CONSTELLATION-X TECHNOLOGY READINESS AND IMPLEMENTATION PLAN (TRIP) REPORT

Prepared for
National Aeronautics and Space Administration
(NASA) Headquarters

Prepared by
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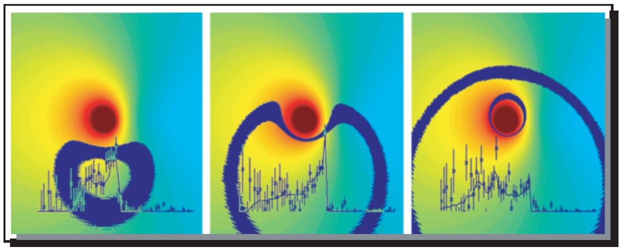
Constellation-X

MISSION FACT SHEET

Constellation-X will use X-ray Spectroscopy to revolutionize our knowledge of the universe. It will probe closer to black hole event horizons with 100 times better sensitivity than ever before.

Constellation-X's four science objectives are tightly connected to NASA SEU themes:



I. Measure the effects of **strong gravity** near the event horizon of supermassive black holes.
What is the nature of space and time?
What powers supermassive black holes?

II. Trace visible matter throughout the universe and constrain the nature of **dark matter** and dark energy.
What is the universe made of?
How does the universe evolve?

III. Study the formation of supermassive **black holes** and trace their evolution with cosmic time.
What roles do they play in galaxy evolution?
What is the total energy output of the universe?

IV. Study the **life cycles of matter** and energy and understand the behavior of matter in extreme environments.
What new forms of matter will be discovered?
How does the chemical composition of the universe evolve?

Well-defined science objectives provide well-defined measurement requirements.

Management: A straightforward approach with few interfaces and highly experienced teams:

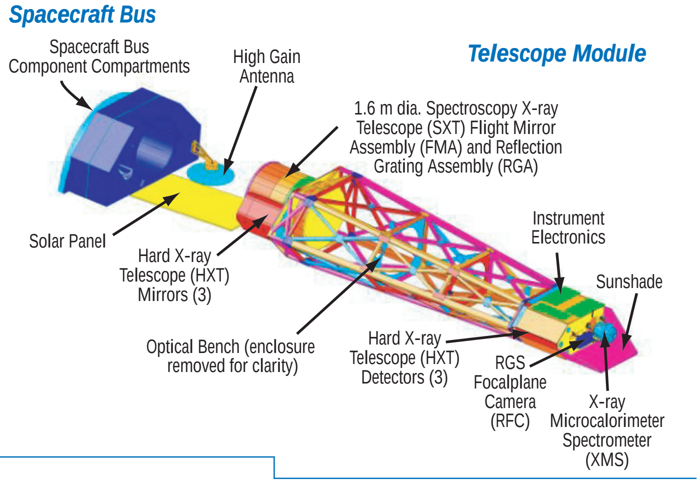
- Mission managed by NASA/GSFC
- SAO part of management team
- Prime contractor for observatory

Mission Overview:

Launch dates:	2010 and 2011
Launch vehicles:	Atlas V (two)
Constellation:	4 observatories point at target (no formation flying)
Mission lifetime:	4 years for fully operational constellation & 10 year goal
Orbit:	L2 Lissajous
NASA mission cost:	$1,597B (RY)

Exploded view of a Constellation-X observatory

- Robust, modular mission design
- Performance verifiable on the ground
- Meets mission requirements traceable to the science objectives



Constellation-X provides:

High observing efficiency (90%)
Large sample sizes of key astrophysical objects
Broad-band X-ray imaging spectroscopy (0.25 - 40 keV)
General observer facility with programs selected by peer review to carry out world-class science
Dramatic improvements in spectroscopic sensitivity, about a factor of 100 over previous missions

Observatory Characteristics:

Number:	4 identical observatories
Wet mass (each):	~2480 kg
Power (each):	~1075 W
Data storage:	42 Gbit
Source location:	5 arcsec, post facto
Attitude control:	3-axis stabilized ~30 arcsec control
Communication:	X/S-band downlink (1.7 Mbps/2 kbps) S-band uplink (2 kbps)
Mechanisms:	Few; low precision focusing

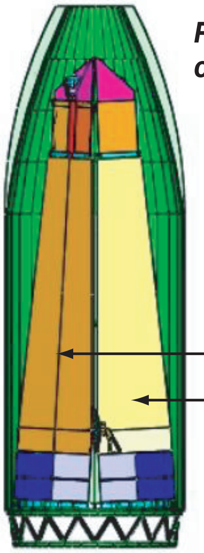
No new spacecraft technologies are required

Modular design minimizes interfaces and simplifies I&T flow

Key Heritage Elements:

- Technologies evolve from existing hardware.
- Our teams bring significant flight experience.
- Chandra provides heritage for systems engineering, key mechanisms, I&T, and the Science and Operations Center.

Technology Area	***Current TRL***	***Date for TRL6***	***Heritage***
Mirrors (SXT, HXT)	3/4	FY06	*ASCA*, Astro-E2, InFocμs *Chandra, XMM-Newton*
XMS Microcalorimeter	4	FY05	Astro-E2
HXT detector	4/6	FY05	HEFT, InFocμs
RGS CCDs	3	FY05	*ASCA, Chandra*
RGS gratings	3	FY06	*XMM-Newton*
XMS Cryocooler	4	FY06	*HST, TES, AIRS*
XMS ADR	4	FY06	Astro-E2



Resource margins are based on a mature mission concept

Mass Margin:	34%
Power Margin:	34%
Schedule Contingency:	5 months (10%) (plus slack)
Cost Reserves: (observatory development)	$191M (22%)

Two observatories are packaged inside an Atlas V fairing

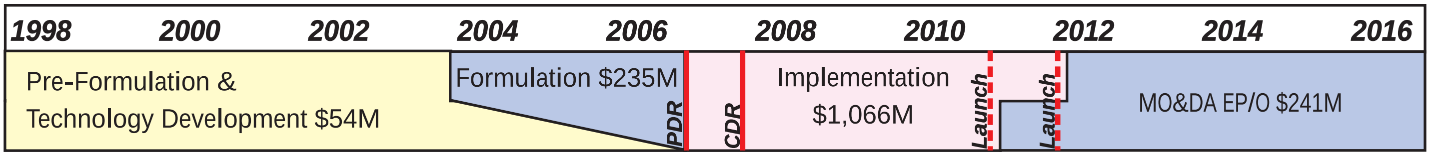
Science Payload: Instruments are extensions of recent, flight-proven hardware, minimizing technology development risks while meeting requirements with adequate performance margins.

SXT FMA:	Primary optic feed for XMS and RGS ≈15,000 cm^2 at 1.25 keV
RGS:	Dispersive spectrometer from 0.25 - 2 keV Resolving power R ≈300 at 0.6 keV
XMS:	Imaging spectrometer from 0.6 - 10 keV Resolving power R ≈ 1500 at 6.0 keV
HXT:	Imaging spectrometer from 6 - 40 keV Resolving power R ≈10 at 40 keV

Why Constellation-X Now?

- Guaranteed, compelling science returns
- Breakthrough discoveries require comprehensive spectroscopic studies
- Addresses priorities of the NASA SEU program
- Technology development has demonstrated readiness to proceed; team is in place

Constellation-X Schedule



RY DOLLARS

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1.0 SCIENCE REQUIREMENTS AND MISSION SCIENCE PERFORMANCE

1.1 TRIP Executive Summary

The Constellation-X mission will revolutionize our understanding of the cosmos. Scientists around the world will use its factor of 100 increase in throughput over previous missions to study the warping of space and time by strong gravity near black holes; determine the distribution of the ordinary matter, dark matter, and dark energy that constitute our universe; and probe the detailed physical processes occurring at temperatures, densities, and pressures far beyond those achievable in Earth-bound laboratories.

Constellation-X Starts "Beyond Einstein" Initiative With a Bang

- Science success guaranteed
- Experienced team with world leaders in field
- Broad technology base plus focused technology efforts provide path to flight program
- Modular approach minimizes risk and cost

Constellation-X builds on three decades of X-ray satellites, including the currently operating Chandra X-ray Observatory (NASA) and XMM-Newton mission (ESA), and builds on proven technology. Grazing incidence mirrors with higher angular resolution than Constellation-X have already been built and flown on Chandra, and replication techniques relevant for Constellation-X's large area mirrors have been used to build optics for XMM-Newton and for Japan's Astro-E and Astro-E2 missions. X-ray microcalorimeters have been developed for Astro-E/E2, while reflection gratings are flying on XMM-Newton and X-ray Charge Coupled Devices (CCDs) on Chandra and XMM-Newton. Hard X-ray telescopes with multilayers and cadmium-zinc-telluride detectors have successfully flown on balloons. Our Constellation-X team members have played key roles in all of these missions. Using this experience, our team has undertaken a comprehensive technology program structured to reach Technology Readiness Level (TRL) 6 in all areas before the mission Non-Advocate Review (NAR) scheduled for August 2006. For the Spectroscopy X-ray Telescope (SXT) mirror, whose fabrication represents the project's "tall pole," X-ray tests of an engineering unit are scheduled for early FY 2004.

The technology requirements flow from the mission science objectives, as articulated by the Facility Science Team (FST) composed of approximately 50 scientists from more than 30 different institutions representing essentially all of the groups presently active in the field. The objectives have been vetted and strongly supported in two different major reviews by the National Academy of Sciences (NAS) in 2001 and 2002. The Constellation-X science, management, and engineering teams, led by Goddard Space Flight Center (GSFC) and the Smithsonian Astrophysical Observatory (SAO) and supported by the leads of the Integrated Product Teams (IPTs), have mapped the science objectives to the technology requirements for the mission. The steps needed to achieve TRL 6 and manufacturing readiness for each of the key technologies have been cast into a technology roadmap used to establish schedules and budgets. This approach provides the flowdown, or trace, from the objectives to the requirements and allows the team to identify and carry out system analyses and trades to optimize resource utilization for the technology efforts and more importantly for the implementation phase.

To illustrate the maturity of the architecture and design based on system analyses and engineering already accomplished, we note design decisions from three significant trades. We have baselined four observatories launched in pairs in 2010 and 2011 to build up the required collecting area and reduce impacts of single failures, while keeping costs at an acceptable level. We have chosen segmented mirrors rather than full shells for the SXT, driven primarily by costs and availability of large mandrels for replicating reflectors. We will fly mechanical cryocoolers for the X-ray Microcalorimeter Spectrometer (XMS), along with a multiple-stage Continuous Adiabatic Demagnetization Refrigerator (CADR) to achieve the required operating temperature. This approach provides substantially longer life for the instrument at much lower weight than expendable cryogens and draws from joint technology efforts of other Office of Space Science (OSS) projects, including the James Webb Space Telescope (JWST) and Terrestrial Planet Finder.

The trace from science objectives to requirements provides clear insight into the impact of scope changes. The technology program provides the path from the large base of demonstrated and flight-proven hardware to the needs of the Constellation-X mission. The breadth of experience and the technology roadmap provide an excellent understanding of the program and a basis for sound cost estimates. During the technology phase, we also allow for potential breakthroughs that might provide substantial increases in performance and/or reduce risks and costs. In some cases, we allocate modest amounts of our limited technology budget to evaluate promising possibilities (e.g., increased grating spectral resolution). For others, we are tracking efforts by team members (Italian and German colleagues on optics) or leveraging industry investments to evaluate options (higher SXT mirror angular resolution). The potential performance gain from well-identified goals is illustrated by the Chandra mirrors, where a few extra hours of final smoothing per surface led to a high frequency surface finish of 0.3 nm RMS (goal) as compared to the requirement of 0.7 nm, at essentially no increase in project cost and with substantial reduction in mirror scatter at higher energies.

Multi-Observatory Mission Approach Reduces Cost and Risk

- Four observatories with common design, manufacturing, assembly, and testing
- Manageable mirror dimensions
- Proven spacecraft subsystems and launch vehicles
- Mission success even with loss of one observatory via longer exposures

Constellation-X does not require formation flying or interferometry. All satellites are simply commanded to view the same target, and the data are added together on the ground. Constellation-X baselines a joint operations and science center co-located with the Chandra X-ray Center (CXC) to maximize synergy with the experienced Chandra team and draw upon the extensive and directly relevant software and procedures already in use.

The management approach to Constellation-X is simple. There is a single manager at GSFC who will draw upon the experienced team of GSFC and SAO engineers and scientists as well as the Instrument Principal Investigators selected via a competitive Announcement of Opportunity (AO). The approach is based on the very effective Chandra model. With at most modest contributions from potential international partners and a single prime contractor for the observatories, interfaces will be relatively simple, responsibilities well-defined, and schedules and budgets easily tracked and managed, leading to less risk and easier decision making.

The science gains with Constellation-X will be enormous. Over the past several years, we have identified the required technology and established the roadmap needed to demonstrate feasibility and readiness for mission implementation. Substantial progress has already been made, and achievable plans are in place for the remainder of the formulation and implementation phases. The mission concept is elegant and resilient; the management approach is simple and strong; the technology will be in hand soon. We are ready to proceed.

1.1.1 Foldout Walkthrough

This report includes four foldouts that provide a framework for the text. Foldout 1 is a traceability matrix that traces each science objective to its corresponding science plan, measurement parameters, performance requirements, and then to the subsystem requirements. Foldout 2 centers on mission elements: the spacecraft and location of key instrument systems; the reference spacecraft block diagram; launch and orbit; and the ground segment approach. Foldout 3 focuses on mission optics, while Foldout 4 illustrates mission sensors.

1.2 Science and Mission Requirements

1.2.1 Science Objectives and Derived Science Requirements

The four top-level science objectives of Constellation-X pursue the objectives of NASA's Structure and Evolution of the Universe (SEU) roadmap and extend recent discoveries of Chandra and XMM-Newton. These objectives have been strongly endorsed by the community-at-large as discussed in the 2001 NAS Astronomy and Survey Committee report[1]. Constellation-X also directly addresses several key questions and long-term goals outlined in two recent NAS physics reports[2][3]. The top-level science objectives are presented here, followed by a summary of a subset of the key requirements that flow to the measurement capabilities (summarized in Foldout 1). These requirements (the full set of which can be found in the Top-Level Requirements Document[4]; [TLRD]) are the baseline requirements, and have been approved by the FST. The associated minimum requirements and goals are discussed in Sections 1.2.3 and 1.2.4, and summarized in Table 1-1. In many cases, a mission science requirement may be derived from several science objectives. All science requirements have been refined based on input from leading members of the scientific community, detailing the specific targets and studies that are needed to meet the top-level objectives, via an Observation Design Reference Mission[5] (ODRM). The ODRM will continue to evolve and be used to refine the requirements. The TLRD has remained stable for the last two years, with only minor modifications.

The specific requirements that flow from each of the following science objectives are described in the Flowdown Requirements Document[6] and are given in Foldout 1. While most have been developed to achieve individual science objectives, mission life and data volume result from considering the ensemble of objectives. Observing a statistically-significant number of sources places a joint requirement on effective area and mission duration.

Objective 1: Measure the effects of strong gravity near the event horizon of supermassive black holes.

X-ray spectroscopy–and in particular the detailed variability of the iron K fluorescence emission line near 6 keV–is a powerful probe of the dynamics and space-time geometry within a few gravitational radii of accreting, supermassive black holes in active galactic nuclei (AGN)[7]. Iron K is produced when X-rays illuminate the accreting material that is the fuel for such black holes. CCD-resolution spectra show that the Fe K line carries the imprint of strong general relativity (GR), but they provide inadequate knowledge of the line origin. Constellation-X will probe the effects of strong GR on this, the only spectral feature that is known to originate from close to the black hole. Conceivably, one might observe variability that cannot be understood within the context of GR, requiring possible modifications to Einstein's theory or suggesting the presence of extra fields near the event horizon that alter particle and/or photon dynamics. Very recent Chandra results have shown unanticipated structure in the Fe K region requiring high spectral resolution to interpret. It is only through spectroscopy that one can hope to unfold the relationship between GR and the detailed physics of black holes (such as mass and spin[8]) and their environment.

Studying the effects of GR in extreme environments requires accumulating high signal-to-noise, high-resolution spectra on the dynamical timescales of the innermost stable orbit of the accretion disk (typically of order 1000 seconds for a 10^8 solar mass black hole). To adequately use such spectra also requires determining the full underlying continuum shape, which allows the properties of relativistically broadened emission lines to be measured with high accuracy (Foldout 1-A). These needs require a resolving power of 1,500 near 6 keV and instantaneous collecting areas of 6,000 cm^2 and 1,500 cm^2 at 6 and 40 keV, respectively.

Objective 2: Trace visible matter throughout the universe and constrain the nature of dark matter and dark energy.

Recent results indicate that most of the energy density of the universe exists in the form of dark matter and dark energy[9]. These findings are a major challenge to physics since there is no unique candidate for dark matter and no present physical theory accounts for dark energy. Clusters of galaxies (the largest known gravitationally organized systems) are important probes of dark matter and dark energy, as well as the structure, evolution and mass content of the universe. In addition, X-ray observations of clusters allow us to constrain cosmological parameters such as the rate of expansion of the universe, the fraction of mass in visible (baryonic) matter, and the amplitude of primordial density fluctuations in the universe[10]. Constellation-X will measure the ratio of baryons in clusters to their total mass and will determine with high precision the distribution of dark matter out to z~2 (where these objects are about 1 arcminute in diameter and have relatively high surface brightness). At higher redshifts, integral spectra of clusters and galaxy groups will provide bounds on the dark matter and baryonic distribution.

In the local universe, the observed baryons fall far short of those predicted by standard big bang nucleosynthesis[11]. Numerical simulations predict that most of these “missing” baryons are in a hot intergalactic medium (IGM)[12]. This IGM is detectable through faint X-ray absorption lines imprinted by highly ionized metals on the spectrum of background quasars (Foldout 1-B). To detect these features requires a resolving power of at least 300 at and below 0.6 keV.

To test fundamental models of the evolution of cosmic structure requires knowing how many objects are forming, where they are forming, and how they are distributed. By measuring the change in the number density of clusters with specific masses as a function of redshift, Constellation-X will trace the entire history of large-scale hierarchical cluster formation. Meeting this objective requires a large collecting area near 1 keV and determination of cluster temperatures (thereby deriving masses) and abundances with the necessary 10% accuracy to distinguish between competing cosmological theories[13].

Objective 3: Study the formation of supermassive black holes and trace their evolution with cosmic time.

The faint sources that make up the X-ray background were discovered by Chandra and XMM[14]. Many of these may be highly obscured AGNs, which are a significant contributor to the accretion luminosity of the universe. Constellation-X will investigate the evolution of black holes by determining spin, mass and accretion rate over a wide range of luminosity and redshift (Foldout 1-C).

To resolve a significant fraction of the X-ray background where it peaks in energy density requires avoiding source confusion at flux limits of ~1 x 10^{-15} erg/cm^2/s below 10 keV and ~1 x 10^{-14} erg/cm^2/s above 10 keV. This requires an angular resolution of ~15 arcsec (1 to 10 keV) and ~1 arcmin (10 to 40 keV).

Objective 4: Study the life cycles of matter and energy and understand the behavior of matter in extreme environments.

Spectroscopic observations of stellar coronae, supernova remnants, and the interstellar medium provide information on chemical enrichment processes and will provide plasma temperatures, pressures, densities, and velocities over a wide range of astrophysical settings, allowing a tracing of the all-important life cycle of elements in the universe. Detailed X-ray line spectra are rich in plasma diagnostics from the abundant metals (C through Zn) that provide unambiguous constraints on physical conditions in astrophysical sources (Foldout 1-D).

Millisecond oscillations in X-ray bursts have been identified as due to inhomogeneous nuclear burning on the surfaces of rapidly rotating neutron stars[15]. Spectroscopy of the burst emission will constrain the neutron mass/radius relation, and lead to important constraints on the equation of state of high-density nuclear matter found in neutron stars. Finally, microquasars are known to possess relativistically broadened iron lines and, similar to supermassive black holes in AGN, Constellation-X will be able to study iron line variability and measure mass and spin of stellar-mass black holes.

Obtaining the plasma diagnostics from the abundant metals (C through Zn) places a requirement on the bandpass and spectral resolving power at low energies. Phase-resolved spectroscopy of neutron stars and studies of quasi-periodic oscillations (QPOs) place a requirement on the absolute timing capability.

1.2.2 Investigations

The investigations to be performed to meet the scientific objectives outlined in Section 1.2.1 have been selected from careful studies by members of the Constellation-X FST and Science Panels in response to an internal call for proposals to help define an ODRM. During the mission operations phase of the mission, the project expects to receive proposals representative of all of these investigations, as well as for many other guest investigations that are not yet represented in the ODRM.

Within the four main science objectives, there are at least 14 distinct classes of objects to be studied (Foldout 1).

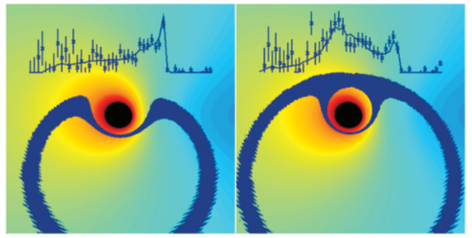
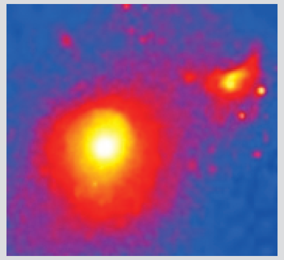
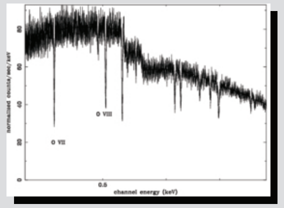
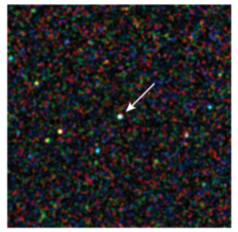
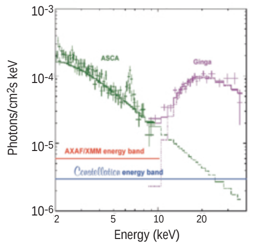
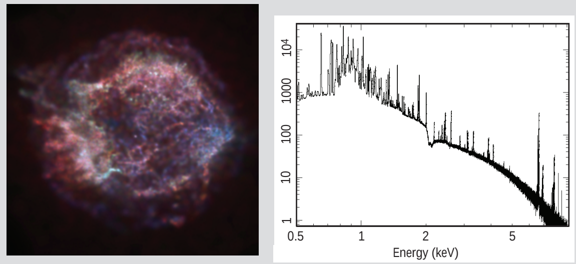
Achieving the science objectives requires investigation of statistically significant samples of these astrophysical sources–unlike Chandra and XMM-Newton which are restricted to the brightest (and hence not necessarily representative) members of each class. Typical exposure times are expected to run up to 100 ksec. For certain classes and sources, monitoring observations will be required. As an example of the types of observations required to achieve the science objectives, one case is described in detail below. The remaining cases are summarized in Foldout 1.

