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Charles F. Lillie*[a], Webster C. Cash[b], Randall L. McEntaffer[c], William W. Zhang[d]
Stephen L. O'Dell[e], Mark W. Bautz[f], Martin S. Elvis[g], and the WHIMex Team

[a]Northrop Grumman Aerospace Systems, One Space Park, Redondo Beach, CA, USA 90278;
[b]University of Colorado, CASA, Campus Box 389, Boulder, CO, USA 80309;
[c]University of Iowa, 704 Van Allen Hall, Iowa City, IA, USA 52242;
[d]NASA Goddard Space Flight Center, Code 662, Greenbelt, MD, USA 20771;
[e]NASA Marshall Space Flight Center, VP62, Huntsville, AL, USA 35812;
[f]MIT Kavli Institute for Astrophysics, Room 37-241, Cambridge, MA, USA 02139;
[g]Harvard-Smithsonian CfA, 60 Garden Street, Cambridge, MA, USA 02138

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 resolution $\geq$ 4,000 and collecting area $\geq$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. This baryonic matter is thought to result from gravitational collapse of moderately over-dense, dark-matter filaments of the Cosmic Web. The chemical enrichment of the Cosmic Web appears to arise from galactic super winds and early generations of massive stars. WHIMex will test these theories, distinguish between competing models, and provide new insights into galaxy evolution and the structure of the universe High-resolution X-ray spectroscopy was identified by the ASTRO 2010 decadal survey as a high-priority capability in the coming decade for a wide variety of science goals. Unfortunately, no other planned mission can address this science until IXO flies, no earlier than the late 2020s. 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 plan to build an optical test module and raise the optical system readiness to TRL 6 during Phase A.

.**Keywords:** High Resolution, X-ray Spectroscopy, Cosmic Web, Missing Baryons, Structure of the Universe, IXO, NuSTAR

1. INTRODUCTION

The Warm Hot Intergalactic Medium Explorer (WHIMex) is a proposed Explorer 2011 mission which, if selected for development, would be 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 for the International X-ray Observatory (IXO) and achieve an important subset of IXO science objectives, a decade earlier at 10% of the cost.

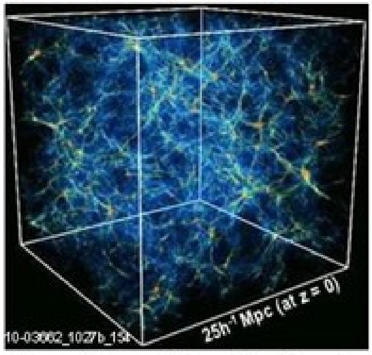

Figure 1. Simulation of the Cosmic Web. WHIMex will detect absorption lines in the high-density filaments of the Cosmic Web.

*chuck.lillie@ngc.com; phone 1 310 814-3774; fax 1 310 812-7443; as.northropgrumman.com

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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.

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.

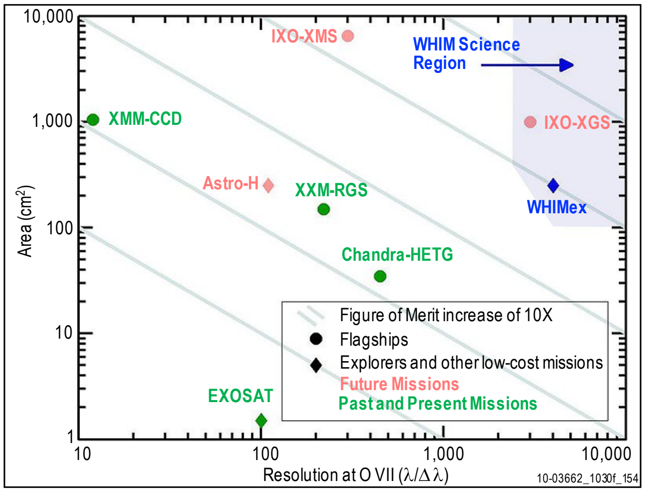


Figure 2. The spectral resolution at 0.57 keV and effective collecting area of WHIMex compared to other missions.

2.3 Baseline Mission

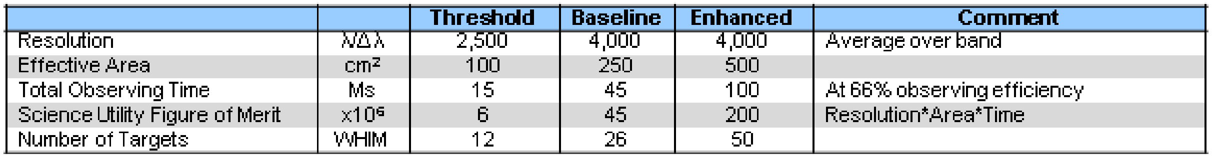
The baseline science mission includes targets that will probe the WHIM, AGN outflow targets, and a variety of other targets of interest (mostly galactic sources). The WHIM target list was selected from several sources, mostly the ROSAT and Swift/ Burst Alert Telescope-detected AGN samples, with a few 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.

2.4 Calibration and Data Flow

While pre-launch calibration ensures that the instrument achieves its scientific goals, the calibration that supports the spectral analysis is accomplished in orbit using X-ray point sources. Chandra and XMM have established a set of celestial calibration targets demonstrated to be non-variable down to the 5% level. Coronal X-ray sources like Capella, Procyon, and λ And provide narrow emission lines of known wavelength to support calibration of the absolute wavelength scale in the spectrograph to better than 0.025%, as required with our baseline resolution of 4000. The widths of the thermal lines emitted by these sources are comparable to our resolution, so the line spread function of the spectrograph can be calibrated by model fitting as a function of temperature and atomic mass. The effective area as a function of wavelength can be measured by observing continuum sources of known flux such as AGN (PKS 2155-30, 3C 273, 1H1426+428, and Mkn 509) and neutron stars (RX J0720.4-3125 and RX J1856.5-3754).

