Intergalactic Medium (WHIM) and Active Galactic Nuclei (AGN) science, and offers a low cost, low risk approach to addressing our exciting scientific goals. WHIMex directly addresses 5 of the 6 goals in the 2010 Science Plan for NASA's Science Mission Directorate.

With its spectroscopic resolution ≥ 4,000 and collecting area >250 cm^2 in the 0.2–0.8 keV band, WHIMex will vastly extend the spectroscopic discoveries of Chandra and XMM with a low-cost, highly-productive Explorer mission. With a modest increase in funding two additional optical modules could be added to the VHIMex payload, doubling its collecting area to >500 cm^2 while maintaining the same spectral resolution.

WHIMex's high resolution spectra will provide a wealth of new information on the physical conditions of baryonic matter from the local regions of our Galaxy out to the Cosmic Web and the large-scale Structures of the Universe. WHIMex builds on recent advancements in X-ray mirror and gratings technology to provide an order of magnitude improvement in spectroscopic performance over existing missions; it will demonstrate technologies for the next great X-ray observatory; and it will achieve an important subset of the IXO science objectives, a decade earlier at 10% of the cost.

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