Detailed studies of the gravitational effects near supermassive black holes will require monitoring observations of the Fe K line variability in about 25 of the brightest AGN. Typical observations will last about 30 ksec (allowing tracking of the line variability on spatial scales ~25 times larger than the innermost

Constellation-X

Traceability Matrix:

Specific objectives have a clear trace to implementation

		Science Objectives	Measurement Parameters								Performance Requirements Table 1-1					
			Science Topics	Category of Targets	No. Unique Targets	Pointings/ Source	Representative Data Quality	Typ. T$_{exp}$ (ksec)	Total Time (ksec)	Primary Data Type Returned	Bandpass	Effective Area	Spectral Resolving Power, R	Imaging	Other	Representative Data Volume (bits)
A	Simulated spectra of two iron K fluorescence line profiles in 1,000 s intervals after a flare erupts above an accretion disk (color image). The profiles change as the flare's echo (dark band) propagates toward the black hole. 	***I. Measure the effects of strong gravity near the event horizon of supermassive black holes***	Study general relativity effects in the presence of extreme gravity	Bright active galactic nuclei (AGN)	30	10	S/N of 50 to 100 in narrow and broad features near 6 keV Constrain continuum >10 keV	30	9,000	Spectra, timing	0.5 to 40 keV	6,000 cm^2 instantaneous at 6.0 keV	1,500 at 6.0 keV 10 at 40 keV	Angular resolution of 1 arcmin above 10 keV		6.6 x 10^8 [bright AGN] example: RGS: 2.9 x 10^7 XMS: 6.1 x 10^8 HXT: 1.5 x 10^7
			Black hole properties	AGN	50	2*	Velocity resolution <100 km/s Spatially separate sources	50	5,000	Spectra	0.5 to 40 keV	1,500 cm^2 instantaneous at 40 keV				3.4 x 10^8 [other AGN]
B	A) X-rays from clusters will constrain models of the formation of large-scale structure in the universe.  B) Missing baryons in the local universe are detectable via X-ray absorption lines in the spectrum of background quasars.  	***II. Trace visible matter throughout the universe and constrain the nature of dark matter and dark energy***	Masses, abundances, dark matter, dark energy, cosmology	Galaxy clusters	120	1	Measure abundance and temp. with 10% accuracy	40	4,800	Spectra, images	0.25 to 40 keV	3,000 cm^2 at 0.6 keV	300 at 0.6 keV 1,500 at 6.0 keV	Angular resolution of 15 arcsec at 1 keV		8.0 x 10^7 [nearby cluster] 5.6 x 10^6 [cluster, z=0.2]
			Cluster formation models, shocked gas	Galaxy clusters	60	1	Velocity resolution <100 km/s Detect Inverse-Compton hard X-rays	100	6,000	Spectra, images	0.25 to 40 keV	15,000 cm^2 at 1.25 keV	10 at 40 keV	FOV of 2.5 arcmin at 1 keV		3.0 x 10^6 [cluster, z=1]
			Masses, abundances, dark matter	Elliptical galaxies and galaxy groups	100	1	Radial temperature profiles	40	4,000	Spectra, images	0.25 to 10 keV	1,500 cm^2 at 40 keV				
			Find low redshift baryons in the IGM	Low-Z QSOs	20	1	Detect OVII and OVIII absorption near 0.6 keV	500	10,000	Spectra	0.25 to 1 keV			FOV of 8 arc-min at 40 keV		
C	A) Constellation-X will obtain high quality spectra of recently discovered sources that make up the X-ray background.  B) By measuring the low-energy (scattered) emission and the underlying continuum, their total energy output can be determined.  	***III. Study the formation of supermassive black holes and trace their evolution with cosmic time***	Properties of Chandra/XMM deep-field sources and the X-ray background	Faint X-ray sources	100 100	1 1	Avoid source confusion at fluxes of ~1 x 10^{-15} erg/cm^2/s below 10 keV and ~1x10^{-14} erg/cm^2/s above 10 keV	50 100	5,000 10,000	Spectra, images	1.0 to 40 keV	15,000 cm^2 at 1.25 keV	1,500 at 6.0 keV 300 at 0.6 keV	Angular resolution of 15 arcsec at 6 keV	TOOs: ~1/month	2.4 x 10^3 [faint AGN] 1.1 x 10^6 [AGN]
			Black hole evolution	AGN	100	1		50	500	Spectra	0.25 to 40 keV	6,000 cm^2 at 6.0 keV	10 at 40 keV	Celestial coordinate accuracy of 5 arcsec		
			Interstellar medium, dark matter, starburst-AGN connection	Spiral and starburst galaxies	60	1	Probe absorbing columns of up to 10^{25} cm^{-2}	40	2,400	Spectra, timing, images	0.25 to 40 keV	1,500 cm^2 at 40 keV		Angular resolution of 1 arcmin above 10 keV		2.0 x 10^8 [galaxy]
D	Spectroscopic observations of stellar coronae, supernova remnants, and the interstellar medium will allow a tracing of the all important life cycle of elements in the universe.  	***IV. Study the life cycles of matter and energy and understand the behavior of matter in extreme environments***	Composition of ISM, nucleosynthesis, life cycle of matter	SNR (maps require many pointings)	30	10**	Spatially resolve SNR ejecta Velocity resolution <100 km/s	30	9,000	Images, spectra	0.25 to 10 keV	15,000 cm^2 at 1.25 keV	1,500 at 6.0 keV 300 at 0.6 keV	Angular resolution of 15 arcsec at 1 keV	TOOs: ~1/month	7.4 x 10^8 [bright SNR]
			Mass function	XRBs	75	1		50	3,750	Timing, spectra	0.5 to 10 keV	15,000 cm^2 instantaneous at 1.25 keV				1.2 x 10^7 [BHC]
			Dynamics	BHCs	50	1	S/N ~ 50 per resolution element near 1 keV	40	2,000	Spectra, timing	0.5 to 40 keV		10 at 40 keV		Timing accuracy: 100 microseconds	3.0 x 10^7 [star]
			Equation of state	Neutron stars	75	1		80	6,000	Timing, spectra	0.25 to 10 keV	1,500 cm^2 at 40 keV				1.2 x 10^{10} [XRB]
			Coronal heating, winds, convection zones, star formation	Stars	180	1-10**	Resolve Lithium-like and He-like lines	50	9,000	Spectra, timing, images	0.25 to 7 keV	1,000 cm^2 at 0.25 keV		FOV of 2.5 arcmin at 1 keV		
			Planets, comets	Solar system objects	10		Phase resolved spectroscopy	40	400	Spectra, images	0.25 to 2 keV				10,000 counts per second per observatory	2.4 x 10^6 [comet]
									86,850 ksec (3 years)	Subsystem Requirements Tables (representative)	1-6, 1-8, 1-9	1-4, 1-6, 1-8, 1-9	1-6, 1-8, 1-9	1-3, 1-6, 1-8, 1-9, 2-1, 2-2	1-8, 1-11, 2-1	2-1, 2-4 Sect. 2.4.1.2, and Sect. 2.4.3

Data volume depends on source spectrum, brightness and integration time. Instrument conversions are XMS: 64 bits/photon, RGS: 48 bits/photon, HXT: 48 bits/photon.

* Multiple pointings for monitoring observations.

** Multiple pointings for mappings.

Red numbers indicate driving requirements.

stable orbit of the accretion disk), but many objects will be monitored on longer time scales, requiring repeat observations for an estimated total of about 9,000 ksec. Studying black hole evolution and general properties over a range of luminosities requires longer, single observations of approximately 150 fainter AGN of 50 ksec each for 7,500 ksec. In total, studies of supermassive black holes will require about 17,000 ksec.

1.2.3 Measurement Capabilities

The mission science objectives are fully supported by the baseline requirements summarized in Table 1-1. The baseline performance requirements can be traced in detail to the science objectives via Foldout 1. Additional mission requirements can be found in the TLRD. The performance margins are determined by comparison of the Reference Mission Performance with the baseline requirements. Note that some requirements are set at levels that already have been achieved on other X-ray missions (e.g., the angular resolution is met by XMM-Newton and exceeded by Chandra).

A preliminary set of minimum requirements has been assigned to the key measurement items to ensure a robust mission (Table 1-1). It has been noted that there is typically graceful degradation in science return as one approaches the minima (i.e., if there is a smaller field of view (FOV) more pointings can be utilized—though at the cost of fewer observations for a given mission lifetime).

Table 1-1: Key Measurement Capabilities

Measurement Parameter	Minimum Requirement	Baseline Requirement	Mission Goal	Reference Mission Performance	Margin
Bandpass (keV)	0.25 to 40	0.25 to 40	0.1 to 80	0.25 to 60 kev	20 keV
Effective Area (cm^2)					
0.25 keV to 10 keV	1,000 cm^2	1,000 cm^2	N/S	1,279 @0.25 kev	28%
1.25 keV	12,000 cm^2	15,000 cm^2	N/S	15,201 @1.25 kev	1%[#]
6.0keV	5,400 cm^2	6,000 cm^2	N/S	6,352 @6.0 kev	6%[#]
10 to 40 keV	1,200 cm^2	1,500 cm^2	N/S	4,990 @10 kev 1,542 @40 kev	230% 3%[#]
Spectral Resolving Power (E/ΔE)					
0.25 to 6 keV	300	300	3000	991 @0.25 keV 354 @0.7 keV** 625 @1.25 keV	230% 17% 108%
				3000 @6 keV	100%
6 to 10 keV	1,200	1,500	3000		
				5000 @10 keV	1567%
10 to 40 keV	5	10	N/S		
				33 @40 keV	230%
Angular Resolution (HPD)					
<10 keV	15 arcsec	15 arcsec	5 arcsec	14.5 arcsec	4 arcsec (RSS)
>10 keV	1.2 arcmin	1 arcmin	20 arcsec	45 arcsec	39 arcsec(RSS)
Fields of View					
<10 keV	2 arcmin	2.5 arcmin	5 arcmin	2.5 arcmin	N/A*
>10 keV	4 arcmin	8 arcmin	10 arcmin	8 arcmin	N/A*
Bright Source Limit[†]	5,000 cps/beam	10,000 cps/beam	N/S	10,000 cps/beam	N/A
Absolute Timing (relative to UTC)	300 μsec	100 μsec	50 μsec	90 μsec	10 μsec

* Limited by detector format, not optics performance ** Overall system minimum resolution **N/S** = not specified

[†] No instrument damage occurs; at very high count rates, there is a gradual loss of spectral resolution

[#] In general, optics designs and coatings are reference and are not yet optimized. Margins should improve significantly prior to Phase B.

1.2.4 Measurement Goals

Some parameters have goals (Table 1-1) that would increase mission capabilities with minimal increases in cost, schedule, or risk, and for which the technology appears achievable. The technology advances needed to achieve these goals will be part of the trades made during formulation, including consideration of impact on project resources. The science to be gained by reaching these goals is discussed below, but there would undoubtedly be many other gains, some that cannot yet be imagined.

High-Energy Bandpass: Extending the energy band beyond 40 keV will provide a longer lever arm for measuring the X-ray continuum in active galactic nuclei and, in particular, will better constrain the high-energy rollover in the Compton reflection signature from accretion disks and other Compton thick structures such as molecular tori, thus constraining the geometry of the X-ray reprocessor.

Spectral Resolving Power: Improving the spectral resolving power enables qualitative improvements in the ability to study more complicated plasmas, including photoionization features, turbulent velocities, tighter limits on gravitational smearing, and improvements in velocity diagnostics. Increasing resolution significantly also improves the detection capability for narrow absorption lines.

Angular Resolution: Improving the imaging capability of the SXT mirrors to ~5 arcsec half power diameter (HPD) allows observations of more crowded fields, achieves lower flux levels by lowering the confusion limit, and allows mapping of supernova remnants and galaxy clusters in greater detail.

1.2.5 Measurements and Data

X-ray astronomy instruments record a separate signal from every photon detected, unlike typical optical CCDs which need to integrate the signal from a number of photons to generate a detectable signal. As a result, X-ray data are stored event by event. This approach retains more information and allows greater flexibility of analysis. Every X-ray "event" (source photon or background cosmic ray) is characterized by a "pulse height" that encodes the energy of the incoming photon, arrival time, quality grade, and typically two position coordinates. The large amount of information for each event allows complex and sophisticated analysis. For example, a user may wish to exclude events that occurred during a period of high background and then display the events as a spectrum vs. time image. Retaining the individual events also retains the Poisson ("counting statistics") nature of the data, and so allows the statistical significance of sources or features to be assessed more readily. The instantaneous data rate depends (nearly) linearly on the X-ray source brightness.

The science data products (Levels 1 and 2) derived from these "events" are X-ray spectra, images, and light curves (Foldout 1).

Level 1: Instrument-dependent corrections, such as the aspect solution, are applied. Level 1 data outputs are reversible (e.g., no photon event rejection). These products are sent to the observer.

Level 2: Takes Level 1 outputs and applies standard corrections. This includes filtering the event file on the good time intervals, cosmic ray rejection, and position transformation to celestial coordinates. A candidate source list and "finished" event file are produced, as well as a dispersed spectrum for grating data.

Level 3: Derives higher level information from the Level 2 outputs, including more precise source detection and characterization (fluxes, morphology), plus cross-correlation with source catalogs and X-ray line identification.

Data validation, analysis, and archiving are discussed in Section 2.4.3.

1.3 Mission Science Performance and Design

1.3.1 Instrumentation

Mission science performance requirements described in Section 1.2.1 are met using four identical observatories that orbit the L2 libration point (Foldout 2-E). All four observatories, activated by stored commands from the ground, view the same target at the same time. The timetagged data from the four observatories are combined on the ground for each observation to meet the top-level mission requirements. ***The observatories do not interact with each other or station keep with respect to one another, and communicate only with the ground.***

System Description: On each of the four Constellation-X observatories, the instrumentation is configured into a Telescope Module (TM).

Each TM consists of two types of telescope systems (Foldout 2-A):

- Spectroscopy X-ray Telescope (SXT) with bandpass from 0.25 keV to 10 keV
- Hard X-ray Telescope (HXT) with bandpass from 6 keV to 40 keV

The SXT uses a single Flight Mirror Assembly (FMA) shared by two instruments:

- Reflection Grating Spectrometer (RGS) with bandpass from 0.25 to 2.0 keV
- X-ray Microcalorimeter Spectrometer (XMS) with bandpass from 0.6 to 10 keV

The RGS and XMS combine to cover the SXT bandpass; the SXT and HXT together cover the mission bandpass. Overlap between systems provides cross calibration.

The SXT mirror, RGS, XMS, and HXT concept descriptions are provided in this section. Technology development efforts relevant to these systems are provided in Section 3. A description of the additional TM systems that provide the structural mounting and alignment, thermal control, calibration support, baffling, etc., is provided in Section 2.4.1.1.

Instrument Interfaces: The Constellation-X mirrors and instruments are modular, with clean and easily implemented interfaces to the observatory. Mechanical alignment tolerances to the TM are on the order of a millimeter in position and arcminutes in angular orientation. Kinematic mounts, similar to those used on dozens of flight missions, along with a stable structural and thermal design, assure that mechanical alignment tolerances are maintained over the mission life. Thermal interfaces between the instruments and observatory are generally passive with heaters, radiators, and heatpipes provided as necessary. The typical instrument science data rates are listed in Foldout 1.

Flowdown of Top-Level Mission Requirements: The following paragraphs discuss effective area, spectral resolving power, and angular resolution error budgets and requirements flowdown.

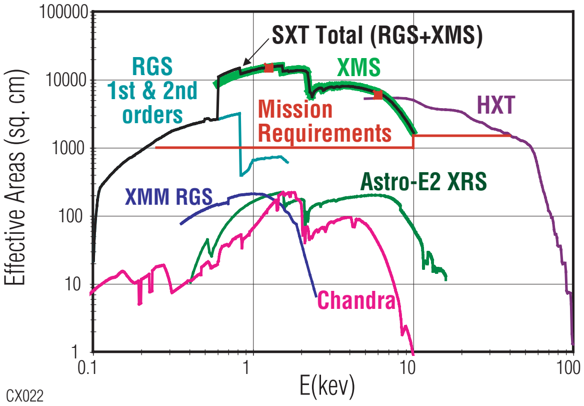


Figure 1-1: Mission Effective Area Curves

As shown in Figure 1-1, the XMS, RGS, and HXT instruments complement each other to meet the top-level mission effective area requirements across the mission bandpass. These effective area estimates are based on the full complement of mirrors and instruments from all observatories. A budget for the mission effective area, which allocates requirements to the telescope system components, is provided in Table 1-2. The current design includes modest margin between the predicted area and nominal top-level mission requirement. Further design optimization, alternate mirror coatings, and reduced structural blockage will improve these margins.

As shown in Figure 1-2, the XMS and RGS instruments complement each other to meet the top-level spectral resolution requirements

Table 1-2: SXT Effective Area Budget (Mission Total)

	Area At Energy		
	0.25 keV	**1.25 keV**	**6 keV**
SXT FMA Geometric Area	59,400	59,400	59,400
SXT FMA Losses			
–Reflectivity Loss	-17,118	-18,641	-50,691
–Structural Blockage	-5,919	-5,747	-1,472
–P-H Shell Alignment	-423	-611	-174
–Aperture Alignment	-211	-306	-87
–SXT Contamination - EOL	-423	-408	-87
SXT FMA Effective Area	35,305	33,687	6,889
Instrument/Telescope Losses			
–RGS Internal Vignetting	-784	-743	-51
–XMS(Cal QE, Filter, Fill Factor)	-19,628	-3,212	-394
–RGS(Grat Effy, CCD QE, Filter)	-12,659	-13,280	0
–Grating Internal Alignment	-157	-149	-10
–Off-axis Operation	-14	-172	-68
–Inst Contamination - EOL	-784	-941	-14
Total Area - Predicted	1,280	15,191	6,352
Total Area - Requirement	1,000	15,000	6,000
Margin (%)	28.0	1.3	5.9

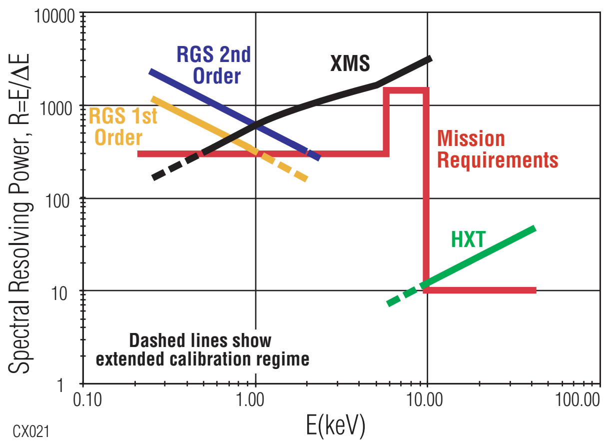


Figure 1-2: Mission Spectral Resolving Power vs. Energy

across the mission bandpass. The spectral resolving power R=E/ΔE of the RGS increases as energy decreases and meets or exceeds the resolving power requirements over the lower energy portion of the mission bandpass (0.25-1 keV). Since the energy resolution of the XMS is nearly constant (~2 eV), the XMS spectral resolving power increases with energy. The XMS is therefore the primary instrument from 1 to 10 keV. The HXT covers the bandpass above 10 keV.

The SXT angular resolution requirement is 15 arcsec (HPD). A preliminary angular resolution error budget is shown in Table 1-3. The SXT mirror on-orbit performance and telescope level effects are combined by root sum square (RSS) with instrument unique terms to show predictions and margins for the RGS and XMS SXT systems.

Number and Size of SXTs: Four SXT systems are baselined for the Constellation-X mission. This is a result of trade studies that considered the number of mission SXT systems (ranging from 1 to 12) and accounted for factors such as mirror fabrication and testing, launch vehicle throw mass and packaging, and number of instruments. Fewer SXTs have the advantage of fewer detectors but require larger diameter mirrors with longer focal lengths, which are more difficult to fabricate and test and require on-orbit deployable optical benches. With four SXTs, the mirror diameter of 1.6 m allows two systems to be packaged within a single 5 m-diameter launch vehicle fairing (Foldout 2-D); the focal length is 10 m, which can be accommodated by a fixed optical bench (OB) within an Atlas V fairing. Any advantages of more, smaller SXT mirrors are offset by the need for additional instrument detector systems, more extensive I&T, and additional launch vehicles, and do not offer any advantage in launch vehicle cost.

1.3.1.1 SXT Flight Mirror Assembly

The SXT FMA, illustrated on Foldout 3-E10, consists of four major components: the SXT mirror, the RGS Grating Array (RGA), and thermal pre- and post-collimators (see Section 2.4.1.1). X-rays enter the SXT FMA through the pre-collimator and are directed to a focus by the SXT mirror. The SXT mirror consists of highly nested reflectors utilizing a two-reflection Wolter Type I design, in which the incident X-rays reflect off confocal paraboloid and hyperboloid surfaces of revolution, at shallow angles. A schematic of the Wolter I concept is shown on Foldout 2-C. In the SXT design, the aperture is optimally filled with mirrors, facilitating high throughput of incident radiation. Approximately half the reflected X-rays pass through the RGA and impinge on the XMS at the telescope focus. The remainder are reflected or diffracted into various orders by the RGA and into the off-axis RGS Focal Plane Camera (RFC). All the X-rays pass through the thermal post-collimator en route to the focal plane.

SXT FMA Requirements: The requirements for the SXT mirror are listed in Table 1-4. These divide into top-level performance requirements and derived (engineering) requirements.

SXT FMA Implementation: The SXT mirror has adopted a segmented Wolter I approach for fabrication. The paraboloid and hyperboloid surfaces of revolution are composed of a number of segments of equal arc length. The segmented approach allows for a modular design amenable to mass production. It also obviates the need for very large reflector forming mandrels and mounting fixtures, the technical feasibility and cost-effective mass production of which are highly questionable. Table 1-5 lists SXT mirror key properties.

The nominal design for the mirror (Foldout 3-B9) consists of 18 modules, six identical inner modules subtending a 60-degree arc and 12 identical outer modules subtending a 30-degree arc. Each segment has two grazing incidence

Table 1-3: SXT Angular Resolution Error Budget (Arcsec)

	Item (HPD - arcsec)	Rqmt	Margin	Allocation/Predictions					Rationale
	RGS Resolution	15.00	4.01	14.46					4 satellites, post-processed
	Co-add 4 satellites				1.00				Superposition of data using X-ray centroids
	On-Orbit Telescope - single satellite				14.42				RSS
	CCD pixelization error					0.41			0.5 arcsec pixels
	• Grating resolution errors					5.00			Estimate
	XMS Resolution	15.00	4.95	14.16					4 satellites, post-processed
	Co-add 4 satellites				1.00				Superposition of data using X-ray centroids
	On-Orbit Telescope - single satellite				14.12				RSS
	• Calorimeter pixelization error					4.08			5 arcsec pixels
Common to XMS & RGS	• Telescope level effects					5.20			RSS
	– Image reconstruction errors (over obs)						4.24		RSS
	– SXT/Telescope mounting strain						2.00		Eng. estimate based on Chandra experience
	– SXT/SI vibration effects						2.00		Chandra experience (jitter)
	– SXT/SI misalignment (off-axis error)						1.00		Chandra experience
	– SXT/SI focus error						0.20		Analysis
	• SXT Optics - on-orbit performance					12.48			RSS
	– SXT Mirror launch shifts						2.00		Eng. est. based on Chandra
	– Thermal errors						2.24		RSS
	– Material stability effects						1.00		Est. based on Chandra work
	– SXT Mirror, as built						12.07		RSS
	--Gravity release							1.50	FEA analysis using vertical assy
	--Bonding strain							3.00	Eng. estimate, analysis in process
	--Alignment errors (using CDA)							3.38	RSS
	--Installation in housing							5.00	Est. based on OAP1 testing
	--Optical elements							9.90	Est. based on tech dev program

Legend: Requirement 🟨 Margin 🟧 RSS Prediction 🟪 Allocation 🟩

reflection stages, referred to as primary (paraboloid), and secondary (hyperboloid).

Key components of the mirror include: (1) Reflectors, consisting of thermally formed glass substrates with an epoxy replicated reflecting surface (Foldout 3-A5). A gold overcoat provides high reflectivity in the 0.25-10 keV bandpass. The primary and secondary reflectors are separate pieces. Each outer module contains 90 reflector pairs, each inner contains 140; an SXT mirror has 3,840 reflectors. (2) Module housings, fabricated from a laminate consisting of carbon fiber composite and aluminum sheets, designed to match the coefficient of thermal expansion (CTE) of the reflectors. (3) A mounting plate, also CTE matched to the reflectors, which form an interface surface to the RGA. Each module, in turn, is incorporated in the FMA (Foldout 3-E).

Table 1-4: SXT FMA Requirements Per Observatory

SXT FMA Performance Requirements		Trace to Top-Level Mission Requirements Foldout 1
Bandpass	0.25 to 10 keV	Allocation of mission bandpass to SXT
Effective area (per mirror)		Provides 33,000 cm^2 at 1 keV and 6,900 cm^2 at 6 keV for the mission. Allows effective area losses due to detector efficiency, etc., to achieve TLRD baseline requirement per error budget summarized in Table 1-2.
@0.25 keV	8,826 cm^2	
@1.25 keV	8,421 cm^2	
@6 keV	1,722 cm^2	
Angular resolution	12.5 arcsec HPD	Error budget allocation to mirror that allows telescope system to achieve requirement of 15 arcsec with 4 arcsec margin combined by RSS (Table 1-3)
Field of view	2.5 arcmin	Exceeds instrument FOV; defined by detector FOV
Derived Requirements: SXT Mirror		**Derivation**
Diameter	1.6 m	To meet mission area requirements with 4 mirrors
Focal length	10 m	Consistent with grazing angle requirements for 1.6 m diameter mirror
Axial length	<70 cm	To fit within envelope and meet fabrication considerations
Operating temperature	20±1° C nominal	Range is per allocation from SXT angular resolution error budget (Table 1-3); minimizes angular distortions imposed by temperature change to components. Operating temperature is determined by optics assembly temperature
Mass	642 kg	Current engineering estimate
Derived Requirements: SXT Grating: See Table 1-3		
Derived Requirements: Thermal Pre/Post collimators		
Temperature gradient	1° C across diameter 1° C axial	Allocation from SXT angular resolution error budget (Table 1-3); minimizes angular distortions imposed by temperature gradients
Mass	47 kg	Current engineering estimate

SXT Mirror Estimated Performance: The expected SXT mirror performance is consistent with the requirements for meeting mission measurement and investigation objectives. Table 1-2 shows the overall SXT effective area vs. requirements. The predicted overall effective area at 1.25 keV is 15,200 cm^2. Based on the measured performance of the prototype components, it is anticipated that the SXT mirror will have an angular resolution of 12.5 arcsec, independent of energy, consistent with the error budget in Table 1-3. This anticipated value leaves a 4 arcsec performance margin. The angular resolution will not degrade appreciably across the instrument FOV.

Table 1-5: SXT Mirror Key Parameters

Parameter	Description
Design	Segmented Wolter I
Reflector substrate material	Thermally formed glass
Reflecting surface fabrication	Epoxy replication
X-ray reflecting surface	Gold
Number of nested shells	140 (inner); 90 (outer)
Total number of reflectors	3840
Reflector length	20-30 cm
Number of modules	6 (inner); 12 (outer)
Module housing composition	Composite/aluminum laminate, CTE-matched to substrate
Largest reflector surface area	0.16 m^2
Substrate density	2.4 gm/cm^3
Reflector thickness	0.4 mm
Reflector microroughness	0.4 nm RMS
FMA mechanical envelope	1.7 m dia x 1.65 m

SXT FMA Design/Flight Heritage and Development Items: Wolter I mirrors have been flown on Einstein, ROSAT, Chandra, and XMM-Newton. The multiple-nested, thin-walled reflector SXT design draws its significant heritage from the segmented, thin foil mirrors developed at GSFC. The reflecting surfaces of the foil mirrors have traditionally been conical approximations of the curved Wolter I surfaces. These mirrors flew on BBXRT, ASCA, Astro-E, and InFOCμS, and are being prepared for Astro-E2. The SXT design has technological overlap with the XMM-Newton mirrors, sharing similar concepts for mass production process and facility, and for multiply-nested thin, lightweight shells leading to comparable imaging performance. The SXT mirror development also exploits the extensive experience gained from Chandra and its predecessors, ROSAT and Einstein, in systems engineering and modeling, alignment, and thermal pre- and post-collimator design. Collimators are further discussed in Section 2.4.1.1.