2.5 Threshold Science Mission

The prime goal of WHIMex, to detect O VII and O VIII in the WHIM, must be reached at the threshold mission level. If the mission performance degrades to the point where we could no longer detect a sufficient number of absorbers (at least 50, requiring 12 targets) to retain the statistical value of the measurements, then the mission should not be pursued. Below this number, we would not achieve enough precision in our measurements to determine the density of baryons in the WHIM and constrain models of structure formation. The three key parameters in determining the ability of the mission to meet this science goal are the spectral resolution, effective area, and total observing time. We define a figure of merit for the mission which is the product of these factors. We have run simulations of the WHIM observations to set the Baseline mission at a comfortable level, where the science will certainly be successful (Table 1). Our simulations show that the spectral resolution can degrade to R~2500 before spectral confusion becomes significant and cannot be compensated for with longer observations. If the effective area falls, longer observations can fully compensate down to effective area~100 cm^2, below which we would not be able to observe enough targets in the three year mission. We estimate that any mission that has a science utility figure of merit of $\gtrsim 6$ million, while simultaneously not violating any individual limit, will accomplish the threshold goal.

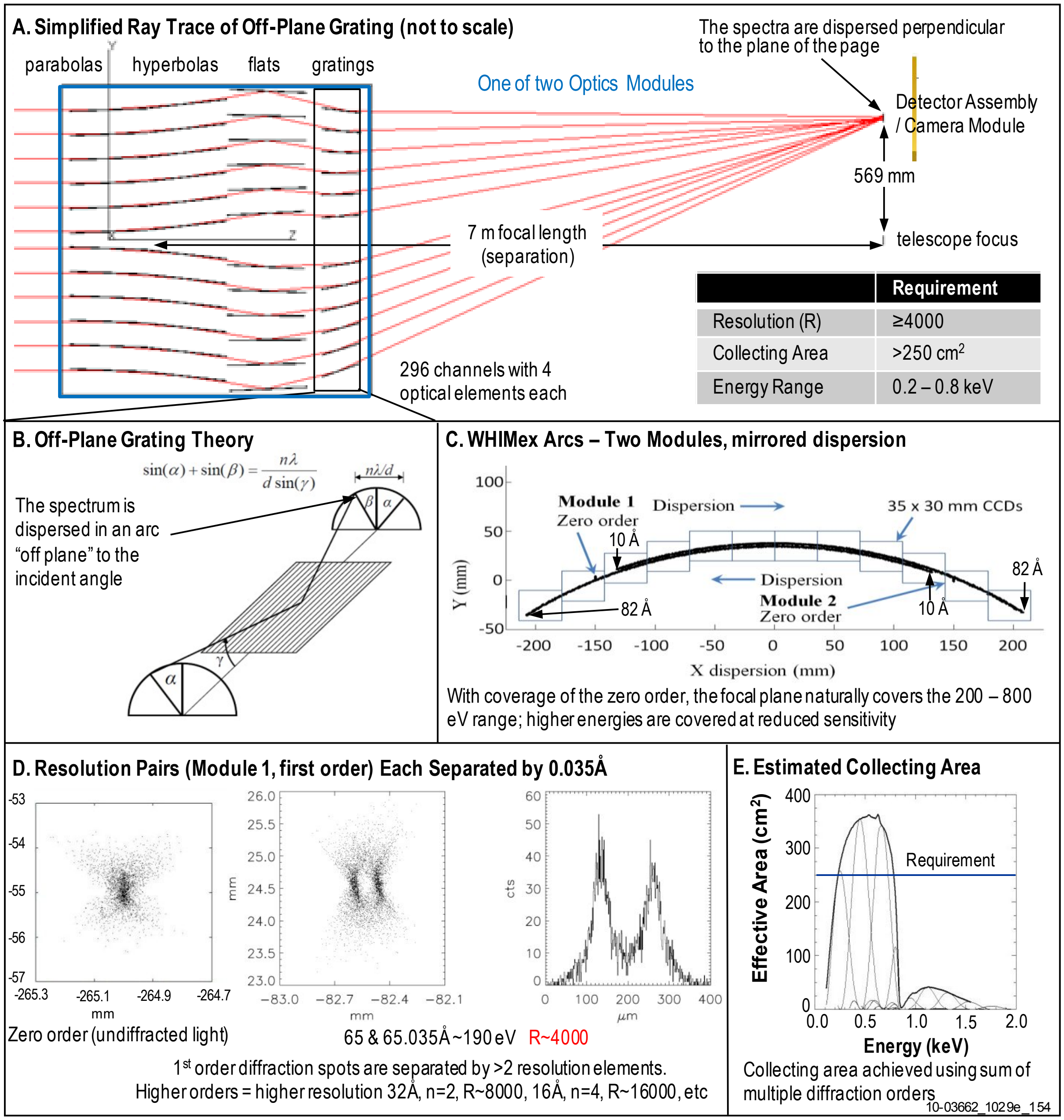


		Threshold	Baseline	Enhanced	Comment
Resolution	$\lambda/\Delta\lambda$	2,500	4,000	4,000	Average over band
Effective Area	cm^2	100	250	500	
Total Observing Time	Ms	15	45	100	At 66% observing efficiency
Science Utility Figure of Merit	$x10^6$	6	45	200	Resolution*Area*Time
Number of Targets	WHIM	12	26	50	

Table 1. Threshold Mission Compared to Baseline. Key performance parameters for the threshold mission compared to the Baseline and an Enhanced missions.