1.3.1.2 Reflection Grating Spectrometer

The RGS is an array of co-aligned reflection gratings (RGA) and an array of back-illuminated (BI) CCD detectors (the RFC) that detect the X-rays reflected and dispersed by the RGA. The RGA, which consists of about 1000 individual gratings held in grazing incidence with respect to the local converging beam, works as a single dispersive optic. It focuses X-rays passing through the SXT onto the RFC in an "inverted Rowland circle" design (Foldout 2-C). The RGS block diagram is shown in Figure 1-3.

The RFC (Foldout 4-B12) uses two separate camera systems: the Spectroscopy Readout Camera (SRC) and the Zero Order Camera (ZOC). The SRC is a long, narrow strip of CCDs that images the dispersed spectrum from the gratings over the RGS bandpass while the ZOC reads out the image of the sky (the grating zero-order image) reflected off the gratings. The ZOC is required to anchor the spectrometer wavelength scale by tracking small aspect drifts on the sub-arcsec scale.

RGS Requirements: The RGS system performance requirements are provided in Table 1-6, along with the trace to the top-level mission requirements, and the derived requirements for the RGA and RFC. The RGS spectral resolution is driven by the SXT mirror angular resolution, resulting in a reflected requirement from the RGS onto the SXT angular resolution performance of 15 arcsec.

RGA Implementation: The RGA uses a modular approach. The thin gratings are aligned and assembled into grating subassembly modules, identical subgroups of gratings that are made up of about 10 gratings each (Foldout 3-D19).

The gratings are aligned with respect to one another and to reference surfaces on the module frames. The alignment fixturing disengages from the gratings after the gratings are bonded to the subassembly frame. These identical grating modules are in turn attached to the array

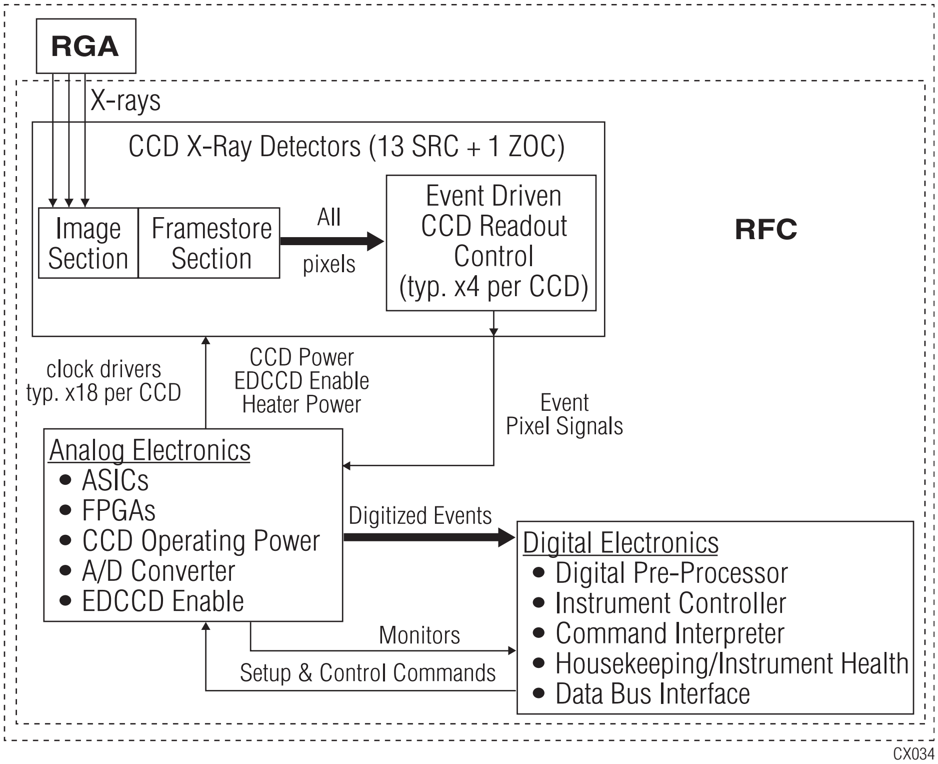


Figure 1-3: Block Diagram of the RGS System

Table 1-6: RGS Requirements Per Observatory

RGS Performance Requirements		**Trace to Mission Top-Level Requirements (Foldout 1)**
Bandpass	0.25-2.0 keV (6 to 50 Å)	In combination with XMS, meets spectral resolution rqmts over the 0.25 – 10 keV bandpass. 1 to 2 keV used for calibration with XMS
Spectral resolving power,R ($\lambda/\Delta\lambda$)	≥300 below 1 keV	Meets TLRD baseline requirement for R
Effective area @0.25 keV @0.6 keV @1.25 keV	 250 cm^2 625 cm^2 175 cm^2	Flowdown from mission baseline effective area requirement
Derived RGS Grating Array Requirements		**Derivation**
Grating efficiency: @0.25 keV (1st Order) @0.6 keV (1st Order) @1.25 keV (2nd Order)	 >0.14 >0.22 >0.06	Flowdown from area requirements. Theoretical efficiency with 50% margin. Met with 40% margin when measured efficiencies for anisotropically etched grating test ruling are used
Interception factor	0.57	Fraction of X-rays entering RGA intercepted by gratings and dispersed in the various orders. Flowdown from area requirements
Straight-through factor	0.38	See Inteception factor (above)
Grating goove parameters α: incidence angle γ: graze angle d: groove spacing	 α = 1.61 deg. γ = 2.21 deg. 1/d = 407 mm^{-1}	Given 15 arcsec HPD telescope, and requiring $\lambda/\Delta\lambda$=400 at blaze (blaze = 0.605 deg.) reflectivity is optimized there using scalar diffraction theory
Grating flatness	≤2 arcsec FWHM	Grating error budget flowdown for spectral resolution. Combined with alignment error, allows broadening of the line spread function core by no more than 30% and SXT mirror dominates
Grating to grating alignment	≤2 arcsec FWHM	See grating flatness item (above)
Mass	50 kg	Current engineering estimate
Derived RGS Focal Plane Camera Requirements		**Derivation**
Quantum efficiency @0.25 keV @0.6 keV @1.25 keV	 >0.86 >0.93 >0.98	Flowdown from area requirements
Energy resolution at 250 eV	> 90% events within 100 eV band	Required to separate spectra from overlapping orders. The requirement is met with 20% margin by state-of-the-art (ACIS-S) BI CCD's
Optical Blocking Filter -Visible light rejection -X-ray transmission @0.25 keV @1.25 keV	 $>10^8$ >0.8 >0.98	 Optical light rejection to avoid CCD pulse height confusion Flowdown from area requirements in conjunction with grating efficiency meets the top-level area requirements
Optical starlight rejection	≤1 electron/pixel/readout for 10 magnitude star	Joint requirement on pre-collimator, SXT straylight performance, and SRC CCD optical blocking filter performance
Pixel size	24 μm	Required to critically sample the Point Respose Function
SRC number of pixels, dispersion direction	1.3 X 10^4	Required to cover the dispersed instrument bandpass (0.25 to 2 keV), given above pixel size and SXT focal length. (1024 pixels x 13 CCDs)
SRC number of pixels, cross-dispersion direction	512	Required to provide adequate areas to enable background subtraction
ZOC CCD format	1024 X 1024	Identical to SRC chips to minimize costs
Frame readout rate	2 second integration time per frame	< 50% pileup in central CCD pixel for bright source limit, assuming 20% flux in single emission line
Operating temperature	-60° C to -80° C	Reduces hot and flickering pixels
Mass	33 kg	Current engineering estimate

integrating structure to assemble the full grating array. Attachment to the integrating structure may be done by preparing precise receiving ends for the kinematic mounts built into the grating module frames or by aligning and bonding each grating subassembly. Table 1-7 shows the RGA design properties.

RFC Implementation: The CCD cameras that make up the RFC feature 13 backside illuminated CCDs with optical blocking filters applied directly on the thin insulating layer of the backside. CCDs in the Spectroscopy Readout Camera are mounted parallel to one another to form an approximate Rowland Circle (Foldout 4-B12). The CCDs' readout frequency is set to avoid X-ray event pileup, noisy pixels, and optical stray light. High frequency readout of the CCDs within the allowed power allocation is made possible by using "event drive" circuitry that involves a non-destructive charge sensor and a CCD "first-in, first-out" readout scheme where the significant pixels are diverted and eventually digitized (Foldout 4-B13). A block diagram of the RFC is provided within Figure 1-3.

Estimated RGS Performance: The effective area of the RGS instrument is shown in Figure 1-1. The predicted RGS effective area at 0.6 keV (including first and second spectral orders) exceeds its requirement by over 100%. The RGS significantly exceeds the mission requirement for resolving power R of 300 at lower energies.

RGS Design/Flight Heritage and Development Items: Mission requirements of the RGS will be met by using a design model with heritage from the reflection grating spectrometer instrument aboard XMM-Newton whose performance parameters are very similar to the Constellation-X RGS. The baseline design for the RGS is a scaled-up version of the existing grating spectrometer aboard XMM-Newton. The two XMM-Newton grating arrays each consist of 182 precision-aligned (2 arcsec), flat (2 arcsec), lightweight grating replicas of a single master grating. Approximately five times as many gratings will be required for each Constellation-X RGS, with a similar alignment budget. Consequently, the major development areas for the RGS lie in reducing the mass per unit mirror aperture area and improving fabrication processes for grating fabrication and CCDs. These areas of development are described in more detail in Sections 3.1.2 and 3.1.3.

Table 1-7: RGS Grating Array Parameters

Parameter	Description
Design	Reflection grating positioned on Rowland circle
Grating substrate material	Slumped glass or silicon wafer
Substrate density	2.4 g cm^{-3}
X-ray reflecting surface	Gold
Number of gratings per module	~10
Number of grating modules per assembly	100
Grating area (per grating)	100 x 200 mm
Grating thickness	< 0.9 mm
Module housing composition	Beryllium or graphite epoxy

1.3.1.3 X-ray Microcalorimeter Spectrometer

The XMS (Foldout 4-A) uses an X-ray microcalorimeter to sense individual X-ray photons as heat[16] and determine their energy with high precision (Figure 1-4). The unique feature of the microcalorimeter is that it combines very high spectral resolution with high quantum efficiency over a broad energy band in a nondispersive spectrometer. Thermodynamic limits determine the spectral resolution and drive the need for operation at a temperature below ~0.1 K. Although extraordinarily cold, such temperatures can be readily

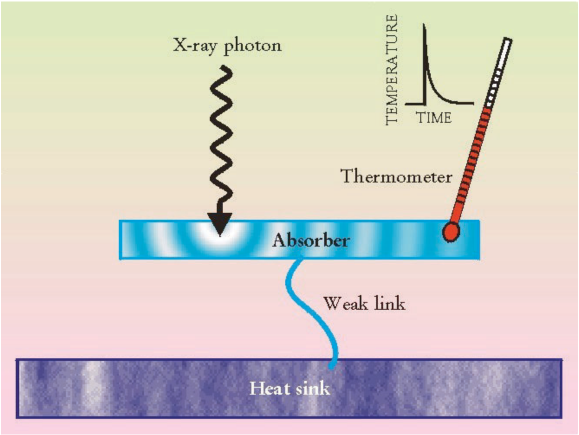


Figure 1-4: Conceptual Diagram of an X-ray Microcalorimeter

achieved and maintained using flight proven techniques.

XMS Requirements: The science requirements on Constellation-X specified in Section 1.2.1 require an X-ray spectrometer with very high resolving power (>1000) and nearly 100% intrinsic quantum efficiency over a ~10 keV energy bandpass, and rapid response time. The field of view and spatial resolution must be sufficiently high to spatially resolve an extended structure larger than the HPD of the SXT mirror without loss of spectral resolution. These requirements can only be achieved with an X-ray microcalorimeter array. Specific performance requirements are given in Table 1-8.

XMS Implementation: A block diagram of the XMS is shown in Figure 1-5 and the key technologies are shown in Foldout 4-A. The reference design consists of a 32 x 32 array of superconducting Transition Edge Sensors (TES) based on microcalorimeters. The TES pixels are read out using Superconducting Quantum Interference Device (SQUID) amplifiers. There will be first-stage SQUID transformers coupled to each pixel, and these will in turn be coupled and multiplexed to a smaller number of second-stage SQUIDs. The second-stage SQUIDs will actually be series SQUID arrays for amplification and coupling to the external electronics. Surrounding five sides of the detector housing will be an active

Table 1-8: XMS Performance Requirements

XMS Performance Requirement		**Trace to Top-Level Mission Requirements (Foldout 1)**
Bandpass	0.6 – 10 keV	TLRD
Spectral resolving power (E/ΔE)	1500 at 6 keV	TLRD
Angular resolution	5 arcsec	Oversample SXT PSF by a factor of 3
Field of view	2.5 arcmin	TLRD
Derived Detector Requirements		**Derivation**
Pixel size	242 μm	Meets TLRD beam sampling requirement
Number of pixels	32 x 32	Gives 2.7 arcmin FOV vs. 2.5 arcmin requirement
Energy resolution	4 eV at 6 keV; 2 eV at 1 keV	Gives E/ΔE = 1500 at 6 keV
Intrinsic quantum efficiency	95%	Flowdown to meet effective area req.
Detector speed	<300 μsec pulse decay time constant	Supports bright source counting rate req.
Time resolution	10 μsec	Allocation to meet absolute timing req.
Derived CADR Requirements		**Derivation**
Detector stage temperature	0.050 – 0.070 K	Required to achieve detector energy resolution
Temperature stability	~2 μK RMS from 1 Hz to 2 kHz	Base temperature of array must be maintained so as not to change detector response
Cooling power	6 μW for array stage 1 mW for “1 K” stage	Based on estimated heat load into detector stage and heat sink for 2nd stage SQUIDs
Derived Cryocooler Requirements		**Derivation**
Cooling power	20 mW at 6 K	Cryocooler cooling power based on overall CADR system design requirements
Lifetime	Same as overall mission	No consumables are being considered for the baseline
Derived Instrument Requirements		**Derivation**
Mass	147 kg	Current engineering estimate
Power (watts)	80/146 (min/max) 150/200 (BOL/EOL)	For analog, digital, CADR control electronics Cryocooler electronics
Data rate (avg/peak)	7.2/640 kbps	Average source rate plus 840 bps H/K data Peak rate from bright sources limit

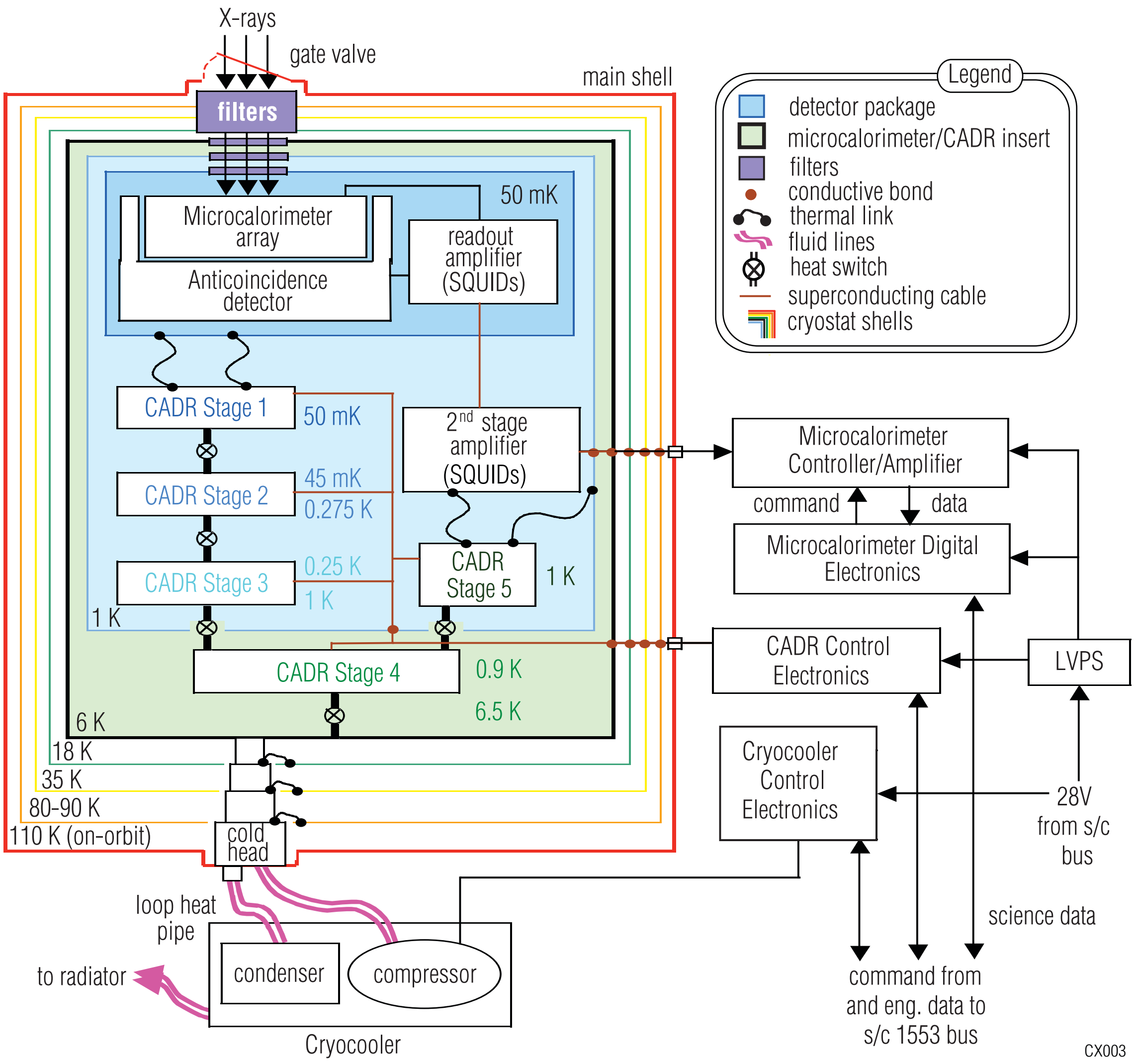


Figure 1-5: XMS Instrument System Block Diagram

anticoincidence detector, based on a thermal detector, sensitive to ballistic photons produced by charged particles. This will also be read out with SQUID amplifiers to simplify the design of the detector. Such detection schemes are typically used in ground-based dark matter searches[17].

The XMS cooling system (consisting of the CADR and cryocooler) has no stored cryogens, thus maximizing the lifetime/mass ratio for the instrument. Cooling of the detector stage will be achieved using a multistage CADR (Foldout 4-A10), which provides the necessary cooling power down to 50 mK. The warmer stages of the CADR are sequentially linked through heat switches and then cycled to transfer heat to the relatively warm cryocooler interface. The intermediate temperatures will be set during Phase B by trade studies involving the blocking filters, series SQUID arrays, and CADR efficiencies. The final operating temperature of the series SQUID arrays will be determined as the system design of the TES, CADR, cryocooler and cryostat matures.

A mechanical cryocooler will provide the 6 K heat sink for the CADR and will actively cool several thermal shields within the cryostat (Foldout 4-A9). It will also thermally anchor internal XMS signal and CADR current leads. The cryostat will provide the necessary structural support and thermal isolation for all microcalorimeter, CADR and cryocooler components contained within the outer shell.

Blocking filters in the aperture of the cryostat prevent heating of the detector stage by non-X-ray radiation. Transmission of these filters determines the low energy limit to the bandpass (~0.25 keV). The high-energy limit (>10 keV) is determined by the X-ray absorption efficiency of the absorber and the SXT mirror reflectivity. The X-ray photons are amplified, demultiplexed, triggered, and then analyzed for pulse height, arrival time, and anticoincidence with the analog and digital electronics external to the cryostat. The cryostat will have a one-time use aperture door that will be opened after launch after outgassing levels are adequately low (typically 2-3 weeks).

The XMS will be calibrated based on the Astro-E/E2 model. X-ray monochromotors will be attached to the XMS cryostat and used to measure the energy gain and spectral redistribution function over a wide range of instrument operating parameters. They will also be used to measure the X-ray transmission of the X-ray blocking filters.

Estimated XMS Performance: The baseline XMS design meets the basic performance requirements listed in Table 1-8. At 6 keV, the overall quantum efficiency is determined by the filling factor of the array. This works out to 95% with 6 μm gaps between pixels (8 μm has already been demonstrated (Foldout 4-A). At lower energies, the transmission of the blocking filters determines the efficiency, and transmissions have been adopted based on Astro-E2-like aluminized-polyimide designs. The overall effective area of the XMS/SXT is shown in Figure 1-2 and meets the baseline requirements.

Single-pixel TES devices with a resolution of 2-4 eV at 1.5 keV have already been demonstrated, and a resolution of about 4 eV has been demonstrated[18] in a TES at 6 keV. Microcalorimeters with semiconducting thermometers (ion-implanted Si or neutron transmutation-doped Ge) have achieved 4-6.8 eV[19]. These values meet the baseline requirements of Table 1-1. An energy resolution of 1.9 eV is possible for an ideal TES detector with T_c = 100 mK, heat sunk to 50 mK and meeting the Constellation-X requirements for pixel geometry and efficiency. Real devices have additional noise that seems to behave in a manner dependent on the device fabrication process. This indicates that it should be possible to reduce this noise component through systematic device engineering and optimization. Progress in this field has been extremely encouraging, and it is anticipated that a resolution of 2 eV at 6 keV will be achieved. Thus, the key development area for the XMS is producing large, close-packed arrays of microcalorimeters with this level of performance.

Technology Heritage and Development Items: Microcalorimeter spectrometers have been developed for space applications for an orbiting observatory[20] (the Astro-E2 high resolution X-ray Spectrometer [XRS]) and two successful suborbital flights[21], the X-ray Quantum Calorimeter (XQC), as well as numerous ground-based instruments. Under construction for a launch in February 2005, Astro-E2 will replace the original Astro-E observatory that was lost during launch in February 2000. Figure 1-6 depicts an actual 36-element flight microcalorimeter array from the Astro-E2 XRS program. Four support beams for each pixel provide thermal isolation and electrical readout (for clarity, the image shows the array prior to absorber attachment; the pixel pitch is 640 microns). The relevance to Constellation-X is that many of the XMS component technologies take their heritage from the designs and flight qualification processes of these programs.

The technology required for the XMS is rooted in extensive space flight development programs at GSFC. XRS and XQC instruments use pixel arrays based on semiconductor thermometers and cooled to 60 mK with single-stage CADRs in cryogenic systems

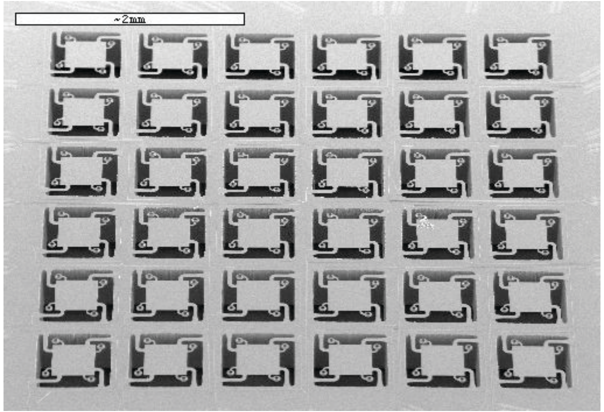


Figure 1-6: Actual flight qualified X-ray microcalorimeter array from Astro-E2 XRS. Shown prior to absorber attachment.

designed to survive the demanding loads of solid rocket launch vehicles. Based on pre-launch thermal balance tests, the XRS He dewar achieved its demanding requirement of < 1.2 mW total heat load with 30% margin[22]. Digital signal processing with optimal filtering has been developed and used onboard these instruments to achieve maximal spectral resolution with minimum telemetry downlink.

The SQUIDs required for readout have also been fabricated at the National Institute of Standards and Technology (NIST). Although these must be further developed and subjected to space environmental testing, SQUID amplifiers have been successfully flight-qualified under the Gravity Probe B program and a Space Shuttle experiment[23].

The aperture door mechanism will be a spring-loaded pyro-activated design based on the Astro-E/E2 units.

The first space flight Adiabatic Demagnetization Refrigerator (ADR) was developed and qualified for the XRS instrument. An identical unit is presently being built for the Astro-E2 reflight. The design is also the basis for two nearly identical ADRs for two SOFIA instruments (HAWC and SAFIRE) that have been fully tested and delivered. The University of Wisconsin, in collaboration with the GSFC, has successfully operated an ADR in zero-g on its suborbital instrument, the XQC. To date, there have been two successful launches of the XQC, with the ADR maintaining stable operation at 60 mK each time.

Fundamental cryocooler technologies exist in flight coolers employed on HST/NICMOS, AIRS, and TES reaching temperatures down to 50 K. Manufacturers of these coolers have laboratory versions that reach lower temperatures, and they are now involved in the development of the needed 6 K cryocoolers.

1.3.1.4 Hard X-ray Telescope

The HXT on each observatory consists of three highly nested, multilayer-coated, grazing incidence mirror assemblies, each of which focuses onto a separate hard X-ray detector. Multiple, modest diameter mirror assemblies provide shallow graze angles, maximizing the reflectivity at energies above 10 keV. Depth graded multilayer coatings on the mirrors further increase the bandpass and FOV over that achievable with standard metal coatings. The HXT is coaligned with the SXT to ensure that both telescopes view the same target. Figure 1-7 shows a block diagram of the HXT.

HXT Requirements: Table 1-9 summarizes the HXT requirements, traced to the top-level science requirements.

Implementation: Each mirror assembly consists of a nested set of approximately 150 shells in a conical approximation of a Wolter-I geometry. In the reference implementation, each shell is divided into six segments in azimuth and four segments along the optical axis, for a total of 24 segments per shell. Table 1-10 lists the HXT mirror parameters.

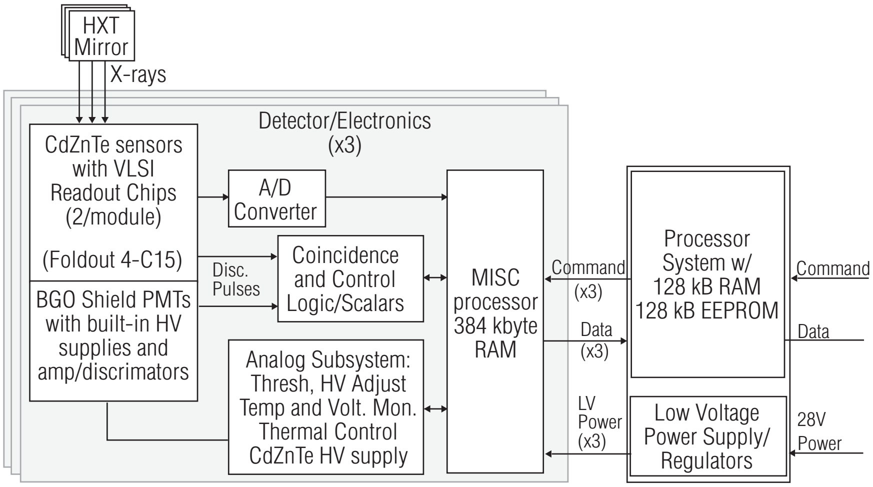


Figure 1-7: Block diagram of the HXT system

Table 1-9: HXT Requirements Per Observatory

HXT Performance Requirements		**Trace to Top-Level Mission Requirements**
Bandpass	6 to 40 keV	Allocation of mission TLRD band pass to HXT; provides calibration with SXT from 6 to 10 keV
Spectral resolving power (E/ΔE)	10	Meets baseline mission requirement for R, for 10 keV and above
Angular resolution	<1 arcmin HPD	Meets baseline mission angular resolution requirement for 10 keV and above
Signal/background	≥1 for T< 2 x 10^4 sec	
Field of view	≥8 arcmin	Meets mission FOV for 10 keV and above
Mass	151 kg	Current engineering estimate
Derived HXT Mirror Requirements		**Derivation**
Focal length	10 m	Provides shallow graze angles for high-energy
Diameter	40 cm	
Collecting area	625 cm^2 for each mirror (7500 cm^2 for mission)	Is requirement
Derived HXT Detector Requirements		**Derivation**
Pixel size	500 micron	Corresponds to 10 arcsec; oversamples by a factor of 6
Number of pixels	28 x 48	2 hybrids per focal plane
Quantum efficiency	0.90	
Operating temperature	-15° C to -5° C	

The reflectors are fabricated by thermally forming thin glass sheet into cylindrical segments of approximately the correct radius. These segments then undergo an epoxy replication step against a polished conical mandrel to remove mid-frequency figure errors. The segments are then coated with a depth-graded W/Si multilayer structure in a magnetron sputtering chamber (Foldout 3-C12). The segments are characterized for reflectance and mounted into the mirror.

Table 1-10: HXT Mirror Parameters

Parameter	Description
Design	Segmented Wolter I conical approximation
Substrate material	Thermally formed glass
Reflecting surface fabrication	Epoxy replication
X-ray reflecting surface	W/Si graded multilayer
Number of nested shells/mirror	150
Number of reflectors/mirror	1800
Reflector length	12 cm
Number of azimuthal segments	6
Largest reflector surface area	250 cm^2
Outer, inner mirror radius	6, 20 cm
Substrate density	2.4 g cm^{-3}
Reflector thickness	0.3 mm
Reflector roughness (RMS)	0.3 nm

The mounting process begins with a central mandrel, which serves as a base and also to locate and align the final mirror assembly in the OB. Using a custom assembly machine, glass segments for a shell are laid down, and graphite spacers epoxied to the back (Foldout 3-C11). The spacers are then machined to the desired surface, and the next shell is laid. This method constrains the segments to the desired final radius and eliminates stackup error.

The focal plane for each mirror assembly contains a high-Z, wide bandgap semiconductor (CdZnTe or CdTe) detector readout by a custom, low-noise ASIC. The detector is hybridized: the anode contact is segmented into pixels (Foldout 4-C15, insert), with each pixel bump bonded to a separate readout channel on the ASIC chip. The pitch of readout circuits matches that of the contacts on the sensor. Due to size limitations on the readout and sensors, each focal plane will contain two hybrids mounted side-by-side on a board (Foldout

Table 1-11: HXT Detector Parameters

Parameter	Description
ΔE (FWHM)	<1.2 keV (6 keV)
Dimension	2.3 x 2.3 x 0.2 cm
Bits/photon	48
Max. count-rate	50 cts/sec/pixel 200 cts/sec/module
Typical count-rate	5 cts/sec/module
Time resolution	10 microseconds

4-C15). Table 1-11 summarizes the detector parameters. The 500 μm detector pixel size corresponds to 10 arcsec at the focal plane, meeting the top-level oversampling requirement. Each module (two hybrids) is supported by a Minimal Instruction Set Computer (MISC) processor situated on a board immediately behind the detectors. This processor controls readout of the ASIC and other external logic functions.

Because the HXT operates at high X-ray energies, where detector background dominates over diffuse emission from the sky, the HXT requires an active anti-coincidence shield to reject particle and locally produced photon backgrounds. The shield will be fabricated from an active inorganic scintillator (BGO or CsI), and will be configured in a well geometry, with the detector at the bottom. Determination of the geometry is awaiting detailed calculations of the background environment in the Constellation-X orbit.

Absolute HXT calibration will be largely performed in flight using cosmic sources. Routine gain stabilization will be accomplished using a pulser built into the ASIC and by small, radioactive ^{241}Am sources placed inside each anticoincidence shield.

Estimated HXT Performance: The configuration described above meets HXT performance requirements as listed in Table 1-9. Figure 1-1 shows a calculation of the effective area for the baseline, which exceeds the required 1500 cm^2 below 40 keV and has sensitivity extending to 60 keV. The HXT angular resolution performance prediction of 43.5 arcsec meets the requirement of 60 arcsec with significant (41 arcsec RSS) margin. This performance estimate is supported by a detailed error budget similar to the one developed for the SXT (see Table 1-3).

HXT Design/Flight Heritage and Development Items: HXT optics technologies are extrapolations of systems developed for balloon experiments. All principal fabrication steps for HXT optics have been demonstrated. Glass segments have been produced with multilayers of the required design and the reflectance demonstrated as high enough to meet the requirement. Segments have been mounted with sufficient precision to exceed the angular resolution goal, and prototype units have demonstrated that 45 arcsec resolution can be achieved with unreplicated shells on the outer radii (Foldout 3-C14). It remains to be demonstrated that replicated shells will meet resolution requirement at small radii, although modeling indicates that this will not be a major obstacle. In addition, the throughput due to obscuration must be improved to meet the HXT specification, and a prototype unit must be tested in the relevant environment.

The detectors (pixel sensor and custom low-noise electronics) have been developed for the HEFT balloon program, and will be demonstrated in flight in Fall 2003. The CdZnTe sensor material will soon have flight heritage from the Swift experiment and has been flown on at least five balloon experiments, including InFOCμS and EXITE. Flight-sized detectors have been fabricated and tested and currently meet the spatial resolution, count rate, spectral resolution, and quantum efficiency requirements. Further development of the ASIC is required to meet the low-energy threshold requirement (to allow cross-calibration with the XMS), and the packaging and interconnects currently are not space-qualified.

1.3.2 Mission Approach

The mission approach is addressed in Section 2. In particular, observatory and operations performance requirements are presented in Table 2-1 and Section 2.1. The mission operations concept is discussed in Section 2.3. Data validation, analysis, and archiving are discussed in Section 2.4.3.

2.0 MISSION IMPLEMENTATION PLAN

This section addresses all aspects of mission implementation, and, together with material in Section 1.3.1, describes the overall mission. Observatory and operations performance requirements addressed below and shown in Table 2-1 follow the overall approach of relating requirements to the science objectives described in Section 1.3.1.

2.1 Mission Approach

The mission approach for Constellation-X uses proven technology and processes for the spacecraft (s/c), launch vehicle, and operations from start to finish. The straightforward mission design demonstrates mission feasibility and readiness to proceed to the next phase, reduces risk, and ensures that mission objectives are achieved within mission constraints. The modular approach to design allows for parallel testing and makes use of simple interfaces, reducing the cost of I&T as well as the technical risk. Observatory performance can be verified on the ground, further reducing cost and complexity. Risk areas have been identified and risk mitigation strategies developed. See Section 4.1.2.7 for a discussion of risk management.

This section describes a Reference Mission design and architecture[24] developed by GSFC and SAO and which includes study results from TRW and Ball Aerospace done under NASA Cooperative Agreement (CAN-555-46-232). This reference configuration is one viable way to meet the science requirements: it proves the mission concept, aids in costing and requirements management, and forms the basis for trade studies. Future proposals will be compared with the reference design to verify that these solutions can meet mission requirements.

2.2 Launch, Trajectory, and Orbit Characteristics

2.2.1 Launch

Two separate launches, each of two observatories, are planned. Each pair of observatories will be launched side by side within a single fairing (Foldout 2). The Atlas V launch vehicle is the baseline for the Constellation-X mission because it better suits the volume and mass characteristics of the payloads, although the Delta IV remains an option. Both launch vehicles had their successful maiden flights in 2002 with commercial payloads rather than dummy loads.

The Atlas V 551 launch vehicle has a usable diameter of approximately 5 m and length of 16 m; the payload fairing (PLF) meets the volume required by the side-by-side Constellation-X observatory configuration. The Delta IV 4450-14 launch vehicle has a medium fairing with a usable diameter of approximately 5 m and length of approximately 14 m. Use of a Delta IV requires an extendable optical bench. Either launch vehicle can insert two Constellation-X observatories weighing more than a total of 5,000 kg into the lunar phasing loop orbit.

The observatories will be launched from Cape Canaveral Air Force Station in Florida. Launches are planned for 2010 and 2011.

2.2.2 Trajectory and Orbit

The Constellation-X orbit is a thermally stable Lissajous orbit at the L2 Sun-Earth libration point, like that used on the Microwave Anisotropy Probe (MAP) mission. The L2 point is located on the Earth-Sun line on the anti-Sun side of the Earth, about 1.5 million km away. The orbit provides high viewing efficiency because targets are not eclipsed by the Earth. Each of the four observatories will move about L2 with an approximately 6-month period and a maximum distance from L2 of approximately 300,000 km.

Each pair of observatories will be launched using a single launch vehicle. After launch they will be separated into non-intersecting injection orbits to avoid collision. After separation, each observatory will be maneuvered into a series of phasing loop orbits about the Earth, perform a lunar gravity assist, then follow a cruise trajectory (approximately 100 days) to L2 to its unique orbit. See Foldout 2 for a schematic of this orbit insertion.

The total ΔV required is approximately 177 m/sec per observatory. This includes correcting for launch vehicle errors, targeting the lunar gravity assist, mid-course correction maneuvers, Lissajous orbit insertion, and station-keeping maneuvers. Routine station-keeping maneuvers will be performed approximately once every 90 days.

2.3 Operations Concept

Top-level requirements that flow to the Operations Concept[25] are shown in Table 2-1.

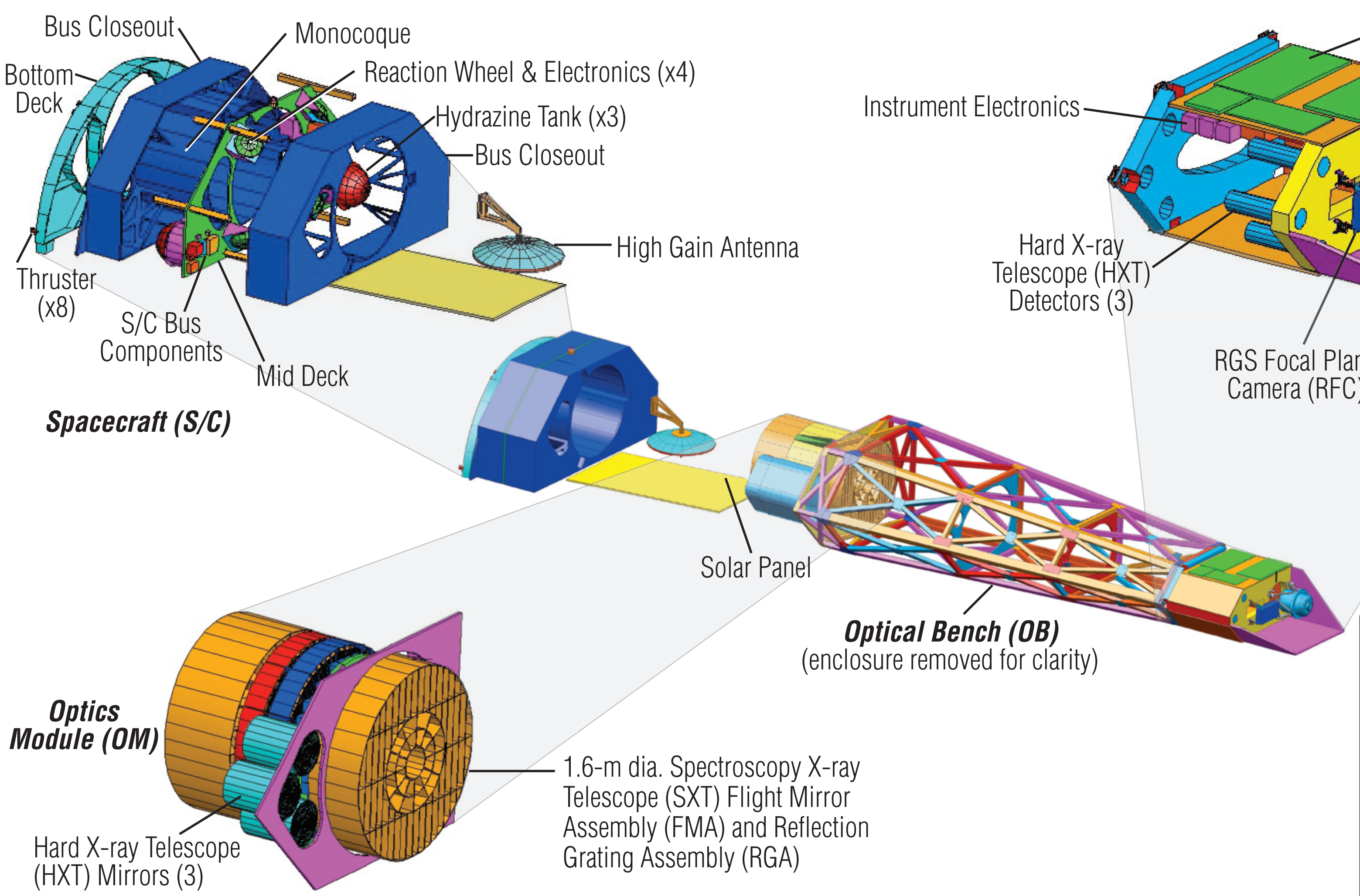
The Constellation-X Science and Operations Center (CXSOC) will evolve from, and be co-located with, the Chandra X-ray Center (CXC) at SAO. This approach is low-risk and

Table 2-1: Driving Observatory and Operations Performance Requirements

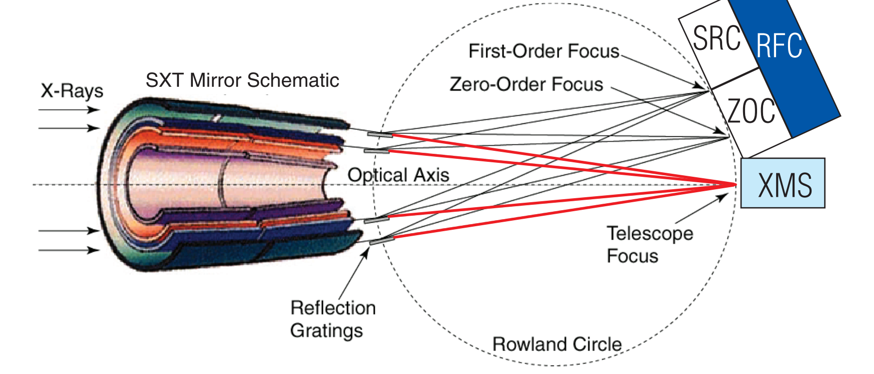
		Parameter	Requirement	Source/Rationale	Performance
Primary Impact On:	Observatory	Telescope pointing (aspect) determination ground-based post processed	5 arcsec, 3σ	Flowdown from aspect determination error budget to meet the celestial location knowledge, Table 1-1	Derived star tracker attitude knowledge requirements is 3 arcsec, 3σ
		Pointing Control	30 arcsec pitch/yaw; 60 arcsec roll	Maintain target within instrument FOV	AOCS system meets the requirement
		S/C Data Storage	On-board memory sized for 3 days normal ops plus 1 bright source observation	Flowdown from Ops Concept to allow missed contacts	43 Gbits for each observatory: sized from instrument data rates (all operate simultaneously)
		Redundancy	No single failure will result in the loss of more than 25% of the mission science	TLRD	Constellation of 4 observatories, each with redundancy in critical systems
		Reliability	Probability of mission success shall be 75% at the end of the normal operations life	TLRD	Each observatory shall be critical-component redundant
		Contamination Control	Level 100 A/3 at launch on all optical surfaces; 100 A at EOL	TLRD, Contamination Control & Implementation Plan: minimize loss of effective area and calibration uncertainties	Dry N_2 purge system (GSE) during I&T and up to launch, witness sample monitoring, adherence to MSFC 1443 for materials selection
		Mass	Meet vehicle throw weight, with margin	RMD	2476 kg observatory mass meets the requirement with 34% margin
		Power	Meet observatory power needs EOL with margin	RMD	1075 W EOL meets the requirement with 34% margin
		Propulsion	Consumables sized to achieve and maintain L2 orbit for minimum of 6 years	TLRD	Tanks sized to meet 10-year goal; wet mass sized for 6-year requirement
	Observatory and Ground Segment	Telemetry Volume	Capable of downlinking 1 day of data per pass; 1 hour per pass	Flowdown from Ops Concept, in conjunction with onboard storage limit	X-band antennas and ground stations sized to meet requirements with link margin
		Downlink Frequency	1 downlink/day/observatory	Ops Concept: joint requirement on sizing of on-board storage	1 downlink/day planned for each observatory
		Timing	Arrival time accuracy of ±100 microseconds (UTC)	TLRD	Arrival time accuracy ±90 μsec
		Mission Duration	4 years normal operations with all satellites	TLRD, Table 1-1	Systems designed to meet requirements
		Observing Efficiency	90%	TLRD, Table 1-1	L2 orbit
		Sky Coverage	90% 2x/year, 100% 1x/year	TLRD	Design meets requirement
		Data Uplink Volume	4 Mb	Ops Concept	Design meets requirement
		Data Uplink Frequency	Once/week	Ops Concept	Science Observing Plan generated and uplinked weekly
		Data Latency	2 weeks (72-hour goal) from completion of observation to product delivery	TLRD	Ground system requirement meets requirement.
	Ground Systems	TOO Frequency	Approx. 2x per month	TLRD, Table 1-1	Design exceeds requirement
		TOO Response Time	<24 hours	TLRD	Meets requirement
		Archive Storage	10 years of all raw and processed (to Level 3) mission data, plus reprocessing	Ops Concept, Table 1-1	Ground system design meets requirement

Constellation-X Mission Description

A Observatory Exploded View



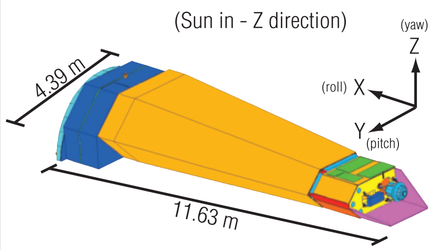
C SXT Optical Path Schematic



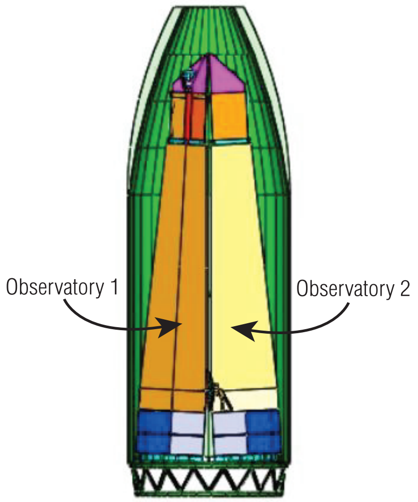
XMS = X-ray Microcalorimeter Spectrometer Instrument

RFC = RGS Focal Plane Camera, SRC= Spectroscopy Readout Camera, ZOC=Zero Order Camera

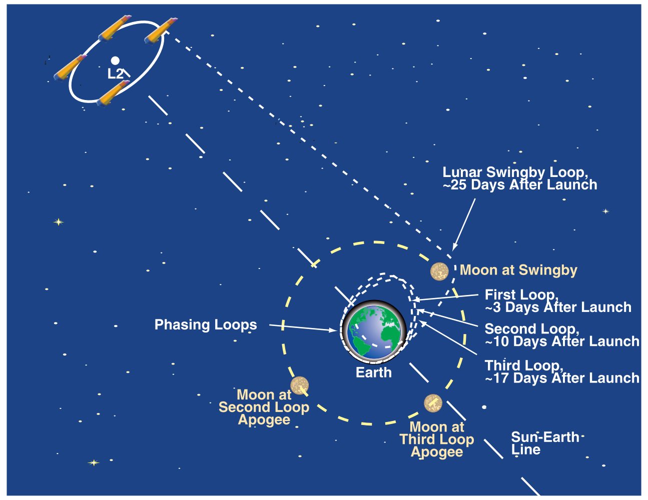
B Constellation-X Flight Configuration (1 of 4)



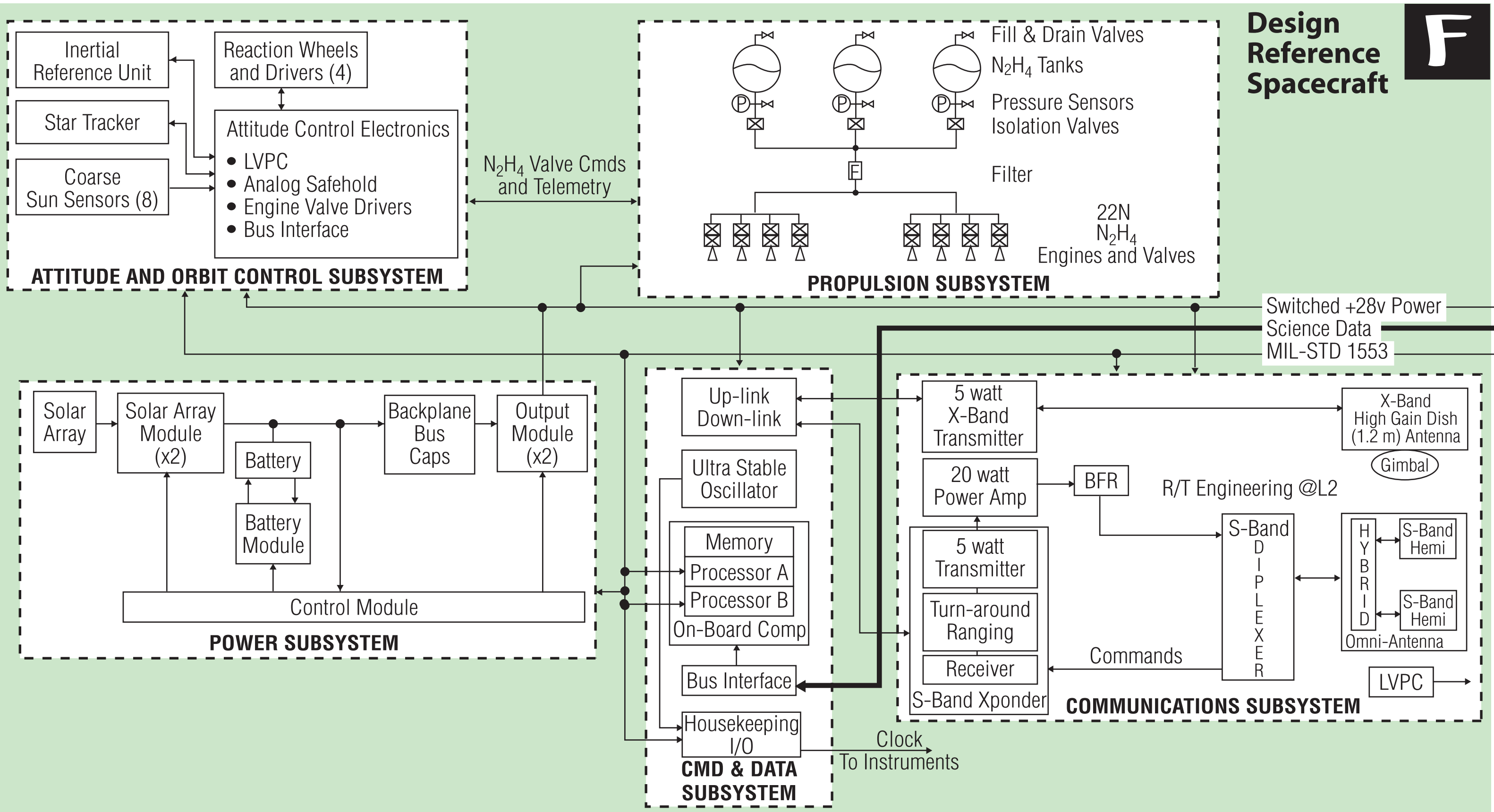
D Constellation-X Launch Configuration



E Trajectory with Phasing Loops and Lunar Swingby



F Design Reference Spacecraft



ATTITUDE AND ORBIT CONTROL SUBSYSTEM

Inertial Reference Unit

Reaction Wheels and Drivers (4)

Star Tracker

Coarse Sun Sensors (8)

Attitude Control Electronics
- LVPC
- Analog Safehold
- Engine Valve Drivers
- Bus Interface