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.


A. Simplified Ray Trace of Off-Plane Grating (not to scale)

The spectra are dispersed perpendicular to the plane of the page

296 channels with 4 optical elements each

	Requirement
Resolution (R)	≥4000
Collecting Area	>250 cm²
Energy Range	0.2 – 0.8 keV

B. Off-Plane Grating Theory

$$\sin(\alpha)+\sin(\beta)=\frac{n\lambda}{d\sin(\gamma)}$$

The spectrum is dispersed in an arc "off plane" to the incident angle

C. WHIMex Arcs – Two Modules, mirrored dispersion

With coverage of the zero order, the focal plane naturally covers the 200 – 800 eV range; higher energies are covered at reduced sensitivity

D. Resolution Pairs (Module 1, first order) Each Separated by 0.035Å

Zero order (undiffracted light)

65 & 65.035Å ~190 eV R~4000

1st order diffraction spots are separated by >2 resolution elements.
Higher orders = higher resolution 32Å, n=2, R~8000, 16Å, n=4, R~16000, etc

E. Estimated Collecting Area

Collecting area achieved using sum of multiple diffraction orders

10-03662_1029e_154

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.

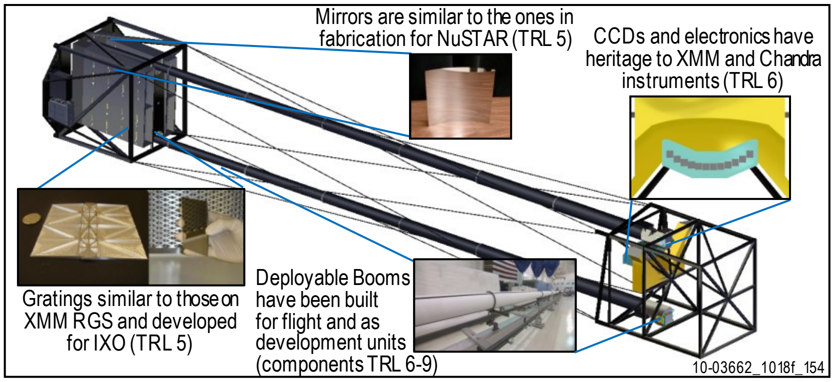


Figure 4. Instrument Overview. The WHIMex spectrograph uses technologies developed under previous efforts to achieve world class science with low cost & low risk.

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.

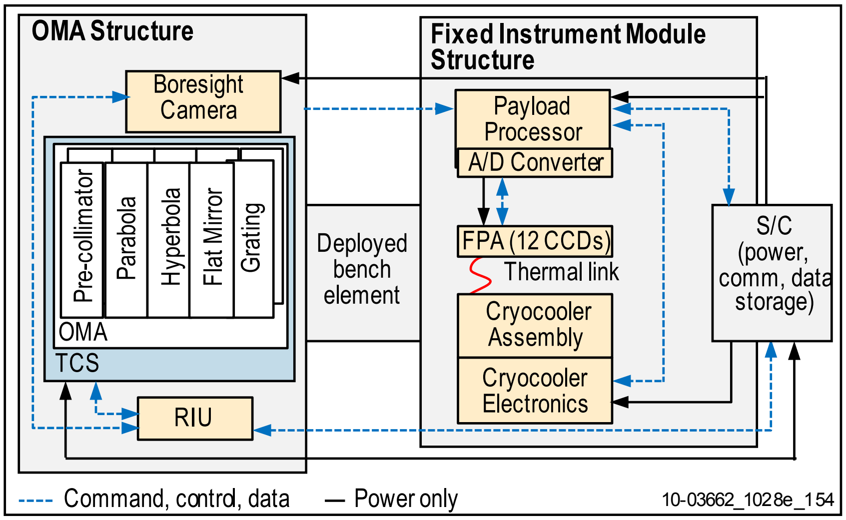


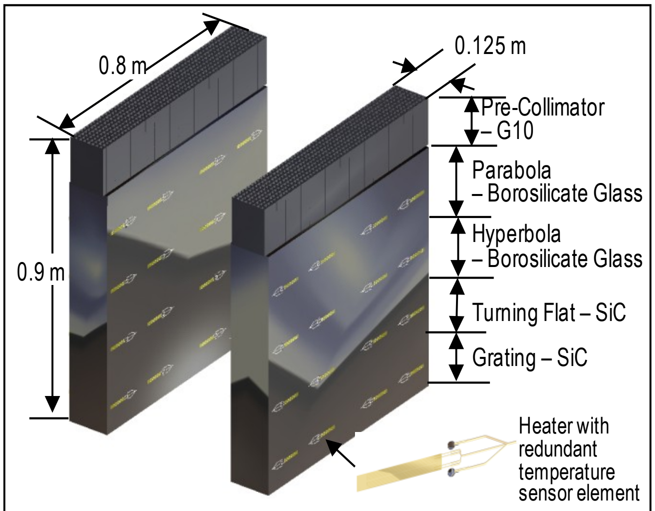
Figure 5. Payload Block Diagram. Simple interfaces to the spacecraft bus provide high reliability and low risk during integration and test.