N_2H_4 Valve Cmds and Telemetry

PROPULSION SUBSYSTEM

Fill & Drain Valves

N_2H_4 Tanks

Pressure Sensors

Isolation Valves

Filter

22N N_2H_4 Engines and Valves

Switched +28v Power

Science Data

MIL-STD 1553

POWER SUBSYSTEM

Solar Array

Solar Array Module (x2)

Battery

Battery Module

Backplane Bus Caps

Output Module (x2)

Control Module

CMD & DATA SUBSYSTEM

Up-link Down-link

Ultra Stable Oscillator

Memory

Processor A

Processor B

On-Board Comp

Bus Interface

Housekeeping I/O

Clock

To Instruments

COMMUNICATIONS SUBSYSTEM

5 watt X-Band Transmitter

X-Band High Gain Dish (1.2 m) Antenna

Gimbal

20 watt Power Amp

BFR

R/T Engineering @L2

5 watt Transmitter

Turn-around Ranging

Receiver

S-Band Xponder

Commands

S-Band DIPLEXER

HYBRID

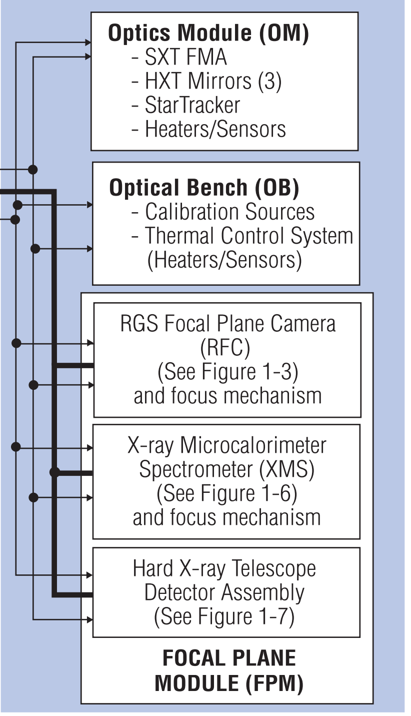
S-Band Hemi

S-Band Hemi

Omni-Antenna

LVPC

G Telescope Module (TM)



Optics Module (OM)
- SXT FMA
- HXT Mirrors (3)
- StarTracker
- Heaters/Sensors

Optical Bench (OB)
- Calibration Sources
- Thermal Control System (Heaters/Sensors)

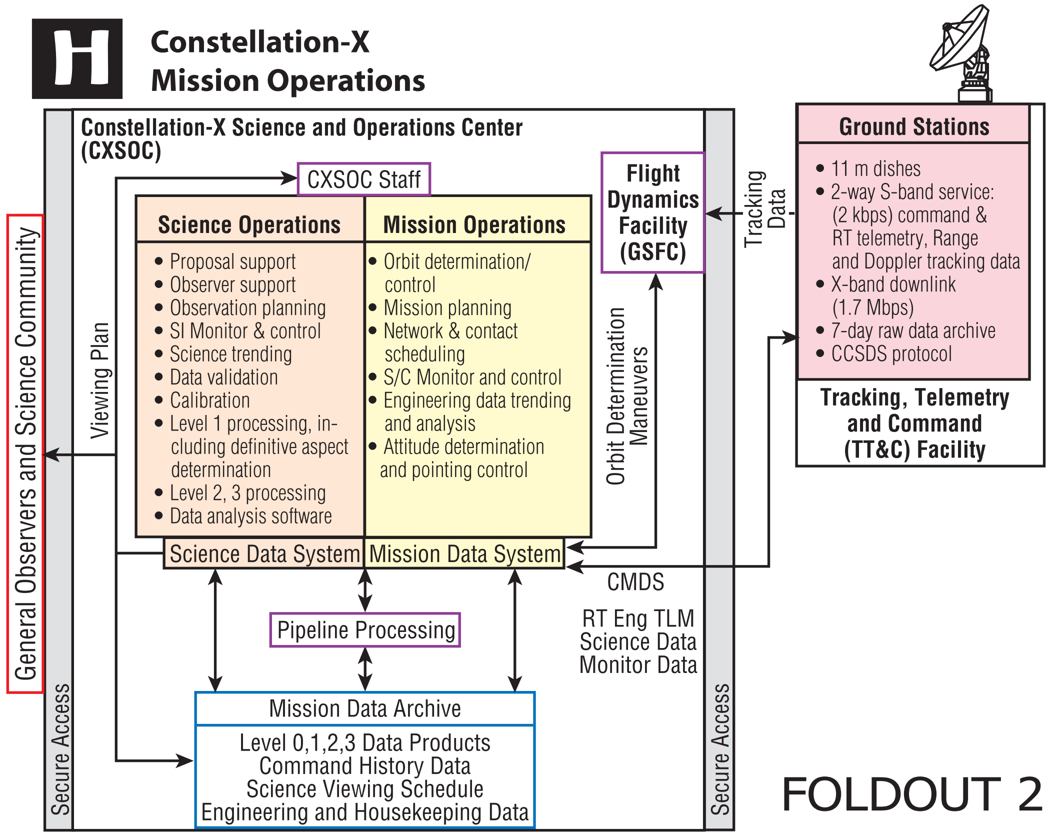
RGS Focal Plane Camera (RFC) (See Figure 1-3) and focus mechanism

X-ray Microcalorimeter Spectrometer (XMS) (See Figure 1-6) and focus mechanism

Hard X-ray Telescope Detector Assembly (See Figure 1-7)

FOCAL PLANE MODULE (FPM)

H Constellation-X Mission Operations



Constellation-X Science and Operations Center (CXSOC)

CXSOC Staff

Science Operations
- Proposal support
- Observer support
- Observation planning
- SI Monitor & control
- Science trending
- Data validation
- Calibration
- Level 1 processing, including definitive aspect determination
- Level 2, 3 processing
- Data analysis software

Mission Operations
- Orbit determination/ control
- Mission planning
- Network & contact scheduling
- S/C Monitor and control
- Engineering data trending and analysis
- Attitude determination and pointing control

Science Data System

Mission Data System

Pipeline Processing

Mission Data Archive

Level 0,1,2,3 Data Products
Command History Data
Science Viewing Schedule
Engineering and Housekeeping Data

Flight Dynamics Facility (GSFC)

Orbit Determination Maneuvers

Tracking Data

CMDS

RT Eng TLM
Science Data
Monitor Data

Viewing Plan

General Observers and Science Community

Secure Access

Secure Access

Ground Stations
- 11 m dishes
- 2-way S-band service: (2 kbps) command & RT telemetry, Range and Doppler tracking data
- X-band downlink (1.7 Mbps)
- 7-day raw data archive
- CCSDS protocol

Tracking, Telemetry and Command (TT&C) Facility

leverages a significant investment by NASA in facilities and expertise. Planning for transition has been initiated. No difficulties are seen in the time frame for CXSOC development. The CXSOC is the primary interface between the General Observer (GO) and the mission. The architecture of the CXSOC is described in Section 2.4.2 as is a discussion of data validation, analysis, and archiving.

CXSOC personnel consist of the following functional teams: Flight Operations, Ground Operations, Mission Data, Systems Engineering, Technical Support, and the Science Division (which works closely with the Science Instrument teams).

Because no inter-observatory communications are required, each observatory is treated separately, and constellation management issues are reduced to managing four identical but independent s/c. CXSOC software contains unique identifying tags for each observatory, ensuring proper control. This allows for re-use of the CXC mission operations tools to the greatest possible extent.

2.3.1 Operations Development

Operations development begins at the start of the implementation phase, with development of the mini versions of the CXSOC Mission Data System (MDS). These provide uniform command, telemetry, data management, and trending functions for use during development, I&T, and flight operations. This minimizes duplication of effort and maximizes commonality in procedures and databases and hence ensures continuity between development and flight operations. The Electrical Ground Support Equipment (EGSE) used by the instrument teams will be planned for integration at the CXSOC to support mission operations.

2.3.2 Launch and Early Orbit

Launch and early orbit support for each launch (two observatories) will last approximately 100 days. The two observatories will be contacted several times per day for health and safety monitoring, observatory checkout and configuration, orbit maneuvers, and science instrument turn-on and initial checkout. Instrument calibrations and checkouts will also be performed during the transit to L2. The Flight Operations Team (FOT), with support from an extended Technical Support Team (TST), will conduct Launch and Early Orbit activities. The TST is composed of civil service, observatory prime contractor, and CXSOC staff. GSFC will provide the Mission Director, and the CXSOC contractor will provide the Mission Manager. Activities associated with launch of the second pair of observatories will be kept physically separate and operationally independent from the ongoing routine operations of the first pair of observatories by using separate hardware and software.

Members of the observatory and instrument test teams will augment the normal operations team during this phase to perform checkouts and verification. After completing this activity, the extended TST will disband and the mission will transition to normal science operations. The core TST will be on-call if needed.

2.3.3 Normal Operations

A long-term Science Plan will be generated based on the accepted proposals submitted by prospective GO. This plan is a timeline of all the current cycle’s time-constrained observations. The remaining (non-constrained) targets will be allocated to one-week slots or pools based on observation length, target visibility, momentum management, and other relevant factors with the goal of maximizing the observing efficiency.

During normal science operations, the CXSOC Science Mission Planning staff will prepare weekly observatory schedules using the Science Plan for the current cycle. This plan, which will be uplinked to each observatory, is a time-ordered set of RA and Dec for specific targets and occasionally a specified roll angle about the boresite. It will include a start/end time to conduct the observation, which may range from 30 minutes to 48 hours in duration. Up to 30 observations will typically be scheduled per week; the sequence of these targets will be selected to help maximize observing efficiency and minimize the momentum buildup in the observatory, as well as meet other observatory pointing constraints. Each target will also have an associated estimated fill rate of the onboard data memory, accurate to approximately 10% after in-flight calibration. The on-board data memory has been sized to accommodate three days of normal operations at the highest nominal mode record rate, plus one day of Target of Opportunity (TOO) operations to allow for flexibility in dumping the memory.

After the observatories are maneuvered to a new target (performed simultaneously to maximize viewing efficiency), any required momentum adjustments will be performed (no more frequently than once every three weeks), and the onboard antenna will be pointed toward the Earth through a combination of antenna tilt angle adjustments and observatory roll angle selection. The FOT will integrate additional observatory activities unrelated to the science observations into the schedule. Constellation-X ground stations will be scheduled for routine operations support using a Contact Plan, which will be generated automatically by the FOT. The Contact Plan will be flexible to allow some leeway in the specific time and/or station used.

At least one (one-hour) ground contact per day to each observatory will be required. During each contact, the on-board data memory will be dumped, and any necessary commands will be uplinked. Tracking data will be collected to refine orbit knowledge. Two stations, separated by at least 40 degrees latitude, will be used on alternate days to achieve the required orbit determination (OD).

The daily downlink of science and engineering telemetry data will take place using a file transfer protocol and be captured in the Constellation-X Mission Data Archive. Nominally, there will be one science observation per file, reducing the need for Level Zero Processing (LZP). The CXSOC will convert the data into Flexible Image Transfer System (FITS) formats; initiate all pipeline processes to be used to validate, process, and calibrate the data; produce mission-related information; and distribute (push/pull) the results. Data products include instrument health and safety, trending information, and the post-facto aspect determination required to meet the celestial pointing accuracy requirement.

Approximately two TOO operations per month may be conducted, which ensures that their execution does not present an excessive burden to operations. A TOO requires that a new observation plan be generated, validated, uplinked, and executed within 24 hours. This amount of data may require additional station passes to downlink the data and will be scheduled separately from routine operations.

2.3.4 Calibration

The CXSOC, with support from the instrument teams, is responsible for planning, implementation, and analysis of the telescope and science instrument calibration of the constellation. Products derived from the analysis of the calibration data are archived to the mission Calibration Database (CalDB). The CXSOC will determine the ground and on-orbit measurements needed to accomplish these calibrations to the accuracy defined in the Calibration Plan[26] and the on-orbit viewing time required to maintain them. The CXSOC will establish calibration viewing requirements prior to each Peer Review, as well as verify that these calibration observations are properly folded into the science plan and the onboard schedule. The CXSOC is responsible for defining the CalDB implementation, its interface to the Science Processing and Analysis software, and for maintaining its content. The CXSOC is also responsible for providing the user interface to the CalDB, and supporting the GO.

2.3.5 Constellation Management

Because the observatories are essentially operated independently and are contacted sequentially only once per day, the existing software systems will be able to handle the mission with few changes. Several operations functions (e.g., station scheduling, trending generation, momentum management, antenna pointing, orbit determination, data management, attitude refinement, timing, correlation, etc.) are easily automated, and other functions produce identical results for all four spacecraft (e.g., science scheduling, attitude maneuvering, etc.). Consequently, these functions result in a small increase in the amount of work over a single observatory. For those functions that are unique to each observatory (e.g., orbit maneuvers, anomaly resolution, etc.), there is a small increase in workload over a single satellite. Flexibility in anomaly resolution is provided by the fact that an anomaly on one observatory does not affect the operations of the remaining observatories, since this is not an interferometric mission. Experience gained with the operations of the first two observatories will be applied to the operations processes of the second pair of observatories.

2.3.6 Staffing

During each launch and early orbit phases of the mission, there will be full shift coverage until stability is achieved. During the transfer orbit, which will last approximately 100 days, and during orbit maintenance activities, staffing will be commensurate with planned activities. The goal is for routine operations to be staffed during a single 8-hour shift 7 days per week. Anomaly recovery and TOOs will likely require some science and operations elements to be on call 24 hours/day, 7 days/week.

2.4 Mission Architecture

2.4.1 Flight Segment/Observatory Concept

Each observatory consists of a TM, and a s/c bus, discussed later in this section (see Foldout 2). The modular configuration of each identical observatory allows parallel processing up to final integration and streamlines I&T. The modules have simple interfaces. The s/c design is straightforward and contains hardware based on mature technologies that have flown successfully on many NASA missions.

2.4.1.1 Telescope Module

The TM comprises mirrors, science instruments, structure, and other associated equipment that combine to form a functioning telescope. This section addresses TM requirements not covered elsewhere.

The TM is subdivided into three modules:

- The Optics Module (OM) includes the SXT FMA, HXT mirrors, star tracker, associated kinematic mounts, and supporting structure.
- The Focal Plane Module (FPM) includes the XMS, the RGS FPC, the HXT detectors and associated electronics, focus mechanisms, support structure, and sunshade.
- The Optical Bench (OB) is a five-sided optical metering structure between the FPM and the OM and also includes both active and passive thermal control systems, X-ray baffles, and electrical harnesses.

TM Structure and Alignment: The TM structure maintains the SXT and HXT mirrors and their respective detectors in precise alignment to each other. The telescope has a nominal 10-m focal length (from optic node to focus). The TM structure is designed to facilitate initial alignment during assembly and maintain alignment through launch and on-orbit operations. Stiffness must be sufficient to maintain alignment in the presence of dynamic disturbance. The first resonant frequency must be greater than 15 Hz. TM components include alignment aids for optical alignment. The TM structures are made of graphite-reinforced epoxy (GREP) optimized for low CTE in specific directions. Two concepts for the OB are under consideration: a truss structure covered with multilayer insulation (MLI) for stray light closeout and a GREP shell structure.

Alignment and alignment stability tolerances between the mirrors and the detectors are given in Table 2-2 along with telescope co-alignment requirements. These tolerances are driven by effective area and angular requirements based on system error budgets as shown in Tables 1-2 and 1-3. These tolerances limit misalignment effects on image resolution to under 1 arcsec (HPD) and effects on throughput to under 1%. Alignment to these tolerances is straightforward and well understood. The alignment process will be similar to the successful process that was used to align the Chandra telescope (not the Chandra mirror).

In Table 2-2, the terms X, Y, and Z refer to displacements between the respective detector center and the mirror focus, in mirror coordinates, and to rotations of the detector axes relative to optical axes. X refers to focus errors (see Foldout 2). The tolerances were derived based on imaging error budget terms. Y and Z are lateral offsets of the detector center from focus position. The lateral stability tolerances

Table 2-2: Alignment and Co-alignment Requirements

Alignment Precision ± Stability	δX (mm) focus	δY (mm) lateral	δZ (mm) lateral	δθX (arcmin) rotation	δθY (arcmin) tip	δθZ (arcmin) tilt
RFC to SXT FMA	1.0±0.2	2.0±0.1	2.0±0.2	4.0±0.5	4.0±0.50	4.0±0.5
XMS to SXT FMA	1.0±0.2	0.7±0.1	0.7±0.1	4.0±0.5	4.0±0.50	4.0±0.5
HXT mirror to HXT detector	10.0±0.2	0.7±0.2	0.7±0.2	4.0±0.5	4.0±0.50	4.0±0.5
HXT/SXT co-alignment	N/A	N/A	N/A	N/A	>0.25	>0.25

were set to limit the image degradation contribution of SXT to detector instability during an observation, per the error budget. HXT tolerances were set in a manner similar to the SXT, with different sensitivities, particularly the effect on image resolution of focus errors. Performance is relatively insensitive to rotations of the detectors. The co-alignment tolerances are defined in terms of boresight-to-boresight rotational alignment. The primary pointing direction will be along the SXT boresight, since the XMS has the smallest detector FOV. Alignment of each HXT boresight to within 0.25 arcmin of the SXT boresight, coupled with the stated HXT lateral tolerances, provides for HXT operation no more than 0.5 arcmin off-axis. This enables HXT image resolution and throughput allocations to be met.

TM Mechanisms: The XMS and the RFC detectors each have on-orbit focus mechanisms to ensure operations at best focus. The TM also includes a combination sunshade/contamination cover in front of the SXT and a contamination cover attached to the aft end of the SXT.

The SXT forward and aft contamination covers are open-once-only mechanisms driven by springs and controlled by pin-pullers. The forward contamination cover acts as a sunshade when open. These covers protect the SXT from contamination during assembly, integration, test, and launch (the HXT has windows with vents). All of the mechanisms have Chandra heritage and have proven to be highly reliable.

Interfaces: The s/c envelops the OM. Three hard points on the s/c carry a mechanical interface with the TM structure. Instrument electrical interfaces include a multiplexed data bus, dedicated high-speed digital links, and an unregulated DC power bus. All instrument data are digitized within the instrument electronics, allowing the s/c-to-TM interface to be completely digital.

TM Thermal Control: Overall, the TM must be controlled so that the TM structure, instruments, and optics maintain required operational temperatures and alignment stability. The observatory is configured so that the detectors, which generally require a cool environment, are located at one end of the TM with a view to deep space, and the optics, requiring a room temperature environment, are enveloped within the s/c. The passive foundation of the control system uses MLI wraps and sunshades to minimize radiation loading and balances losses to cold-bias certain TM elements. Control is attained by active local heating and cooling.

OM Thermal Control—The SXT mirror must maintain absolute temperature and gradients close to the conditions under which the mirror was assembled. These requirements are mainly driven by the overall angular resolution requirement and the CTE of the materials in the mirror assembly. The thermal tolerances for the SXT are defined in Table 1-4. The thermal design will be optimized during the iterative optical-mechanical-thermal design process, accounting for all features including glass and housing.

Pre- and post-collimators as successfully used on Einstein, ROSAT, and Chandra, control heat flow through the main mirror. A collimator works by reducing view factor and thus radiation losses. It also provides a surface for thermal coatings that further reduces losses, and it provides an assembly for mounting heaters and blankets to control gradients in reflectors.

The RGA, mounted between the SXT mirror and the post-collimator, requires 1° C absolute temperature gradient control, as achieved in XMM-Newton with a similar design.

The HXT mirror assembly uses aluminized membranes covering the front and rear optical apertures. Actual thermal control is provided by heaters on the HXT structure. MLI and insulation mounts are also used to isolate the HXT from its environment.

FPM Thermal Control—FPM thermal control is achieved by MLI wrap of the electronics bay and instrument platform, a sunshade to block direct solar loading on the instruments, and available cold views of space. Some active heater control of structural elements will be used to maintain alignment stability during observations. The exterior anti-Sun surface of the bay is reserved for electronics, cryocooler and detector radiators. Apertures in the instrument platform will be minimal and designed to lessen thermal load on the instruments from the electronics bay.

XMS temperature is controlled within the XMS cryostat. However, the instrument relies on TM thermal control for its external conductive and radiation environment. FPM thermal control designs must include provisions for safe-hold conditions so that the electronics and cryocooler do not get too cold.

OB Thermal Control—The OB is wrapped in an MLI blanket. Active thermal control is provided by heaters on the OB. The interior is mostly open to accommodate the converging telescope beams, but it also facilitates a stable interior thermal environment. Adequate margin will be designed into the cold-bias to maintain control following degradation of the MLI and any radiating surfaces.

Visible Stray Light Control: Stray light over the band 300-1100 nm will be limited at the entrance aperture of the RGS CCD detector to less than 2 x 10^9 photons/cm^2/second. This will be achieved by careful closeout of the TM and will be tested during telescope integration by a "solar lamp test." Ascent venting of the mirror and telescope cavities will be provided for by incorporation of baffled vents. Vent paths must strictly limit the pressure differential during launch, but must be baffled to limit stray light.

Cosmic X-Ray Background Baffles: The cosmic X-ray background (non-imaged) on the XMS should be limited to 0.01 counts/sec over the SXT PSF. Protection from cosmic X-ray background is provided for each of the telescopes by a set of X-ray baffles that block the view from each detector to sky that is outside the FOV. The planar baffles are fabricated from GREP for strength and rigidity with a thin layer of tantalum applied to the detector side of the bulkhead to block X-rays and eliminate florescence from the GREP.

Calibration Sources: Calibration sources, in addition to those mounted within the detectors, are carried within the OB. They include passive radioactive sources (Fe^{55}, etc.) and (possibly) an active electron impact source. The sources will have an actively driven, fail-safe cover to allow them to be used as needed and not compromise the X-ray data.

Radiation Protection: An on-board radiation detector will be carried and used to autonomously safe the instruments in high radiation environments. A modified version of the AmpTEK™ Compact Environmental Anomaly Sensor (CEASE) has been baselined. This sensor is currently used in several Department of Defense programs to provide inputs to the radiation safing system.

2.4.1.2 Spacecraft Bus

All Constellation-X subsystems use mature technologies, proven designs, and proven s/c components that are easily obtainable from several vendors. Baselined components were used successfully on previous s/c including MAP and EO-1 and will be adapted for use on Constellation-X, resulting in a design that is essentially "off-the-shelf." The subsystems described in the following paragraphs reflect the in-house s/c design adopted for the Reference Mission, including the Atlas V, and trace back to the performance requirements seen in Table 2-1. The values provided in this section represent expected subsystem mass and power based on experience and heritage hardware.

Spacecraft Mechanical Subsystem: The requirement for the s/c structure is that it be able to interface with the launch vehicle and TM and accommodate the s/c subsystems. The primary s/c structure is a large cylindrical shell that surrounds the SXT, plus additional structures that envelop the optics. S/c equipment is mounted to this structure. The s/c needs no major structural deployment mechanisms. A central monocoque cylinder with radial stiffener provides the structural load path between the modules and the launch vehicle interface.

Separation of the s/c from the launch vehicle occurs by means of a non-pyrotechnic, low shock, lightweight, one-fault-tolerant system. The mechanical interface from the s/c to the launch vehicle consists of two half circles that join to the bottom platform of each s/c. These remain attached to each s/c upon separation while the lower common truss adapter ring remains attached to the launch vehicle.

Thermal Subsystem: The Thermal Subsystem easily meets the requirements, as highly stable conditions exist in the L2 environment. This orbit allows the use of inexpensive and reliable passive thermal control technologies as used on many other NASA s/c. The s/c exterior is covered with MLI blankets, and thermal radiator panels maintain s/c components within a safe temperature range. Thermostatically controlled heater circuits are also provided for components of the hydrazine propulsion system, batteries, etc. A low-conductivity mounting system joins the TM and the s/c and limits heat exchange between them.

Attitude and Orbit Control Subsystem (AOCS): The primary requirement of the AOCS is to point

Table 2-3: Observatory Attitude Performance Specifications

Description	Parameter	Specification	Note
Pointing Range	Roll	± 20 degrees	Max
	Pitch	± 20 degrees	Max
	Yaw	± 180 degrees	
Star Tracker Attitude Knowledge 3σ Accuracy	Roll	60 arcsec	
	Pitch	3 arcsec	
	Yaw	3 arcsec	
Telescope Pointing Determination (Aspect) 3σ Accuracy	Pitch	5 arcsec	Ground-based post processed
	Yaw	5 arcsec	
Pointing Control 3σ Accuracy	Roll	60 arcsec	
	Pitch	30 arcsec	
	Yaw	30 arcsec	
Pointing Stability	Pitch	0.6 arcsec/sec	Max
	Yaw	0.6 arcsec/sec	Max
Pointing Jitter	Roll	5 arcsec	Max
	Pitch	2 arcsec	Max
	Yaw	2 arcsec	Max

and stabilize the SXT boresight to the intended X-ray source and maneuver efficiently between targets (see Table 2-3). In addition, the AOCS nulls tipoff rates and performs all other maneuvers after separation from the launch vehicle, including momentum management and orbit adjustments. Constellation-X does not scan except for rastering during boresighting.

The AOCS uses proven component designs: digital controllers hosted on the on-board computer (OBC); an analog safehold controller contained within the attitude control electronics (ACE); eight coarse Sun sensors placed to provide coverage and redundancy at all attitudes and to process attitude information during initial acquisition, maneuvers, and safe modes; a star tracker for mission attitude sensing and which enables the observatory to have sufficient accuracy, knowledge, and stability for its attitude; an inertial reference unit (IRU) that computes the angular rates of the observatory to provide dynamic attitude information to the Command and Data Handling (C&DH) computer; four reaction wheels (RWs); a propulsion subsystem; and associated interface electronics. The sensors interface with the ACE, which also interfaces with the C&DH computer. This computer processes AOCS sensor data and commands the RWs or thrusters to control the attitude of the satellite. Each Constellation-X observatory will nominally be held in a 3-axis stabilized, inertial attitude using a star tracker as the primary reference and a 3-axis rate integrating gyro package for determination of attitude rates. It will be able to report its orientation (referenced to the star tracker) to within 3 arcsec, 3σ. (See Foldout 2 for a diagram of the AOCS.)

In this system, gyro bias and drift-induced errors are removed by frequent updates from the star tracker. Requirements on the gyro package are therefore derived requirements, based on top-level attitude requirements, and will be determined during the design phase. Gyro "jitter," or high frequency-angle noise, will also affect attitude stability and accuracy; specifications will be derived in the design phase. There are several standard, space-qualified gyro packages available that can meet project requirements.

No mechanisms will be operated nor antennas moved during science observations, so no science data will be compromised. The solar arrays are fixed.

Periodic on-orbit instrument calibrations for several different items including telescope boresights, best focus, effective area, resolution, and contamination are planned. All of these calibrations will use standard science observations and will place no added requirements on the AOCS. The system is sized to accomplish maneuvers between targets in less than one hour.

All data will be telemetered to the ground for further processing. Ground-based processing, using forward and backward Kalman smoothing plus calibration, will produce more accurate attitude estimates for the aspect solution.

Command and Data Handling Subsystem : The C&DH Subsystem is configured to manage the command and data requirements from the instruments and s/c as indicated in Table 2-4. It processes the commands received from the ground and data from the observatory subsystems and the instruments. It also manages the timekeeping functions. The C&DH subsystem can be seen in Foldout 2.

Communications Subsystem: Communications Subsystem requirements are to support telemetry, commanding, ranging, and science data transmission to the ground stations. Each

Table 2-4: C&DH Subsystem Requirements

Description	Requirement	
Mission level science data ingest rate		
• Average mission science data rate	192 kbps	
• Mission bright source data rate	2.56 Mbps	
Observatory data ingest rate (per observatory)	Daily Average (kbps)	Peak (kbps)
• Science	48	640
• Instrument housekeeping	4	4
• Spacecraft housekeeping	4	4
Total	56	648
Observatory X-band downlink rate	1.7 Mbps	
Observatory S-band downlink data rate	2 kbps	
Observatory S-band uplink data rate	2 kbps and 150 bps	
Spacecraft time distribution accuracy	± 10 microseconds	
Spacecraft time synchronized to UTC accuracy	± 10 microseconds	
Time resolution	± 10 microseconds with ± 1 microsecond goal	
Observatory data storage	42 Gbits minimum based on contact time of 300 minutes every 4 days	

observatory carries its own communications subsystem consisting of a primary S-band coherent uplink/downlink for commanding/ranging and a low-rate downlink for housekeeping telemetry. An 8250-MHz X-band downlink transmits science and s/c engineering data.

S-band uplink frequency is 2096 MHz. The 2-kbps uplink commands are phase-modulated on a 16-kHz subcarrier. The S-band downlink is a 2-kbps phase-modulated signal at 2250 MHz. The S-band antenna system consists of two omnidirectional antennas, each providing a hemispherical gain pattern. An S-band hybrid combines the antenna signals. The S-band transponder provides transceiver functions and coherent turnaround ranging. The transponder transmitter output of 5 W is increased to 26 W by an external power amplifier (PA). The output of the PA is passed through a band reject filter and diplexer combination to protect the transponder receiver input circuitry. The X-band equipment consists of a 5-W X-band BiPhase Shift Keying (BPSK) transmitter followed by a 1.2-m 37-dB high gain gimbaled antenna system.

Link analysis has been performed by the GSFC Communications Link Analysis and Simulation System (CLASS). The worst-case link margins are: S-band uplink 6.3 dB, S-band downlink 3.8 dB, and X-band downlink 3.9 dB.

Electrical and Power Subsystem (EPS): The EPS supports the orbital average load through all mission phases, as stated in Table 2-7. The EPS provides conversion, generation, storage, control, and distribution of unregulated power for the operation of all s/c subsystems and components. It performs power balance, battery charge control, power distribution, power safing, and ground power interfacing functions.

The subsystem consists of a solar array, battery, and power supply electronics (PSE). The solar array is a 6.2-m square, 28% efficient, body-mounted panel that provides 1525 W beginning of life (BOL) and 1442 W end of life (EOL) power to support the required load plus losses. One 40AH eight-cell battery provides energy storage. The orbit is a full Sun orbit with no eclipses. Battery power will be required from the launch phase until Sun acquisition occurs. It will also be used during peak load periods at a limited duty cycle and during safing events. The PSE is a direct energy transfer (DET) system that converts solar energy to electrical energy and provides it directly to all s/c loads at an unregulated voltage from 22-32 V. The EPS is simplified by the operational constraint that observing will only be within 28 degrees of the plane that is perpendicular to the Sun-Earth line.

The EPS design incorporates functional redundancy. The solar array is composed of multiple strings, and the system can tolerate the loss of several strings without affecting mission science. The PSE uses a staged power control configuration that can tolerate the loss of a single stage. Battery-charging circuitry enables safe charging. Software allows the EPS to be re-configurable to compensate for system degradations. The battery consists of at least eight cells and incorporates bypass switches that allow it to bypass a bad cell without affecting mission performance. Multiple switched and unswitched output services are provided with cross strapping of critical functions.

The electrical subsystem will provide adequate grounding and shielding to prevent noise from affecting the operation of each subsystem and instrument. To accomplish this, classical methods of equipment bonding, ground isolation, and a single point ground design will be coupled with minimum path signal ground returns to minimize induction, noise, and ground bounce.

Propulsion Subsystem: The Propulsion Subsystem is required to provide launch vehicle tip-off management, lunar phasing and swingby, orbit insertion and corrections at L2, and momentum unloading. The consumables requirement for a six-year mission amounts to a 177 m/s ΔV. The subsystem is a blowdown monopropellant hydrazine system. A total of 180 kg of propellant is loaded to provide the 177 m/s ΔV. The BOL pressure is 2757.6 kPa (400 psi) and the EOL pressure is 689.4 kPa (100 psi). Each set of four redundant thrusters can perform all the functions required by the propulsion subsystem. Preliminary assessment indicates no plume impingement concerns; however, further analysis is planned. The components are listed in Table 2-5.

Flight Software (FSW): Functional requirements of Constellation-X flight software include FSW Executive services (e.g., central processing unit (CPU) modes, commands, telemetry, time management, external hardware bus management); C&DH applications such as stored command handling, telemetry event detection, and response; radiation effects detection and handling; onboard data storage and playback from the on-board data memory; ground communications and antenna gimbal management; active power management and battery control (very similar to the power control accomplished on the MAP mission); L2 orbit acquisition and maintenance (reference data modeling and thruster controls); sensor data processing; actuation command generation and output; maneuvers and science target inertial fine pointing (attitude determination and control); momentum management; safing control modes; s/c to science instrument interface and instrument-unique support; and autonomous anomaly/failure detection and responses.

Table 2-5: Propulsion Components Specifications

Propulsion Component	Size	Qty
Hydrazine tank	55 cm OD sphere	3
22.24 N thruster	7 cm OD, 18 cm length	8
Miniature fill and drain valve	7 cm length, 1.4 cm OD max.	6
Filter	8.4 cm length, 1.5 cm OD max.	1
Pressure transducer	6 cm length, 5 cm OD	3
Isolation valve	5 cm x 7 cm x 8 cm	3
Miscellaneous hardware	0.635 cm OD tubing, etc.	N/A

FSW for each observatory will be identical except for s/c ID, calibration factors, flight hardware-unique parameters, and unique parameters required for ground interface. FSW will be exhaustively tested on the highest fidelity FSW test bed. Changes in FSW will be exercised via only a regression test set. FSW staff will support each observatory's I&T activities as well as launch preparations and transition to normal operations. Constellation-X FSW will benefit from the knowledge gained from the MAP mission with Lissajous orbit at L2.

2.4.1.3 Resources

Tables 2-6 and 2-7 indicate estimated mass and power resources for the instruments and the s/c subsystems. The estimated resources do not include any contingency. However, the sum of contingency and margin for the entire observatory is sufficient for implementation. During mission formulation, the instruments and subsystems will be allocated contingency out of the margin, depending on the maturity of design, production, and testing.

Mass Budget: The total mass estimate for each observatory and launch vehicle is shown in Table 2-6.

Power Budget: The power estimate for each observatory is shown in Table 2-7.

2.4.2 Ground Segment Architecture

The Constellation-X ground data system consists of four principal data processing elements:

Table 2-6: Observatory Mass Estimate

Item	Total Mass (kg)
Telescope Module	
SXT FMA (w/o RGA)	642
RGA	50
RFC	33
HXT mirrors and detectors (3)	151
XMS	147
Thermal	29
Integration and miscellaneous materials	81
Structure and mechanisms	454
Subtotal for TM	**1587**
Spacecraft Bus	
Structure and mechanisms	342
Power	67
Thermal	18
Propulsion hardware	35
AOCS	68
C&DH and control electronics	18
Communications	85
Integration materials	76
Propellant	180
Subtotal for s/c	**889**
Total per observatory (wet)	**2476**
Total wet launch load (two observatories)	4952
Total dry launch load (two observatories)	4592
Launch vehicle performance	6498

$$\%\text{MassMargin}=\frac{\text{LaunchVehiclePerformance}-\text{LaunchLoad}}{\text{DryLaunchLoad}}\text{x}100=34\%$$

Table 2-7: Observatory Power Estimate

Item	Average Power (watts)	Peak Power (watts)
Telescope Module		
Thermal		
SXT mirrors and RGA	300	310
HXT mirrors	36	40
OM	35	40
OB	50	55
FPM heaters	25	30
Thermal subtotal	**446**	**475**
Electronics		
TM mech. controller	2	5
RFC	40	45
XMS electronics/ADR	80	146
Cyrocooler	150	200
HXT electronics	30	35
Radiation detector	10	10
Electronics subtotal	**312**	**441**
Spacecraft Bus		
Communications	10	60
C&DH	45	45
AOCS	160	240
Propulsion	41	90
EPS	36	36
Thermal	25	25
Subtotal for s/c	**317**	**456**
Total per observatory	**1075**	**1412**
Solar array EOL	1442	

$$\%\text{PowerMargin}=\frac{\text{SolarArrayEOL}-\text{ObservatoryAvg.Load}}{\text{ObservatoryAvg.Load}}\text{x}100=34\%$$

the Tracking, Telemetry and Command (TT&C) facility, the Flight Dynamics Facility (FDF), the MDS, and the Science Data System (SDS). The MDS and SDS are co-located at the CXSOC. The FDF is at GSFC. The Constellation-X ground segment requirements are developed in the initial Constellation-X Operations Concept document; key requirements that drive the ground system are shown in Table 2-1. The Chandra ground system architecture is based on a multiple mission support design and can be extended at low cost to support Constellation-X.

CXSOC Science and Mission Operations: The CXSOC science and mission operations consists of the facilities, data systems, and staff required to conduct the mission operations and all aspects of the science program including s/c and science instrument operations, calibration, mission planning, data system development, mission and science data archiving, distribution and analysis, public education and outreach, and grants programs. These activities are conducted from a single facility in order to reduce operations costs and maximize team integration and synergy.

Spacecraft and Instrument Health and Safety: Constellation-X will use an integrated health/safety processing system combined with a telemetry data capture and science processing facility to minimize operational staffing requirements.

Tracking, Telemetry and Command Facility: The TT&C facility is baselined to consist of two commercially provided ground stations (required to achieve the orbit determination accuracy commensurate with the 100-microsecond timing requirement [Table 2-1]), with network connectivity to the CXSOC. Each station consists of an 11-m antenna plus RF and digital hardware and commercial off-the-shelf (COTS) software necessary to provide and interface with S- and X-band space/ground links. Facility remote control capability over a network is required. COTS station scheduling aids will be executed by the MDS using predicted orbits as required. Each station shall have the capability to generate sufficient status data ("monitor data") so that station configuration and health can be assessed remotely at any time (i.e., regardless of whether a contact is ongoing or not). The ground stations are responsible for on-board data memory capture via the X-band downlink. Commands, real-time and dump telemetry, tracking, and monitor data are recorded at the station and retained for at least one week. A maximum requirement of 25 Gbytes results from the worst-case assumption of network outages. Operational margins will be imposed for manual re-dumps in the event of TOOs or downlink anomalies in addition to design margin. Command and telemetry data will be formatted using Consultative Committee for Space Data System (CCSDS) recommendations. Different virtual channels will be used for real-time, playback, and other data streams.

Flight Dynamics Facility: The FDF provides trajectory design, OD for early mission, maneuver planning, and calibration for ΔV burns and for orbit analyses as needed for the duration of the mission.

Mission Data System: The MDS performs the traditional mission data processing functions for the s/c platforms including commanding, real-time safety and health monitoring, trending, anomaly resolution, and for science instrument health and safety. The MDS consists of the data system resources required for commanding the s/c, real-time health and safety monitoring of s/c and science instrument engineering data, observatory and science instrument scheduling, scheduling tracking support, power management, thermal management, orbit and attitude verification, and on-board computer file management. The MDS provides the capabilities for Constellation-X operations planning and observatory and contact scheduling, as well as command interface to the TT&C facility and real-time data displays to the FOT during communications contacts. All commands and data sent to the observatories are under strict configuration management and are archived in the Mission Archive. The MDS is capable of generating and validating uploads within 24 hours in response to TOO requests. The MDS receives s/c and science instrument housekeeping data from the TT&C ground station, removes the artifacts of the space-to-ground transmission, and provides quality annotation as part of the data validation process. It also provides the capability to limit check and monitor exceptions to both real-time and back-orbit on-board data memory.

Science Data System: The SDS provides for all science processing functions including data validation, pipeline processing, management, and distribution of calibration and science data within the required 2-week period to the GO, and support for dissemination of images and data to the public. The SDS supports planning of science observations and science operations decisions such as the observation of calibration targets or TOOs, archives the scientific data products into the Mission Archive, distributes validated data and software to the user community, and supports the GOs. The SDS generates standard products, including calibration products, on subsets of Constellation-X data (using algorithms and/or software specified or provided by the CXSOC science staff) and generates products that require information from multiple instruments, as well as information from other observatories. The SDS provides capabilities for observation evaluation and planning, as well as science instrument monitoring, configuration, and software maintenance. It also provides software that can be used to interactively analyze the data returned from the science instruments, assisting in data validation and instrument health monitoring. This software is portable within UNIX operating system (OS) variants and can be provided to observers for use on their computer facilities. This software shall use the same core processing code as the automated processing pipelines that produce the standard products and shall utilize adopted scientific standards for data formats and exchange (e.g., FITS, TCP/IP). The SDS can process 12 hours of data in approximately two hours, is easily capable of meeting the 2-week data delivery requirement; the limiting step is the downlink intervals and receipt of data from the TT&C facility.

Using the SDS, the science processing team performs pipeline processing on the instrument and ancillary data to remove instrument artifacts and register the events on the sky, producing standard Event Lists and other Level 1 products. Level 1 products are processed further to produce images, spectra, and time series Level 2 products. The time to process the data depends on the type of observation and the SDS implementation but is expected to be one hour per 12-hour period of data.

The design of both the MDS and SDS will use COTS hardware exclusively and COTS software to the extent possible. Both data systems will use a common architecture and application interfaces, and will include automation of routine operational functions wherever possible. The intent is to reserve operational personnel resources for non-routine activities. This architecture minimizes costs by centrally receiving and managing all mission data including longterm storage, accountability, and distribution. This architecture also minimizes costs by centralizing and consolidating systems requiring high reliability and availability.

2.4.3 Data Validation, Analysis, and Archiving

Validation: The CXSOC is responsible for verifying the scientific results, detecting anomalies in the hardware and the software, reporting and documenting errors, and diagnosing and correcting problems. As in the Chandra experience, a combination of automated and manual checks (by scientists) will verify integrity of science data and identify any problems with the software and its products. These checks will allow both predictable and unpredictable problems to be detected while minimizing the labor required. Validation applies to instrument performance, data processing algorithms, and scientific analysis algorithms, and to meta-data.

Implementation Phase—A testing procedure will be designed in parallel with the software coding and verification effort to allow automated and reproducible testing of the scientific performance of all aspects of the software and its products. Test procedures will be prepared corresponding to the test requirements. Tests will be designed in terms of each scientifically distinct analysis task. Each step will generate sufficient output to provide traceability of spurious results. The testing procedure will be a natural extension of the software testing and verification activity performed and will be applied to all software subsystems in each software release.

A test dataset will be developed from actual Chandra, XMM-Newton, and Astro-E2 data, as well as simulated Constellation-X data, to be used for cross-mission validation. It will include examples of each type of data Constellation-X will collect, with sufficient variety to fully exercise the software, and will contain representative examples of all known source properties. The example source detection will require data containing extended sources, many weak point sources, strong point sources, and combinations of these. Both the testing procedure and dataset will be developed in parallel with the software and will be designed so that all or part of the software can be tested at a given time. The datasets used in testing and verification will be used/modified whenever possible to minimize duplication of effort.

An automated checking procedure will be developed to check the output products of both the standard processing and the testing procedure for: existence of relevant data files, presence in output files of standard keywords, results of analyses that are outside pre-defined ranges compared with the known input data (e.g., negative fluxes). The procedure will generate a report of checks made and their results and will enter them into a database.

Mission Operations Phase

➟*Calibration Objects:* Pre-mission testing and checking procedures will be modified to run on a set of specific cosmic sources to be used as calibration objects; results will be stored in a calibration database. Analysis of the calibration database will continue to ensure that software and products are scientifically correct.

The set of celestial calibration sources will include objects with a variety of spatial, spectral, and flux variability properties. These sources will be located throughout the sky and by definition will address the calibration requirements of each instrument. For each calibration source, an allowed range for each derived quantity will be specified and the automated checking procedure will flag any values outside these ranges.

➟*Scientific Observations:* During the mission, data quality is thoroughly monitored so that the mission's scientific productivity will be maximized. A combination of manual checks by the CXSOC scientists and automated verification procedures will enable this to be achieved effectively.

The automated checking procedure will be applied to the output products of all observations. CXSOC scientists will review the automated checking output and will manually inspect all outputs of the archives. Any anomalies will immediately be evaluated in detail, with analysis continuing until the problem is understood and appropriate corrective actions taken. The results of all stages of this process will be reported and archived, so that problems and the resulting corrective measures are documented. Once approved, the processed data, along with the output of the checking procedure and the scientist's report will be archived in the products database with appropriate protection. All are considered part of the standard data products generated by the CXSOC for the observer. The scientist's check will be made on a confidential basis. Should unexpected scientific results be apparent, the scientist will do no more than alert the observer.

➟*Level 3 Validation:* Standard Level 3 catalog products also require evaluation to assure they are scientifically correct. For example, catalogs including positions of stellar objects must be compared with positions of their optical counterparts to ensure the absence of systematic positional errors. Catalogs of X-ray line identifications must likewise be validated. Spectral parameters must be checked against those derived from high-resolution studies and against X-ray sources observed by previous missions.

Data Analysis: The CXSOC science staff, in coordination with the instrument teams, will define the suite of science tools for the standard processing and analysis environment. For cost effectiveness, these tools are extensions of those used by Chandra (the CIAO system). The CIAO release includes the GUI analysis applications PRISM and TOOLAGENT, the SHERPA modeling and fitting application, the ChIPS plotting and imaging application, three source detection tools, several instrument specific tools, and numerous data manipulation tools (e.g., dmcopy, dmlist, dmextract). This package includes tools to create, extract, calibrate, and analyze data from Event Lists and to produce and analyze images, spectra, and time series from these Event Lists. In addition to the tools and applications, a number of software libraries (e.g., the Data Model, ChIPS) are present within src/lib and src/libdev of the source code distribution and can be used to build new tools and applications. All source code will be freely available in support of any CIAO release. The Science Data Systems Division, with the active participation of science staff, will develop, distribute, and maintain these tools. The science staff will make these tools available to observers and the scientific community through the public portion of the Constellation-X web site.

Data Archiving: Based on the expected nominal daily average data rate for all three instruments (estimated from the ODRM and extrapolated from Chandra observations of comparable sources) plus engineering data, the Constellation-X mission will generate a total of ~1 Tbyte of raw data per year. Including Level 1 products and higher-level products, as well as reprocessed data, yields an estimated total data archive requirement of approximately 10 Tbytes per year, corresponding to 40 Tbytes for the four-year mission lifetime required and 100 Tbytes if the mission reaches its lifetime goal. The raw data must be validated, processed, and ingested into the archive within 24 hours of receipt from the TT&C facility.

All raw telemetry data are archived, as are processed engineering and science data, ancillary data, and higher-level products. The SDS saves all event data in FITS format in the Constellation-X Data Archive. The Constellation-X Data Archive will be updated both when new data are accumulated and when the data are reprocessed as the understanding of the instruments improves on orbit. Archived Level 1 and Level 2 data products will be available to the observer over the Internet. Observation data will have a nominal proprietary period during which the data will be available only to the relevant observer(s). Following expiration of the proprietary period, the data will be accessible by the wider community through the public portion of the Constellation-X Data Archive. Calibration observations are always public. The CXSOC staff is responsible for protecting the archived data from inadvertent loss or unauthorized disclosure, but may access proprietary data only if required for Constellation-X operations. Mirror sites will replicate the public portion of the Constellation-X Data Archive for wider geographical access. Upon mission termination, all data will be delivered to the High Energy Astrophysics Science Archive Research Center (HEASARC).

2.5 Approach to Mission Success

The success of Constellation-X is being assured through the adoption of proven mission assurance practices during development and implementation. These include implementing a comprehensive quality program consistent with ISO 9001; following accepted systems engineering practices; conducting appropriate and timely trade studies; using flight-proven and mature designs wherever possible; adopting suitable redundancy and reliability concepts; parts and materials selection following I&T procedures appropriate for multi-satellite missions; adhering to GSFC procedures for environmental testing; and strictly adhering to contamination control measures and exposures.

2.5.1 Heritage and Maturity of Mission Elements

Spacecraft Bus: Constellation-X is fortunate in that, although the science it will conduct is breaking new ground, it is able to take advantage of mature technologies and elements. Most Constellation-X s/c components are being patterned after flight-qualified components used on MAP, Swift, EO-1, or other NASA missions. A few will require slight modifications that can be accommodated easily. A high percentage of s/c components will be flight proven (Table 2-8).

Ground Segment—The CXC at SAO has supported the Chandra mission and will be supporting Constellation-X operations in the next phase. The FDF supports all missions launched by GSFC.

Launch Vehicle—NASA and the U.S. Air Force are developing launch vehicles that can be used for Constellation-X. The successful maiden flights of Atlas V and Delta IV occurred in 2002. The payloads carried on these flights were actual commercial payloads, not dummy loads, thus demonstrating the users' confidence in these rockets' reliability. By the time Constellation-X is ready for launch, it is expected that a minimum of 44 Atlas Vs and 20 Delta IVs will have been launched.

Table 2-8: Flight Heritage of Constellation-X Components

Component (Typical)	Past Vendors (Examples)	Flown On (Examples/ Similar)
Mechanisms/covers	SAI, BASD	FUSE, STIS, MSO/GRO
Spacecraft structures	GSFC, SAO	MAP, Chandra
TM structures	COI, Ball, TRW, Kodak	Chandra
Star trackers	Goodrich	P-81, GLAS
Wheels/drivers	ITHACO	TRMM, RXTE
Inertial reference units	Litton	NEAR, TDRSS, EO-1
NiH_2 battery	Eagle Pitcher	HST, MAP, GOES, AQUA, Terra
Solar array	EMCORE	RHESSI, ICESat, Starshine3
Hydrazine tanks	PSI	STEP, ROCSAT
Thrusters (22 N)	Atlantic, Primex	MAP, TRMM
Processors	BAE Systems	Swift, Triana
Ultra stable oscillator	FEI, JHU/APL	RXTE, TRMM, GRACE

2.5.2 Redundancy and Reliability Measures

Redundancy: Constellation-X shall be configured so that no single failure will result in the loss of more than 25% of mission science, excluding launch vehicle failure. A constellation of four observatories may meet this requirement by means of selective redundancy; however, full redundancy is the goal. Failure Mode, Effects and Criticality Analysis; Fault Tree Analysis; and Probabilistic Risk Analysis will be performed to identify critical components needing redundancy. These risk reduction activities will ensure mission success in a cost-effective way. It is expected that the C&DH processor, RWs, etc., will be redundant.

Reliability: A high degree of reliability means that there is a high probability that the mission will achieve its science objectives. The reliability criterion is that the probability of success that 75% of mission science will be available over the mission design life is 0.75. This reliability is achieved by careful selection of parts, processes, and redundant elements in design. The design will be carefully analyzed for parts stress, worst-case analysis, and reliability prediction. Thus, reliability is carefully designed into the system and will follow MIL-STD guidelines.

The components, assemblies, and observatories will go through burn in, environmental testing, stress tests, and comprehensive performance tests at all levels. At the conclusion of the test program, the flight segment shall have demonstrated minimum reliability acceptability by trouble-free performance testing for at least the last 300 hours of testing. Major hardware changes during or after the test program will invalidate the previous demonstration. All the above measures will weed out the infant mortality and ensure high reliability.

2.5.3 Integration and Test

Instruments are delivered flight-qualified for I&T. Each detector and its electronics will be integrated onto the FPM in parallel with integration of the FMA and HXT mirrors into the OM. Both will be functionally and environmentally tested and aligned.

The FPM and OM will be integrated onto the OB to become the TM. The TM will undergo alignment and integrated functional testing.

The TM will be integrated with the s/c to become the observatory. The s/c will arrive integrated and environmentally tested. Integration will consist of mechanical and electrical integration, mating of the TM to the bus, functional testing, and comprehensive performance testing (CPT), where the observatory performance baseline will be established. Mission operations activities will also be performed. This is an important risk reduction strategy and has proven useful on Chandra and SIRTF in uncovering system-level problems. Mission operations activities include use of operational databases and procedures and “day-in-the-life” and mission scenario tests.