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

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 will 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 will 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 1^{st} 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

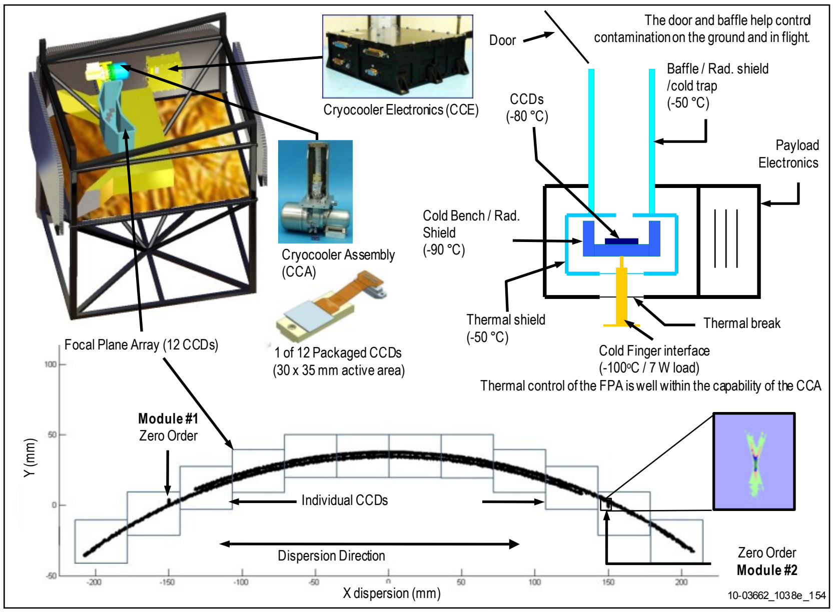


Figure 7. Detector Assembly. The two module Optics Module Assembly is matched to a 12 CCD Focal Plane Array with the modules dispersing their spectra in opposite directions.

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.

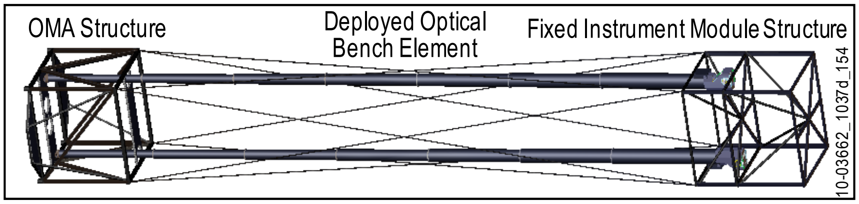


Figure 8. Deployable Optical Bench. The DOB architecture allows it to be accommodated in the smaller fairings of the available launch vehicles.

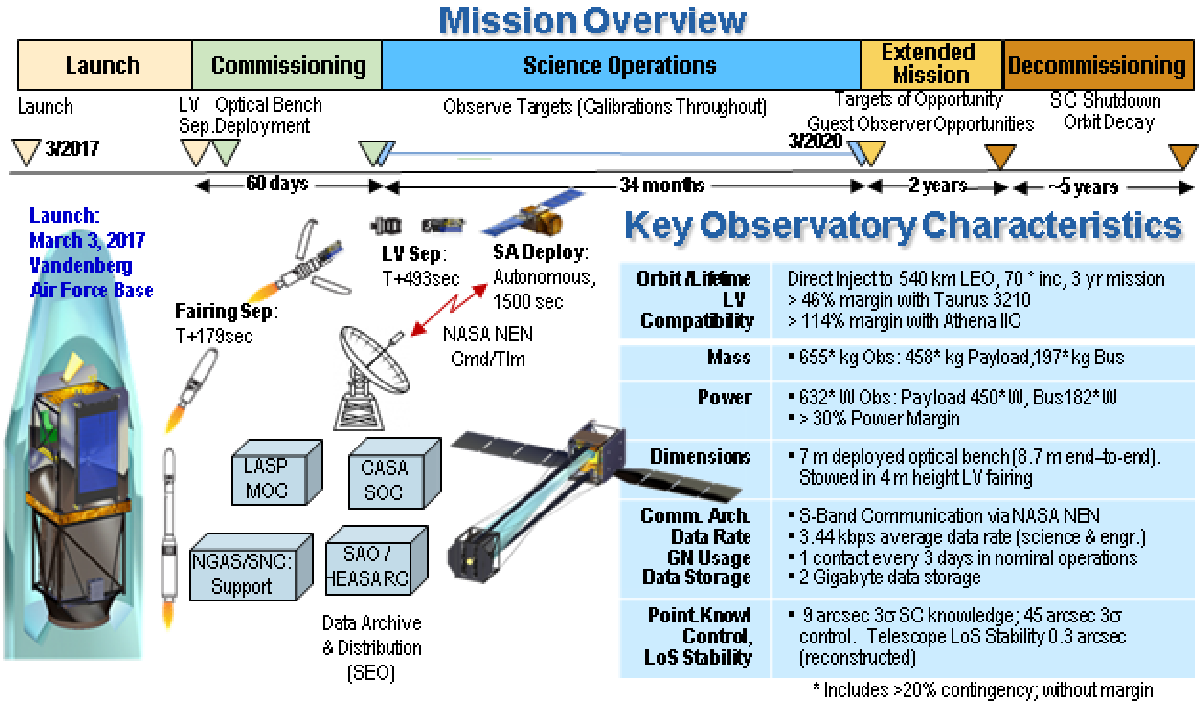
4.1 Mission Overview

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.



Orbit /Lifetime LV Compatibility	Direct Inject to 540 km LEO, 70 ° inc, 3 yr mission > 46% margin with Taurus 3210 > 114% margin with Athena IIC
Mass	▪ 655* kg Obs: 458* kg Payload,197* kg Bus
Power	▪ 632* W Obs: Payload 450* W, Bus182* W ▪ > 30% Power Margin
Dimensions	▪ 7 m deployed optical bench (8.7 m end-to-end). Stowed in 4 m height LV fairing
Comm. Arch. Data Rate GN Usage Data Storage	▪ S-Band Communication via NASA NEN ▪ 3.44 kbps average data rate (science & engr.) ▪ 1 contact every 3 days in nominal operations ▪ 2 Gigabyte data storage
Point Knowl. Control, LoS Stability	▪ 9 arcsec 3σ SC knowledge; 45 arcsec 3σ control. Telescope LoS Stability 0.3 arcsec (reconstructed)

* Includes >20% contingency; without margin

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.

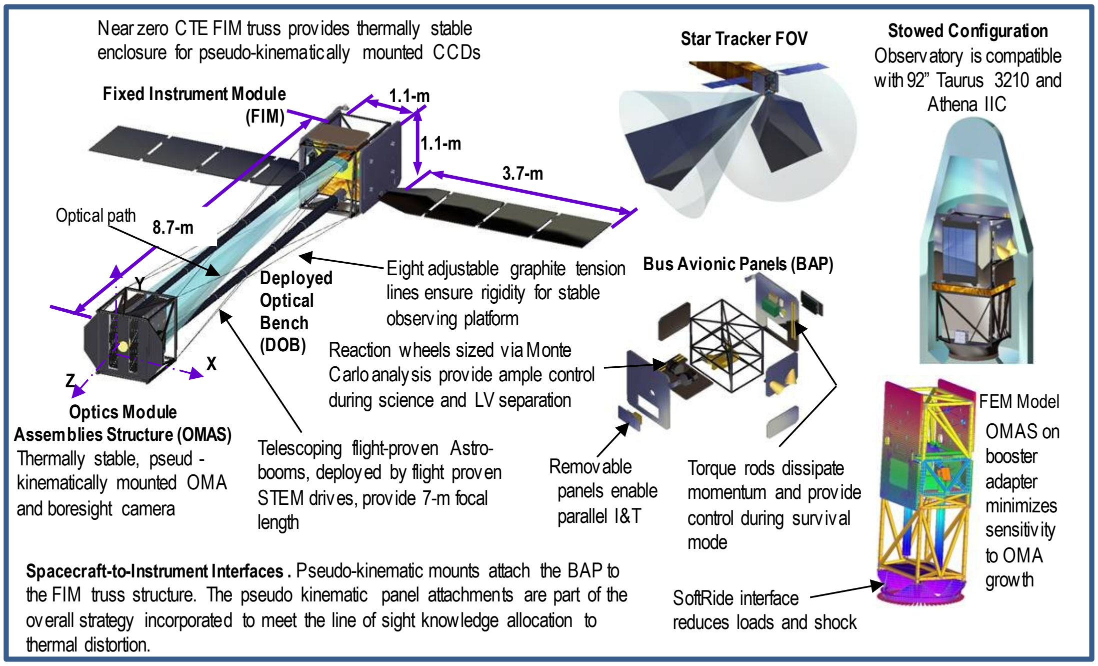


Figure 10. Spacecraft Configuration. WHIMex is a modular, three-axis stabilized platform that leverages X-ray astronomy observatory design from Chandra and IXO to provide a reliable flight system for the WHIMex mission.