Observatory environmental testing (ET) will be performed. A protoflight ET program will be performed on the first set of hardware, while an acceptance ET program will be performed on the remaining three identical sets of hardware, thereby reducing cost and schedule. Functional tests will be performed before and after each environmental test. Post-environmental activities will be performed, which will include alignment, functional, and CPT to reverify the baseline. A schematic of the I&T test flow is shown in Figure 2-1.

Multiple teams will be used for parallel processing of the four observatories, per the schedule shown in Appendix B.

GSE is to include instrument-provided detector stimulators and simulators, mirror stimulators, thermal GSE and s/c provided high-fidelity s/c simulators.

Plans for each segment of testing will be used to control the I&T process. These will include, but are not limited to, an Observatory Verification Plan; an Assembly, Test, Launch, and Operations Plan; a Contamination Plan; Instrument Verification Plan(s), etc. A complete list of plans that will be used to govern the I&T process will be part of a Constellation-X Documentation Tree.

2.5.4 Contamination Control

Each component of the Constellation-X observatory will be evaluated for molecular and particulate contamination sensitivities and requirements. The components sensitive to contamination are the SXT mirrors and gratings, HXT mirrors and detectors, the CCD array, cooler, calorimeter, sunshade, and s/c thermal control surfaces, star trackers, antennae, and solar panels. Allowable contamination levels at EOL are 100A for SXT and HXT optics and detectors and 200A for the solar panels and sunshade.

The project will develop a Contamination Requirements document and a Contamination Control Plan to monitor contamination buildup throughout mission lifetime. Further, detailed contamination control plans will be developed for each instrument and for the integrated s/c. Body-mounted witness mirrors will be periodically analyzed to assist in the monitoring activity.

2.5.5 Product Assurance Activities

Constellation-X will use the traditional GSFC approach to Product Assurance, reaping the benefit of an independent look from personnel with years of experience in the Office of Systems Safety and Mission Assurance (OSSMA) Directorate. A System Assurance Manager (SAM) will be assigned to the Project, and will be responsible for implementing the Product Assurance program. The OSSMA is an organization independent from

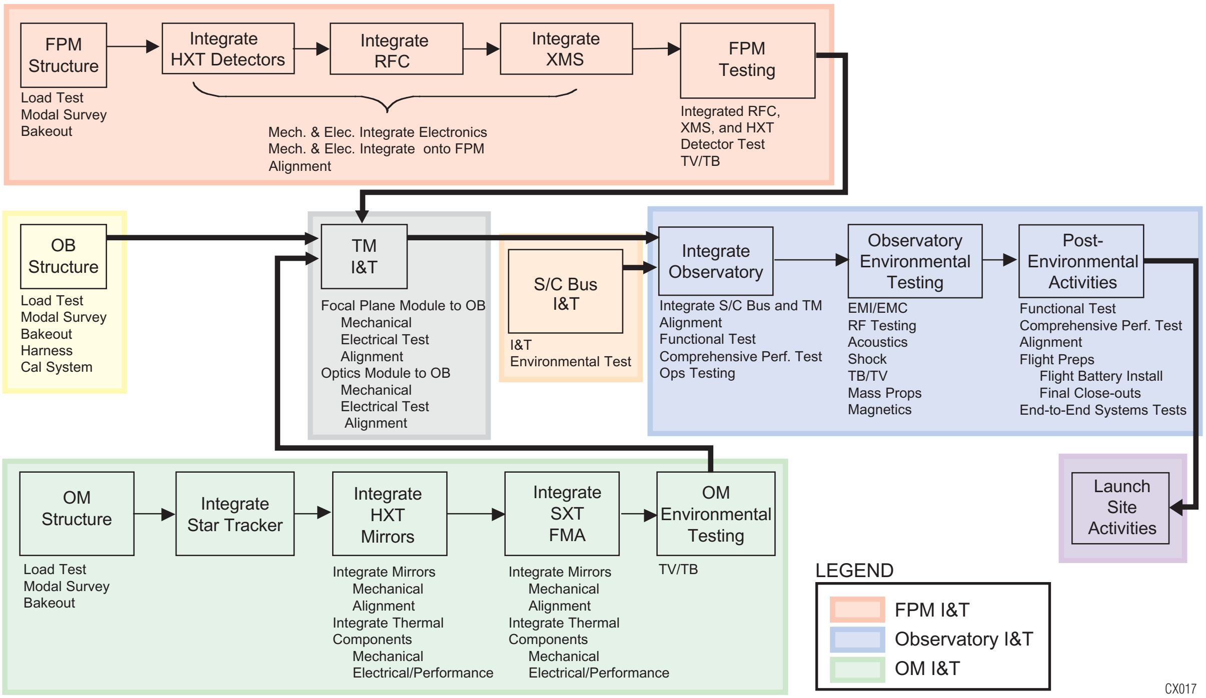


Figure 2-1: I&T Test Flow

the Flight Programs and Projects Directorate (FPPD), which ensures an independent path for verification of assurance requirements. The activities include safety, hardware and software quality; software independent verification and validation (IV&V) (performed at the West Virginia facility); reliability, parts, and materials, processes; workmanship; independent system reviews, and nonconformance/corrective action processes. Specific workforce levels are included in the Project budget to cover each of these areas.

Independent reviews will be performed in the GSFC Integrated Independent Review Team (IIRT) approach, as described in GPG 8700.4D, “Integrated Independent Reviews.” The independent reviews currently planned for Constellation-X are the Technology Readiness and Implementation Plan (TRIP), Systems Requirements Review (SRR), Preliminary Design Review (PDR), Critical Design Review (CDR), Pre-Environmental Review (PER), Pre-Shipment Review (PSR), Operations Readiness Review (ORR), Missions Operation Review (MOR), Flight Readiness Review (FRR), Launch Readiness Review (LRR) and Peer Reviews. This list includes all the major reviews required for GSFC-managed missions.

During the formulation phase, a Mission Assurance Requirements (MAR) document will be developed by the SAM. This will specify the requirements that all elements have to follow. The SAM will then monitor each element during design and build to ensure compliance with the MAR. The requirements will also be called out in each contract, and flowed down to subcontractors. Parts and materials must meet requirements driven by the reliability and contamination requirements (discussed in Section 2.5.4). The reliability approach is discussed in Section 2.5.2.

2.5.6 Systems Engineering

Plan and Philosophy: The systems engineering approach for Constellation-X follows the guidelines detailed in GPG 7120.5, “Systems Engineering” (draft). The collaborative approach uses expertise from GSFC and SAO. It is led by GSFC management, draws its lead systems engineers (SEs) from each organization, using their combined experience of more than 40 years in s/c missions, including X-ray missions such as Chandra. As the mission progresses into the implementation phase, a systems engineering IPT will be formed, consisting of SEs from all elements of the project–each instrument, s/c, telescope, project

SEs (including mission systems, s/c systems, and instrument systems), and mission operations—and led by the Mission Systems Engineer. Regular meetings of the IPT will ensure communication across all systems.

The overriding responsibility of the SE staff is to ensure that all systems work together and that issues that cut across different systems are identified, resolved, verified, and tracked. To achieve this, key systems engineering activities have included initial mission architecture design, which used discipline engineering support at GSFC and SAO and inputs from industry. Other key systems engineering activities include interface control, requirements flowdown, control and verification, assigning and managing technical resource allocations (e.g., mass and power), and design optimization including trade studies. Analyzing mission environments and obtaining independent insight at milestone reviews (e.g., SRR, PDR, CDR, etc.), as well as peer reviews, will be done.

Constellation-X has identified the key mission science requirements, which are delineated in the draft “Top-Level Requirements” document. These have been flowed down to component-level requirements in the “Requirements Flowdown” document. SEs will track, trace, and monitor the requirements during the implementation phase using a database tool such as DOORS. The validation and verification of each requirement will also be done by systems engineering. When Constellation-X requirements are baselined (during the formulation phase), they will be put under project configuration control and can be changed only with approval of the Constellation-X Configuration Control Board (CCB), which includes the SEs and is chaired by the Project Manager. Managing technical resources for each element also falls in this category–changes are monitored by the SEs and recommended to the CCB.

As specified in GPG 7120.5, the two Constellation-X documents written to date, included as reference documents, are the Reference Mission Description document and the Operations Concept document. A Systems Engineering Management Plan will be developed during the project formulation phase.

Constellation-X will use a prime contractor for the combined s/c and TM. This is a distinct advantage because it enhances the contractor’s ability to perform end-to-end systems engineering for the observatory. The contractor’s SEs will be part of the Project-led IPT, tying them in with the rest of the mission systems.

Trade Studies: Optimization of the mission reference architecture is an ongoing process and includes trades that have been identified to reduce cost, as well as to increase performance. Design optimization includes monitoring the interfaces between elements, which necessitates systems engineering cognizance of Interface Control Documents (ICDs). Risk management is also an important aspect of systems engineering and is described in Sections 4.1.1.7 and 4.1.2.7. To refine and enhance the reference mission concept and architecture, and develop cost effective high-quality requirements, further studies will be conducted during the formulation phase of the mission. The trades already completed have effectively used the Constellation-X teaming and management structure, inspiring confidence in the completion of future trades. The primary trades already conducted are listed in Table 2-9, as well as future trade studies that have been identified.

2.5.7 Equipment and Facilities

Constellation-X has modest requirements for equipment and facilities. Ground-support equipment (GSE) for the detectors will include instrument-provided detector stimulators and simulators, mirror stimulators, thermal GSE, lifting and handling GSE, alignment GSE, and s/c simulators. GSE for the TM will also include TM-provided lifting and handling GSE. GSE for observatory I&T will include s/c-provided lifting and handling GSE, ground system (GS), umbilical, power, and RF GSE.

Integration facilities will include a cleanroom of sufficient size and cleanliness for TM and observatory I&T, a crane for lifting operations, and a control room to house the GS, umbilical, power, and RF GSE, and the I&T team.

Environmental facilities will include EMI/EMC, vibration, acoustics, TV/TB, mass properties, and magnetics test chambers. The X-Ray Calibration Facility (XRCF) at MSFC will be used for X-ray testing and calibration of the FMA wedge assembly.

Table 2-9: Mission Trade Studies

Trade	Options	Drivers	Status/Selection
Number of observatories in constellation	12, 8, 6, 4, 3, 2, 1	Cost, schedule, science requirements reliability	4 baselined; 2 will be studied further in Phase A
Number of SXT FMAs	12, 8, 6, 4, 3, 2, 1	Effective area, s/c accommodation, ground test, cost	Closed/4 selected
Orbit	HEO/L2/LEO	Thermal environment Viewing efficiency	Done/L2
Launch vehicle	Delta II, Atlas III, Delta IV, Atlas V	Cost, performance	Done/Atlas V baseline, Delta IV backup option
Cryo system	Stored cryogen or mechanical system	Mass and life	Done/mechanical system
Timing	USO, crystal oscillator	Long-term accuracy	Done/USO
Grating design	• In-plane • Off-plane	Effective area, resolution	Ongoing/end FY03
Ground station	• Dedicated • Commercial	Cost Timing capability	Commercial at present; redo before launch
SXT contamination requirements	Level of cleanliness	Effective area, image quality, calibration accuracy	Future/SRR
Need for on-board radiation monitor	• EPHIN-like detector • Commercial detector (CEASE) • None	Protection of instruments from radiation damage	Future/SRR
Need for focal plane electron suppression	• None • Magnetic broom	Detector background	Future
Fiducial light system	• None • Chandra-type system • Lower cost alternate	Angular resolution (15 arcsec), OB stability	Done/none For angular resolution of 5 arcsec, may be revisited
Focus mechanisms	• One for both CCD and calorimeter • Separate mechanisms for CCD and calorimeter • None	Image quality, risk reduction	Future/PDR
On-board calibration sources	• Radioactive source(s) • Electron impact source	Need to maintain calibration throughout mission life	Future/PDR
Optical bench construction	• Truss with stray light closeout • Shell	Mass, stray light protection	Future/PDR
SXT calibration	• Full aperture testing in 1 G • Sub-aperture testing	Calibration accuracy	Future/CDR
HXT optics	• Segmented glass • Full shell Ni	• Multilayer deposition • Mass	Mid FY04

3.0 TECHNOLOGY ROADMAP AND PROGRAM FORMULATION

Constellation-X has achieved significant technology development progress since the beginning of its “pre-formulation” in 1996. Section 3.1 describes the current level of technology readiness, heritage, and the technology development plan for each enabling technology. Section 3.2 covers all other activities required to complete project formulation.

3.1 Technology Readiness and Development

The Constellation-X technology requirements and development roadmap were first documented in the Technology Roadmap in February 1997. This document defined the technologies needed for the mission, the technical path to develop these technologies, and nominal budgets. Based on these requirements, a NRA for Constellation-X technology development was issued in January 1998 and contracts awarded later that year. These contracts supported technology development of the X-ray microcalorimeter, grating, CCD, and HXT.

All required technologies are extensions of existing technologies that have been proven on previous missions. The Technology Development Roadmap in Table 3-1 summarizes the enabling and enhancing technologies, the improvements required, the current TRL and anticipated arrival of TRL 6.

Significant progress has been made on developing each of these technologies. Development efforts have leveraged off funding sources including Supporting Research and Technology (SR&T), and the Cross Enterprise Technology Development Program (CETDP), to maximize the return on limited project investments. The TRLs are currently in the 3 to 4 range, with required performance demonstrated at the component or bread board level.

The summary schedule to complete technology development is provided on Foldouts 8 and 9. Detail for each technology development showing the transition to flight instrument is provided in Appendix B. TRL 6 will be demonstrated for all technologies prior to the mission Non-Advocate Review (NAR) in late 2006. ***No flight demonstrations of the technologies are required.***

The technology development plan provides a clear path with defined milestones and attention toward minimizing risk in a cost-constrained environment. When appropriate, parallel

Table 3-1: Technology Development Roadmap Summary

System	Technology	Heritage	Required Improvement	Req't	Subsystem Technology Readiness Level by Fiscal Year				
					1998	Current	2004	2005	2006
FMA	SXT Mirror	Astro-E/E2, BBXRT, ASCA	Angular resolution	12.5 arcsec	TRL 2	TRL 3-4	TRL 4	TRL5	TRL 6
		XMM-Newton	Larger diameter	1.6 m					
RGS	Gratings (RGA)	XMM-Newton, Chandra	Low mass	0.2 g/cm^2	TRL 3	TRL 3	TRL 5		TRL 6
			Mass production	25/day					
	CCD Detector* (RFC)	Chandra, ASCA	Production yield	20%	TRL 2	TRL3	TRL 4	TRL 6	
			Event drive						
XMS	Microcalorimeter	Astro-E/E2	Larger array	32 x 32	TRL 3	TRL 4	TRL 5	TRL 6	
			Energy resolution	4 eV					
	ADR	Astro-E/E2 HAWC, XQC	Warmer sink	6 K	TRL 3	TRL 4		TRL 5	TRL 6
			Cont. operations						
	Cryocooler*	HST, TES, AIRS	Lower temperature	6 K	TRL 3	TRL 4		TRL 5	TRL 6
HXT	HXT Mirrors	HEFT, InFOCμS	Angular resolution	60 arcsec	TRL 3	TRL 4	TRL 5	TRL 6	
	HXT Detectors	HEFT, Swift	Low energy response	6 keV	TRL 3	TRL 4-6	TRL 5	TRL 6	

** Enhancing improvements; not required for mission implementation.*

approaches are pursued, which serves to mitigate risks while allowing competitive development for technologies where there is no clear determination a priori which technology is the most advantageous for the mission. Build up of sequentially more complex demonstration systems, as planned for the mirrors and XMS arrays, provides early development of components and processes.

The SXT and HXT mirrors and the RGS gratings require mass production to fabricate the large quantities required. This is factored into their development. Concepts to meet the production challenges for the flight build have been established and are summarized in the discussions of each technology.

Technology Development Risk and Mitigation: The technology development phase risks are summarized in Table 3-2, with assessments of their criticality and likelihood of occurrence, if no mitigation activities are implemented. These risks will be retired by the time mission implementation begins. The implementation phase risks are summarized in Table 4-3.

The mitigation plan for each risk is also provided. The criteria for evaluation of criticality and likelihood are:

- Criticality:
  - **High:** increases mission budget >3%; or delays launch date; or degrades performance below minimum science requirements
  - **Medium:** increases mission budget 1-3%; or delays major mission milestone >2 months; or degrades performance below baseline science requirements
  - **Low:** increases mission budget <1%; or delays major mission milestone ≤2 months; or loss of design margins
- Likelihood:
  - **High:** >50% probability of occurrence
  - **Medium:** 25-50% probability
  - **Low:** <25% probability

3.1.1 SXT Mirror Technology Readiness and Development Plans

3.1.1.1 SXT Mirror Technology Readiness

The SXT mirror requirements have been provided in Section 1.3.1.1. The mirror will have a diameter of 1.6 m and a focal length of 10 m.

Technology Description: The SXT mirror design is a segmented, highly nested Wolter I. The mirror consists of 18 modules, 6 inner and 12 outer. Reflectors are 440 μm thick glass, 20-30 cm long, and subtending a 60 degree arc in the inner module, 30 degrees in the outer. They are thermally formed to a precise figure, with a gold X-ray reflecting surface imparted via epoxy replication.


CX015

Figure 3-1: Astro-E flight mirror has a 40-cm diameter and a mass of 17 kg. The design utilizes tightly nested, segmented epoxy-replicated reflectors. The SXT mirror is based on this approach, scaled to 1.6 m, incorporating more accurate replication mandrels, more stable reflector substrate, and more precise alignment.

The heritage of the SXT mirror is addressed in Section 1.3.1.1. The closest predecessors are those flown on BBXRT, ASCA, XMM-Newton, and Astro-E/E2 (Figure 3-1). This style of mirror meets the Constellation-X mass requirement. The mass production approach for these mirrors serve as a model for the SXT mirror. Previous foil mirrors had conical optical surfaces; the SXT mirror will have a Wolter-I (axially curved) surface. The fabrication steps for the SXT mirror are similar to those for the conical thin-foil mirrors. In particular, the SXT mirror uses the identical method of epoxy replication for creating X-ray reflecting surfaces, in which a thin layer of epoxy is sprayed onto the reflector substrate and used to impart a final optical surface replicated from an ultra-smooth, precise mandrel. The higher angular resolution requirement of the SXT mirror has necessitated substantial development of new processes. These include the use of new substrate material (glass), forming process (slumping) and

Table 3-2: Technology Development Risk Summary

Technology	Reference	Risk	Mission Impact	Criticality	Likelihood if no Mitigation	Mitigation
SXT Mirror	SXT-1	Reflectors do not meet angular resolution at the required dimensions	Reduces mass reserves, no science impact	Medium	Low	Use thicker substrates
			Reduces throughput margin, remains above Mission Minimum Effective Area Requirement	Medium	Low	Use smaller reflectors
	SXT-2	Unable to verify mirror performance in 1 g	Does not meet image performance requirement	Medium	Low	Design for 1 g analysis Fabricate vertical test facility
RGS Gratings	RGA-1	Thin substrates do not achieve required flatness	Reduces mass reserves and/or reduce grating area and/or schedule impact	Medium	Low	Use same production scheme as XMM Newton RGA
	RGA-2	Inability to efficiently mass produce gratings	Reduction of grating area Reduces schedule reserves	Medium/ Low	Low	Use same production scheme as XMM Newton RGA, use thicker substrates. Parallel study off-plate gratings
RGS CCD Detector	CCD-1	MBE yield lower than anticipated	Reduces funding reserves; schedule impact	Low	Medium	Use existing BI X-ray CCDs (TRL 9)
	CCD-2	EDCCD circuitry impractical	Larger power consumption, decreased timing resolution	Low	Low	Disable EDCCD feature
XMS Microcalorimeter	XMS-1	TES detector does not meet 4 eV requirements	Does not meet spectral resolution performance requirement	Medium	Low	Parallel TES and NTD/Ge development; reoptimize array geometry
	XMS-2	High density array interconnects	Use schedule reserves	Medium	Low	Parallel approaches in development; stacked insulated leads; reoptimize array
	XMS-3	SQUID MUX Speed	Lower margin on ADR cooling	Low	Medium	Trade number of MUXed channels with heat load and complexity
XMS ADR	XMS-4	ADR heat rejection Incompatible with cryocooler	Detector "livetime" is limited	Medium/ Low	Low	Design cryocooler and ADR with significant margin; cycle ADR more frequently
	XMS-5	SQUID noise from magnetic fields	Lowered energy resolution	Low	Low	Fund superconducting wire fab. Install magnetic shielding
XMS Cryocooler	XMS-6	Required cooling efficiency not achieved	Reduces mass, funding, and schedule reserves; limit mission life	Medium	Medium	Use alternate cryocooler under ACTDP Parallel development Use hybrid 35 K cryocooler with stored cryogen
HXT Detectors	HXT-1	Do not reach low-energy threshold	Reduced overlap with XMS for calibration	Low	Medium	Electronics architecture redesign

mounting approach (precision mounting of individual or small groups of reflectors, in contrast to gang alignment of an entire module).

The SXT program will benefit from prior reflector mass production efforts, including those for the conical mirrors and for XMM-Newton. The SXT program also makes extensive use of systems and thermal engineering experience from Chandra, utilizing a similar alignment approach (though on a larger scale), using the CDA that was developed for Chandra. Equally important, the SXT mirror technology development approach has similar key milestones to the highly successful Chandra mirror development: production of a small prototype, followed by a demonstration that the largest mirror can be fabricated, prior to the production of the flight mirror system.

TRL Status: At the start of technology development, the thin foil mirror from which the SXT mirror draws its heritage had already flown on several space missions (TRL 9). The current design, with its large radius, new materials and new production process, was at a much less mature level (TRL 2).

Currently, the SXT mirror system as a whole is at TRL 3-4, with all components at TRL 4 or higher. A pathfinder module has been designed, analyzed, and assembled. The performance of this module has been shown to meet expectations based on analysis, providing confidence in the analytical models.

A pathfinder housing has been built that has been shown to be able to adjust a reflector over the range and with the accuracy necessary to align flight mirrors. Reflectors have been fabricated using the flight development approach that satisfies the error budget (Table 1-3); the process is currently being scaled to full-sized reflectors. Metrology and alignment procedures for individual reflectors have been developed and demonstrated. The largest replication mandrel needed for the flight mirror has been delivered; it meets or exceeds specifications.

3.1.1.2 SXT Mirror Technology Development Plan

Strategy and Logic: The major steps in the SXT mirror technology development plan are described below. Some key principles underlying this plan are:

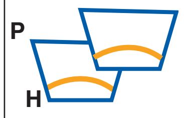
- maximum use of existing facilities for metrology and calibration
- reuse of previous technology developments
- development and demonstration of all processes for assembly, alignment, and bonding, and transfer of these to industry
- progressive build toward flight prototype (see details below); attacking the “tall poles” in the error budget first, and solving problems incrementally as they are encountered
- design and test supported by full analysis (finite element mechanical and thermal analysis plus optical ray tracing)

Technology Development Plan: The SXT mirror technology development relies on progressive development from components to a full prototype. Starting with relatively simple units, progressively higher complexity is added in each step along the development path, allowing a careful study of all key fabrication, assembly, and alignment issues. The end product is a full-size segment of a SXT mirror that will be fully environmentally and performance qualified. A representative group of reflector pairs will be incorporated, spanning the full range of diameters, and ensuring that the prototype has sufficient fidelity to the flight unit. The technology development plan is summarized in Table 3-3.

The key steps in the technology development plan are summarized below. Some of these steps are called out specifically in Table 3-3, while some are precursor or parallel activities. Four key stages in the progressive development are identified in Table 3-3. These are the Optical Alignment Pathfinder (OAP), the Engineering Unit (EU), the Mass Alignment Pathfinder, and the Flight Prototype.

- Refining processes for reflector forming, replication, and cutting.
  - —Individual freestanding reflectors must have an RMS figure error <7 arcsec. This constrains the figure error introduced during thermal forming and the surface quality obtained from epoxy replication. Small (20-30 cm diameter by 10 cm length) reflectors meeting this requirement are being produced on a regular basis. Scaling to flight-sized reflectors (50 cm diameter by 20-30 cm length) is underway.
  - —The modeling of the effect of the thin epoxy layer on reflector mechanical and thermal properties must be verified. The epoxy shrinks while curing, introducing

Table 3-3: SXT FMA Technology Development Roadmap

	Optical Assembly Pathfinder		Engineering Unit	Mass Alignment Pathfinder	Prototype	
	OAP #1	OAP #2				
Configuration						
Module type	Inner	Inner	Inner	Inner	Outer	Wedge (2 Outer & 1 Inner)
Housing material	Aluminum	Titanium	Composite	Composite	Composite	Composite
Focal length	8.5 m	8.5 m	8.5 m	8.5 m	10.0 m	10.0 m
Reflector length (P&H)	2 x 20 cm	2 x 20 cm	2 x 20 cm	2 x 20 cm	2 x 20-30 cm	2 x 20-30 cm
Nominal reflector diameter(s)	50 cm	50 cm±	50 cm±	50 cm±	160 cm 120 cm± 100 cm	160 cm±;40 cm± 120 cm± 100 cm±
Goals	• Align 1 reflector pair (P&H) • Evaluate mirror assembly design, alignment and metrology	• Align 1 reflector pair • Evaluate reflector gravity sag • Evaluate mirror bonding	• Align up to 3 reflector pairs to achieve <12.5 arcsec • Eval. assembly gravity sag • X-ray and environmental test • Evaluate composite housing	• Align 3 reflector pairs • Evaluate tooling and alignment techniques for mass production • X-ray test	• Flight-like configuration outer module • Environmental and X-ray test • Largest reflectors	• Demonstrate largest and smallest diameter reflectors • Demonstrate module to module alignment • Environmental and X-ray test
Timeframe	Q2 of FY03	Q3 of FY03	Q1 of FY04	Q1 of FY05	Q4 of FY05	Q4 of FY06

stress in the reflectors. Mismatch of its thermal properties with the glass places constraints on temperature gradients. The degree of distortion will be quantified and verified that its properly accounted for in the error budget.