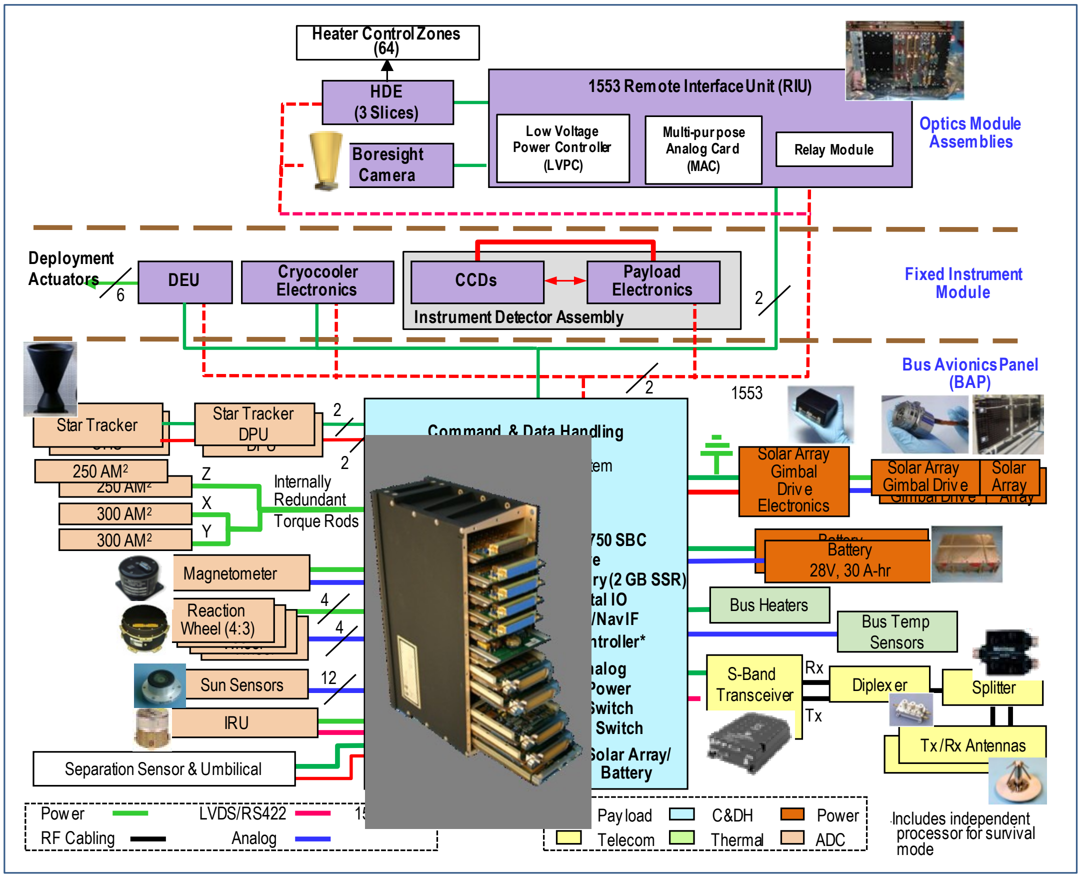


Figure 11. Spacecraft Block Diagram. Simple electrical interface between spacecraft and instrument (1553 and power only) reduce risk and simplify transformation of photons to science data.

5. SCIENCE OPERATONS

WHIMex's 70% observing efficiency is enabled by widely distributed sources, a simple set of observing modes with no time critical observations, and the selection of an orbit to accommodate the long observation period needed for each target.

5.1 Science Observing Profile

The observing profile requires long (0.5 to 2 Ms) observations of relatively few objects. These objects are distributed all over the sky, and require a total of ~45 Ms of integration time to meet mission requirements. To optimize efficiency we selected an orbital inclination that maximizes the number of targets available in a Continuous Viewing Zone (CVZ) for many days at a time, and an altitude low enough to eliminate the need for propulsion for orbital maintenance and disposal. Figure12 shows the distribution of our targets and the pointing exclusion zones for 16 December 2017 using the given orbital parameters. The orbital altitude gives a decay lifetime ≥7 years, ensuring an extended mission option and meeting the required decay time of <25 years for disposal. This orbit provides two 25° diameter CVZ which precess across the sky over a 140-day period. Our distribution of sources provides continuous access to targets. The largest contributor to lost observing time is the SAA where the number of high energy particles adds too many background particle counts to easily use the data. The exact orbital parameters are not critical, as star trackers on the SC and the BC provide pointing knowledge for processing the science data. Infrequent updates provided by ground station tracking are sufficient to provide orbital elements for mission operations.

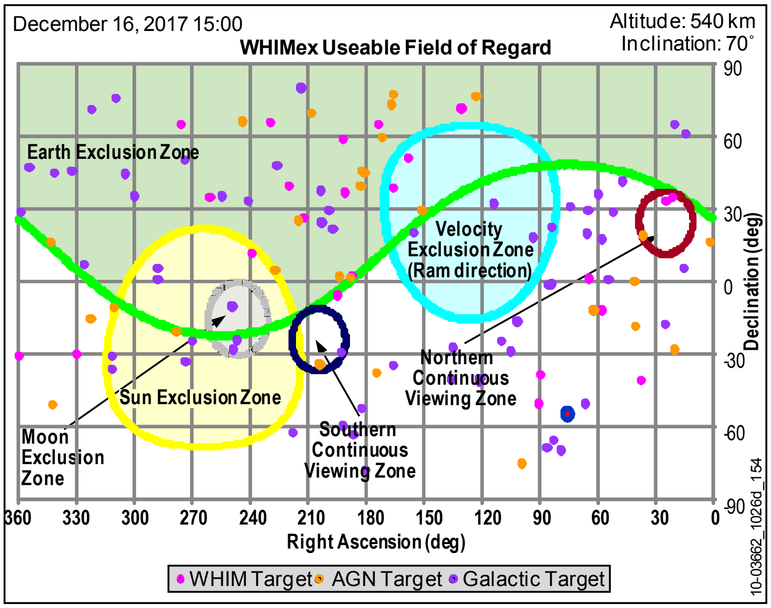


Figure 12. Target Distribution and Accessibility. Our target distribution and accessibility enables high observing efficiency over the mission lifetime.

5.2 Observing Timeline

The science observing plan will be continuously updated over the course of the mission as the performance of the system is better understood and the observing list is refined. The timeline is relatively simple given a single instrument and one observing mode. Based on a nominal target list and performance estimates, we have developed a mission plan, calculated data volumes, and evaluated contact times as shown in Figure 13. As observations are driven by target availability, we have no time critical operations after the SC is separated from the launch vehicle and the solar array is deployed. The deployment of the DOB should take place as early as possible to allow out gassing of the structure and MLI to start observations as soon as possible, but there are no stringent time requirements for the operation. Calibration target observations are scheduled by the science team and will be obtained on a monthly basis.

5.3 Data Management Plan

The Mission Operations Center (MOC) at LASP provides the conduit for the SC data, managing the downlink to the ground typically scheduled for once every three days during nominal science operations. Special downlinks can be scheduled for bright targets which greatly increase the data volume. The DA collects the event data along with the BC quaternion data and sends them to the SSR. The SC packages the science data into Consultative Committee for Space Data Systems (CCSDS) packets that are transmitted to the ground station, oldest data first. The CCSDS data are sent to the MOC for processing. Figure 14 shows the entire data processing chain with time estimates.

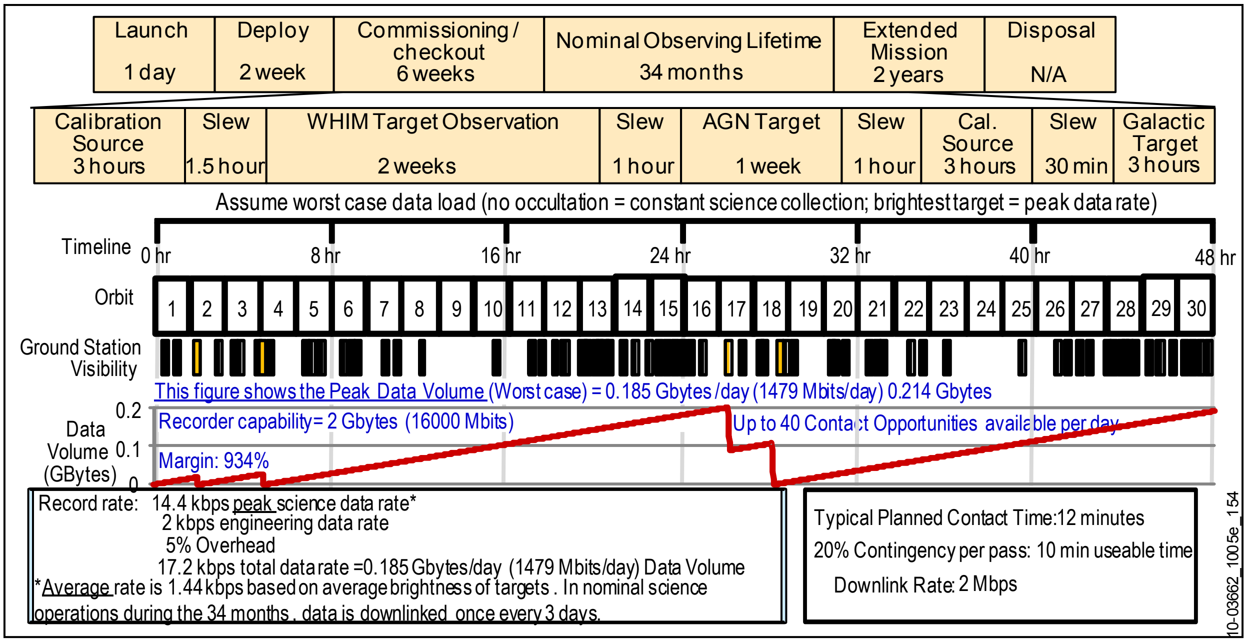


Figure 13. Science Mission Timeline. A simple mission operations plan provides margin for contact times and data volume capacity, to accommodate anomalies during operations.

5.4 Data Archiving

During the baseline mission, CASA provides the archiving function for WHIMex data, both the raw data from the SC and the processed data and related documentation developed by the science team. LASP provides a second archive of all the SC telemetry data for the duration of the mission. CASA processes the data products and documentation into the proper format, and submits the data packages to High Energy Astrophysics Science Archival Research Center (HEASARC) within 6 months of data collection, or sooner if released by the science team. We anticipate a total raw data volume of ~212 Gbits of raw science and engineering data plus an equal amount of ancillary data for the mission duration. Processed data products (L1, L1.5, and L2) add ~600 Gbits for a total data storage requirement of 128 Gbytes for the mission duration.

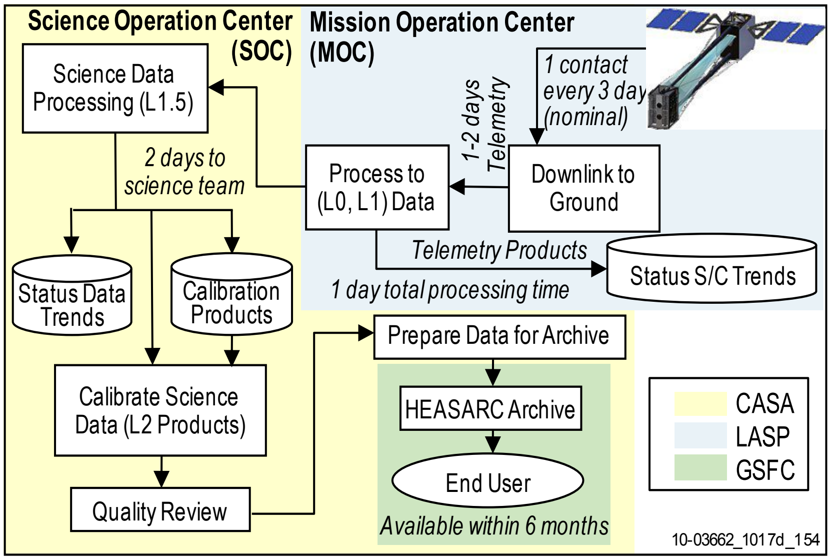


Figure 14. Data Management Plan. An efficient data processing pipeline gets the mission data to the science team within 3 days and then to the HEASARC Archive**.**

5.5 Guest Observer Program

Historically, GOs have found many of the most interesting and innovative uses of a space observatory. If a GO Program SEO is approved for WHIMex, we will engage SAO and the Chandra X-ray Center (CXC) to develop a GO module based on their extensive Chandra heritage. This will provide a fully searchable data archive that stores all levels of data from raw through Level 2 products. Level 2 products are anticipated to be comparable to Chandra

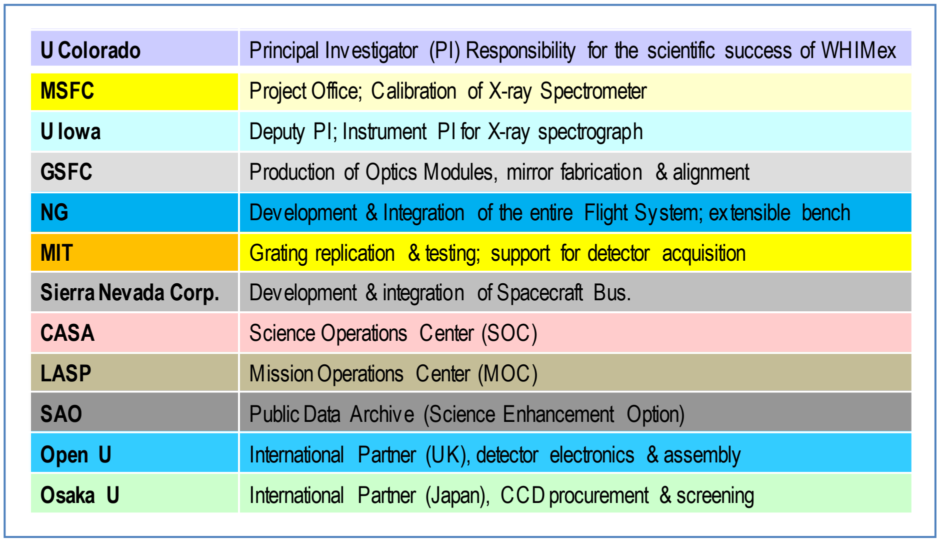
LETG Level 2 products. These products will comply with all applicable HEASARC and Virtual Observatory standards, enabling users to analyze the data using common analysis tools that the high energy astronomy community is already familiar with. We will provide a WHIMex-specific data analysis package to enable users to recalibrate the data where needed. Calibration data management will be provided by a HEASARC-standard Calibration Database. The data archive will also provide proprietary rights protection for GOs and automatically distribute data as soon as they are processed (typically within 24 hours of telemetry receipt). In addition, it will provide a web-based interface for searching the archive and retrieving data, modeled on Chandra's WebChaSeR interface.

6. MANAGEMENT

The WHIMex team has the heritage, experience, and discipline required to execute the project to cost and schedule. Our key personnel have extensive experience executing successfully on X-ray and optical payload systems, including the Chandra X-ray Observatory (CXO), as well as rapid response missions such as the Lunar Crater Observing and Sensing Satellite (LCROSS).

6.1 WHIMex Team Organization

The roles and responsibilities for the mission management and participating organizations for WHIMex are shown in Figure 15. The Principal Investigator (PI) is responsible to the NASA Explorer Program for the overall success of the WHIMex mission, and retains direct management of the science team. The PI delegates the management of the technical baseline, project schedule, and mission budget to the Marshall Space Flight Center Project Manager. Northrop Grumman (NG) is responsible for payload development, space vehicle integration and test, and launch processing. The Deputy PI at the University of Iowa (UI) leads the development of gratings, detectors and detector electronics. The Goddard Space Flight Center Astrophysics Laboratory develops the optics modules. The optics modules and detector assemblies will then be provided as government furnished equipment (GFE) to NG.



U Colorado	Principal Investigator (PI) Responsibility for the scientific success of WHIMex
MSFC	Project Office; Calibration of X-ray Spectrometer
U Iowa	Deputy PI; Instrument PI for X-ray spectrograph
GSFC	Production of Optics Modules, mirror fabrication & alignment
NG	Development & Integration of the entire Flight System; extensible bench
MIT	Grating replication & testing; support for detector acquisition
Sierra Nevada Corp.	Development & integration of Spacecraft Bus.
CASA	Science Operations Center (SOC)
LASP	Mission Operations Center (MOC)
SAO	Public Data Archive (Science Enhancement Option)
Open U	International Partner (UK), detector electronics & assembly
Osaka U	International Partner (Japan), CCD procurement & screening

Figure 15. Mission Management and Participating Organizations . The members of the WHIMex team have extensive experience designing, developing, and operating and managing Chandra, XMM and other X-ray observatories.

The Sierra Nevada Corporation will provide the space avionics to NG on panels for integration with the observatory. MIT will perform the grating replication and testing and support detector acquisition. LASP will provide and operate the mission operations center and CASA will provide and operate the science operations center. SAO will provide a public archive and support for a Guest Observer Program if and extended mission is funded.

WHIMex has baselined Osaka and Open universities as the detector and detector electronics provider. The PI and DPI have been engaged in discussions with these Universities as possible cooperative partners, funded by their governments. The contributions from Osaka and Open are well within the experience both institutions gained on past international mission. Should these cooperative agreements not occur, we anticipate a competitive procurement. MIT Lincoln Labs is considered an alternate source for these elements as well, having extensive X-ray detector experience from programs such as Chandra. The technical and management interfaces and acquisition of these assemblies will be through the University of Iowa.

6.2 Science Team and PAB

Our Science Investigation Team includes the leading experts in X-ray mirror technology, grating technology, detectors, X-ray spectroscopy and high energy astrophysics. The depth of the team ensures that the highest quality hardware, software, data products and scientific results will be produced by the WHIMex mission. The science team advises the PI throughout the program, and actively engages on mission and science requirements and implementation trades. A Program Advisory Board (PAB), consisting of senior executives from the major organizations, meets quarterly, reviews the progress of the program, and provides guidance to the PI/PM and Level 2 managers on technical and programmatic issues.

7. 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 $\geq$ 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. 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.

ACKNOWLEDGEMENTS

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