—Cutting the reflector edges to an accuracy of 20 μm is required for some of the mass alignment approaches being explored.

- Synergistic with the reflector fabrication is the requirement on the mandrels used for forming and replication. Forming mandrels must remain stable when cycled to 600° C. Replication mandrels require a figure precise enough to allow a minimum epoxy thickness to be used. Significant research is being performed to determine cost-effective materials and fabrication approaches.
- The distortions introduced when a reflector is placed in a housing and aligned must be understood and shown to remain within the error budget[36]. [OAP1]
- Means for bonding an aligned reflector into a housing without introducing unacceptable distortions will be developed. [OAP2]
- A matched paraboloid (P) and hyperboloid (H) pair must be aligned, forming an image that meets the 12.5 arcsec HPD angular resolution requirement. [OAP2]
- Reliance must be placed on analytical modeling of the effects of temperature and gravity on alignments. Smaller, simpler units are to be used early in the program to validate and verify the model predictions. [OAP2]
- The near term critical milestone for the SXT technology development is a demonstration in X-rays of the required imaging performance of a reflector pair after environmental tests. This demonstration will take place in early FY04. [EU]
- Incorporating flight compatible housing materials such as carbon fiber composite with engineered CTE will reduce sensitivity to temperature effects. [EU]
- Alignment of a reflector pair without introducing misalignment into previously aligned

and bonded pairs, will be demonstrated. X-ray imaging performance will be verified before and after environmental testing. [EU]

- An approach will be developed for the rapid assembly and alignment of a module, with simultaneous alignment of multiple reflector pairs to meet the angular resolution requirement. [Mass Alignment Pathfinder]
  - —A current approach uses microcombs (accurate to <0.1 μm) that have already been fabricated (see Foldout 3-B8 and 3-D18).
  - —Rapid, computer-controlled alignment of individual pairs will also be investigated.
- Fabricating the largest (1.6 m) reflectors requires development of infrastructure at the scale needed for flight mirror production. Infrastructure items are forming and replication mandrels, associated handling equipment, a robotically controlled epoxy spray station, coating and replication chambers, a precision glass-cutting fixture, and metrology equipment. The possibility of producing longer reflectors will be investigated: longer reflectors require fewer nestings, fewer forming and replication mandrels, and is a potential cost savings. [Outer Prototype]
- A flight-like unit will be assembled and shown to meet requirements through X-ray and environmental testing. [Outer Prototype]
- Three flight-like units will be co-aligned and X-ray tested. [Wedge Prototype]
- A flight prototype will be integrated with a prototype grating, and the performance of the combined unit measured in X-rays. [Wedge Prototype]

Technology Investments to Date: Investment in the segmented approach has resulted in the establishment of an infrastructure for producing the OAP units. This includes precision replication mandrels, forming mandrels, a forming oven, an epoxy spray station, glass cutting fixtures, a replication chamber, metrology equipment, alignment housings, and Si microcombs (Foldout 3-A and 3-B).

Initially, the segmented mirror technology was developed in parallel with full shell mirrors fabricated via nickel electroforming. The full shell approach was abandoned when it became apparent that the required massive, monolithic mandrels would be impossible to fabricate. The segmented program has utilized much of the infrastructure originally produced for the full shell approach, including the EU replication mandrels and several pieces of metrology equipment.

Test Beds and Simulators: The facilities at GSFC used for prototype development serve as test beds for SXT mirror fabrication. A reflector development laboratory is being used to establish the facilities and processes that will be incorporated into a reflector production facility, and an optical alignment test bed has been developed to define processes for assembling and aligning reflectors within housings.

Equipment and Facilities for Technology Development: The SXT mirror program has maximized use of existing equipment at GSFC, MSFC, and SAO. Equipment has been modified or upgraded to meet SXT needs when this was deemed more cost effective than new equipment. Examples of reuse of existing equipment and facilities are: (1) use of optics fabrication facilities at GSFC and MSFC for pathfinder mandrel development; (2) use of existing metrology equipment (WYKO microscopes, coordinate measurement machines, and interferometers); (3) use of the CDA; and (4) planned use of long beam X-ray facilities at MSFC.

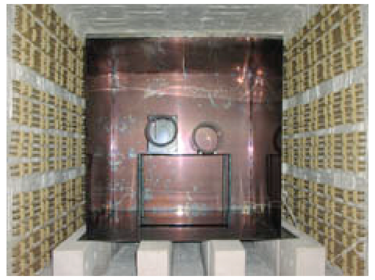
At this time, nearly all facilities and equipment needed for the completion of the SXT mirror technology demonstration are either on hand or on order. Equipment bought specifically to support the SXT mirror includes: (1) the contents of the GSFC reflector development laboratory–forming oven, spray booth, precision cutting fixture, storage and transport apparatus, and clean room enclosures; (2) the SXT mirror alignment facility large interferometer (on order); folding mirrors, large retroreflector, and CDA (on loan); (3) MSFC metrology equipment–horizontal and vertical long trace profilometers.

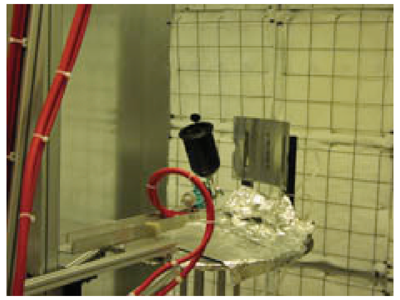
Plans for Mandrel and Mirror Production: The acquisition strategy for the SXT mirror flight production entails partnering with a mirror contractor as early as possible. The Constellation-X project will solicit contractors for a six-month prototype design study starting late in FY03. On the basis of the study outcome, one contractor will be selected at the end of FY04 as the SXT contractor. The contractor will set up a reflector production facility, incorporating processes transferred from the SXT

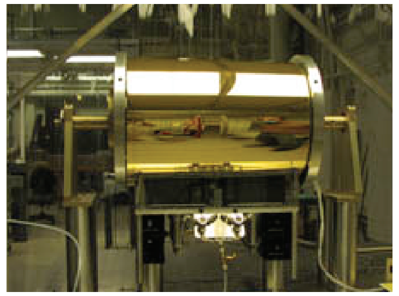
Constellation-X Optics

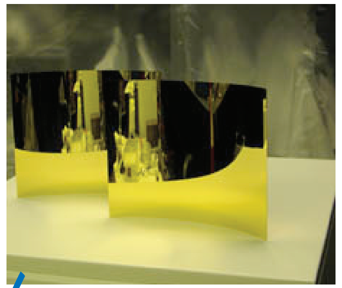
A Spectroscopy X-ray Telescope (SXT) Mirror Reflector Replication


1) Prototype segmented replication mandrel for 1.6 m diameter reflectors. This Zeiss Mandrel, composed of Zerodur, is the largest mandrel needed for the SXT mirror.

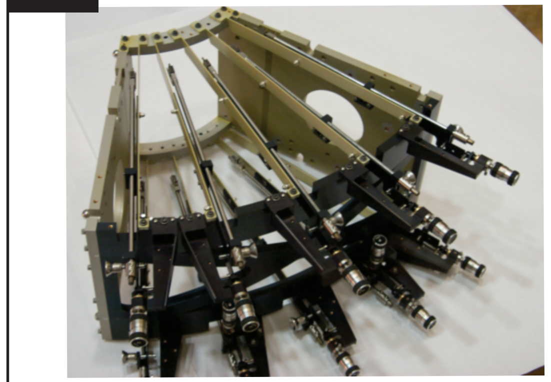

2) Thermal forming of glass reflector substrates in 1.5m^3 GSFC furnace. Mandrels have 20 cm diameter. The substrate material is Desag D263 glass.

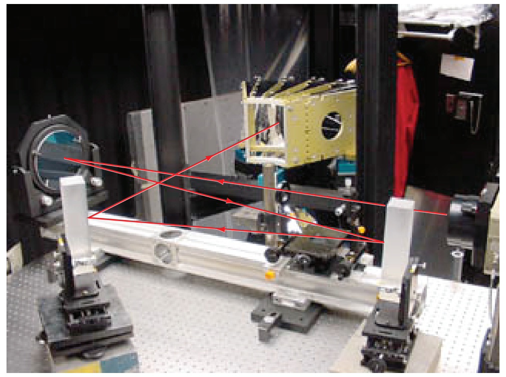

3) Epoxy application on glass substrate using robotic sprayer. Typical epoxy thickness is 10-20 µm; epoxy thickness is accurate to 1 µm.

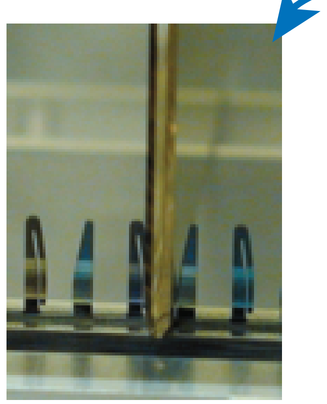

4) Attachment of glass substrate to 50 cm replication mandrel. Attachment is performed under vacuum, in housing from below. Replicas from this mandrel will be used for the Optical Alignment Pathfinder (OAP) and Engineering Unit (EU).

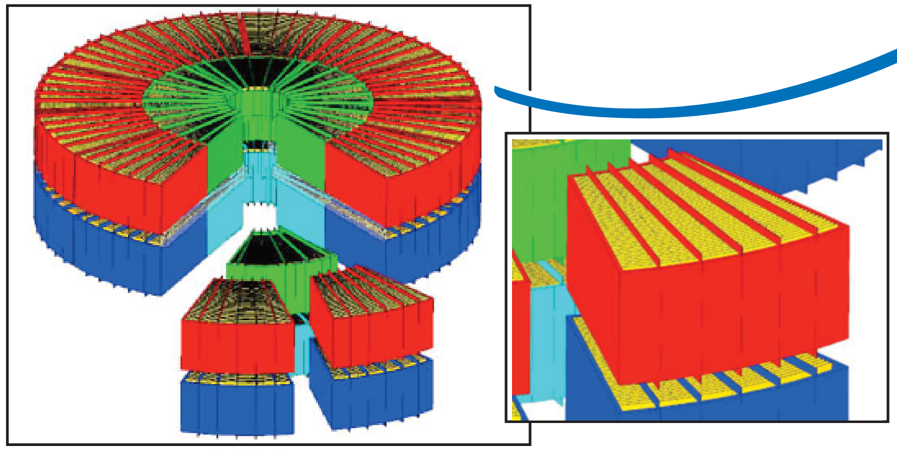

5) Final replicated glass segment. The segment subtends a 60-degree arc with a 25 cm radius of curvature. Its height is 20 cm.

B SXT Mirror Assembly and Alignment

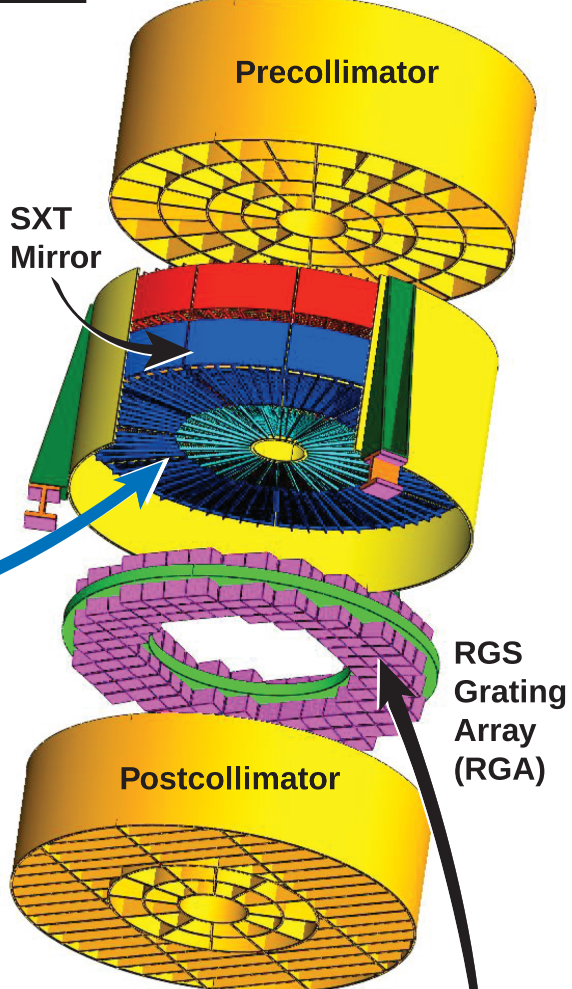

6) Reflector alignment housing for OAP-1. Housing is constructed of aluminum and has precision actuators at five azimuthal locations top and bottom to position a reflector to submicron accuracy. OAP-1 has two identical, stacked housings, for primary and secondary reflectors.


7) OAP alignment using the Centroid Detector Assembly (CDA). Red line indicates light beam path between CDA (not shown) and reflector.


8) Etched Si microcombs for mass alignment of reflectors and gratings. Microcombs are accurate to 0.1µm.

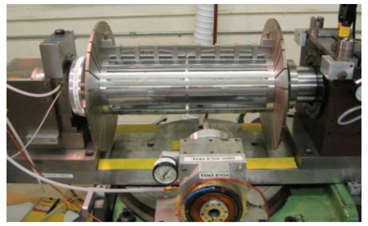

9) Concept drawing of the SXT Mirror. The mirror consists of 6 inner 60-degree modules and 12 outer 30-degree modules. Each module consists of a primary and secondary housing, each 20 cm tall. The total number of nested reflector pairs is 230; the overall diameter of the mirror is 1.6 m. Inset: Close up view of an outer module, showing radial reflector mounting struts.

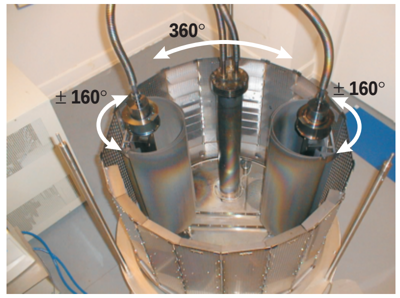
E SXT Flight Mirror Assembly



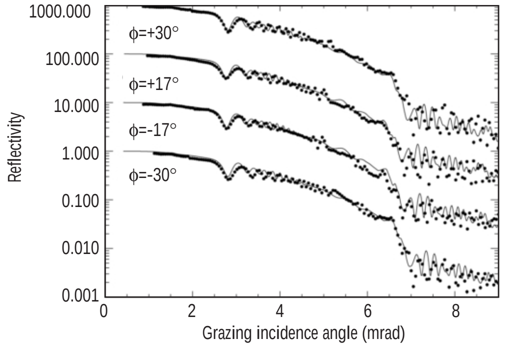
10) Exploded view of the SXT Flight Mirror Assembly (FMA) design concept.

C HXT Mirror

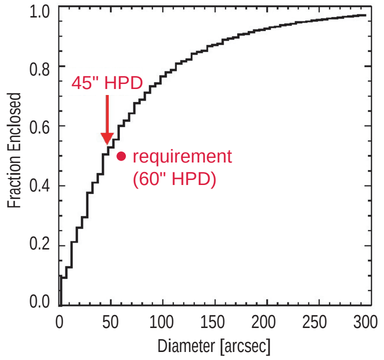

11) Glass prototype segments being assembled on a custom machine.



12) Top view of the custom magnetron sputtering facility at the Danish Space Research Institute.

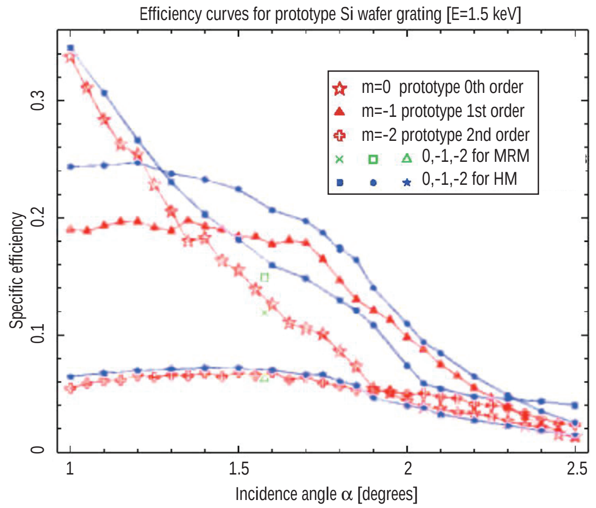


13) Measured reflectivity at 34 keV of a formed glass substrate coated with a W/Si graded multilayer, plotted in terms of incidence angle. Phi is the azimuth angle around the shell. Points are data; solid lines are model.

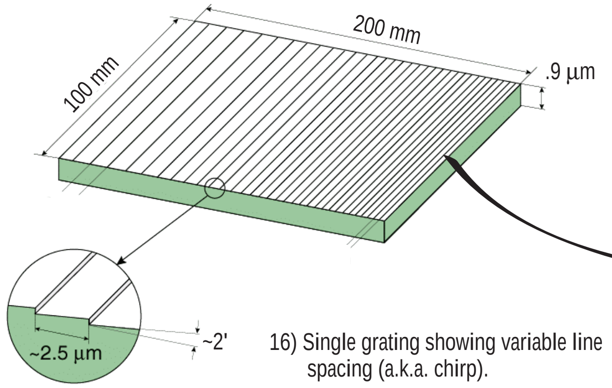


14) Measurement of performance of a prototype HXT mirror. This prototype exceeds the HXT angular resolution requirement.

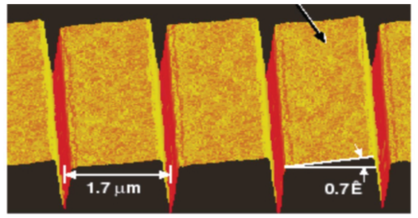
D RGS Gratings



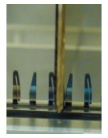
15) X-ray efficiency measurements for a prototype Si wafer grating at 1.5 keV (8.34Å), compared to master gratings. Red: test ruling: blue holographic master (HM); green: mechanically ruled master (MRM).

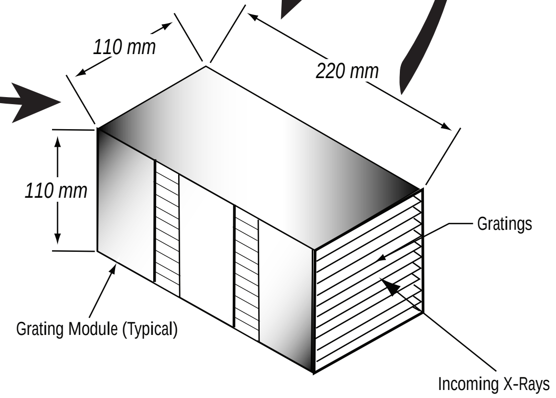


16) Single grating showing variable line spacing (a.k.a. chirp).



17) Micrograph of an anisotropically etched test ruling grating with atomically smooth groove facets, formed by Si (111) planes in the crystal.


18) Si microcombs are used for both the SXT Mirror and the RGA.



19) Grating flight module concept showing 10 identical gratings within the module.

technology development. Forming and replication mandrels will be acquired by the SXT team under separate contract, and supplied as GFE to the contractor. The contractor will be responsible for construction of reflector housings, integration and alignment of modules, full mirrors, and the FMA. The RGA will be delivered as GFE for integration into the FMA.

The SXT team has investigated the feasibility of this approach through discussions with potential partners including Kodak, Goodrich, and Lockheed Martin. Vendors for forming and replication mandrels have been identified through the procurement of prototypes. Carl Zeiss (Oberkochen, Germany) is under contract to fabricate three replication mandrels for the flight prototype (30-degree segments with radii of 1.0, 1.2 and 1.6 m). Zeiss has delivered the 1.6 m mandrel (the largest one necessary for the flight program) on schedule and meeting or exceeding specifications. Other vendors that should be capable of producing replication mandrels have expressed an interest. Several vendors have been identified that could provide some or all of the forming mandrels, including Schott Glas (Mainz, Germany) and Rodriguez Precision Optics (Lafayette, LA).

3.1.1.3 Key Risks and Mitigation

The key technical risks during the SXT technology development phase are shown in Table 3-2.

Reflector Substrate (SXT-1): The ability to make reflectors with the required figure and dimensions will be demonstrated. There is a low-probability, medium-criticality risk of not meeting the requirements. Mitigation will be achieved through either increasing substrate thickness (at the cost of mass), or making smaller reflectors (trading either a more complex design, or a loss of throughput).

Performance Verification (SXT-2): The SXT design is strongly coupled to gravity and temperature variations. There is a low-probability, medium criticality risk that the resulting distortions on the structure cannot be modeled with sufficient fidelity to ensure required performance verification. The risk will be mitigated by testing modules in a temperature controlled vertical facility.

3.1.2 Grating Technology Readiness and Development Plans

3.1.2.1 Grating Technology Readiness

Requirements for the RGA were provided in Section 1.3.1.2. Its development benefits from heritage from the RGS instrument aboard XMM-Newton[27, 28, 29], which met the requirement of 2 arcsec alignments[30]. Scaling up the RGA concept requires a reduction in mass per unit interception area[31], as well as a different approach to grating mass production. Following is a discussion of both the baseline approach using traditional “in-plane” gratings, and an alternate “off-plane” concept that potentially requires fewer modules and relaxed fabrication and alignment tolerances, reducing risks while decreasing costs.

Technology Description: For XMM-Newton, the RGS gratings met the flatness requirement along the optical axis by using a rib running axially along each substrate. Residual twist figure distortions were corrected by constraining the grating corners in the integrating structure. To meet the mass and throughput requirements of Constellation-X, the substrates will not feature such stiffening ribs. Instead, the thin (<0.2 g/cm^2) substrates will be prepared to be flat (<2 arcsec) when freestanding. The capability to produce such grating substrates in large quantities is a substantial part of the technology development plan.

A consequence of using thin, un-stiffened substrates is that the epoxy replication technique used for XMM-Newton must be replaced in favor of direct fabrication. The reason for the change in the fabrication approach is that epoxy replication imparts significant surface stresses on the substrate, which causes distortions to the optical surfaces. Using anisotropic etching of Si wafers graze-cut with respect to the (111) crystal plane, gratings have been produced (see Foldout 3-D17) that feature atomically smooth groove facets (blaze) aligned with the (111) plane. X-ray testing of these gratings confirmed a very high diffraction efficiency performance, even better than the master grating used for the RGS aboard XMM-Newton (for similar geometric parameters at 8.34Å and 13.34Å, see Foldout 3-D16). The crucial benefit of direct fabrication is neither the superior groove efficiency nor the complete bypass of the multigenerational replication process, but the fact that well understood, photolithographic and microfabrication mass-production technologies can be exploited for producing the many grating sheets required.

Because of the large number of gratings required (~1000 gratings per SXT), combined with their increased fragility, the XMM-Newton RGS alignment scheme will be too time-consuming and costly. For the RGS, a modular approach is taken in which the thin (<0.9 mm) gratings are aligned and assembled into "grating subassembly modules." These identical modules each contain approximately 10 gratings (also all identical). This highly modular approach (Foldout 3-D19) with no unique components is a key to the process. The GSE alignment fixturing disengages from the gratings after the gratings are aligned and bonded to the subassembly frame. These identical grating modules are in turn attached to the array integrating structure to assemble the full grating array (see Foldout 3-10). Attachment to the integrating structure may be done with kinematic mounts built-in to the grating module frames, or by aligning and bonding each grating subassembly to the local converging beam with the help of the CDA.

An alternate approach to the baseline utilizes high efficiency, "off-plane" gratings in place of the anisotropically etched gratings [32, 33]. In this approach, a substantially smaller number of gratings are required to build up the array, and therefore, constraints on the per-grating mass and fabrication time are relaxed. When combined with looser grating alignment tolerances, the off-plane option offers a "low-tech" solution that provides a comparable end product[34].

Aggressive technology investigations are being pursued into the "off-plane" approach concentrating on fabricating the master grating, replication gratings, fidelity studies, and arraying studies. The first test ruling procured from Jobin-Yvon was only recently delivered (December 2002) and its initial characterization is underway. A highlight of this technology program is the fabrication of a full-size, flight representative master (radial groove) grating against which replicas could be pressed. If epoxy replication proves to be a suitable technique for "off-plane" grating fabrication, most of the technology is already available and proven, reducing development risks. A parallel effort of direct fabrication for high density, off-plane gratings (at MIT's Space Nanostructures Lab) reduces risk.

Following a scheduled downselect between grating geometries, to take place at the beginning of FY04, only one of the two candidates will be considered for the flight instrument. The remainder of the discussion here will be limited to technology development for the "in-plane" (baseline) gratings.

TRL Status: While gratings themselves have flown and are at TRL 8-9, the thin gratings required for Constellation-X are currently at TRL 3. Test rulings have been fabricated, verified, and X-ray tested, with extremely promising results. The test rulings have been smaller than the flight gratings and without the ruling density gradient (or chirp) required for the flight gratings (Foldout 3-D16). The path toward TRL 6, and the milestones that define those levels, is outlined in Section 3.1.2.2.

Substrate flattening was demonstrated by Magneto-Rheological Finishing (MRF) a free-standing Si wafer from an initial 14-arcsec slope distribution to 1.5 arcsec. The technology is clearly available, and methods to exploit it efficiently are under study.

The anisotropic etching process that produces super-smooth grating facets is well understood but requires tuning to work over large surfaces. A controlled interference pattern with high contrast must be set up over the entire 100 x 200 mm, and the plasma etch step must be performed over the same area. Etch facilities will be identified in industry.

Alignment fixturing for the gratings when assembled into the subassembly modules is planned to be done using microcombs[35] (also used for the SXT reflector assembly[36], see Section 3.1.1, Foldout 3-B8 and 3-D18), fabricated to 200 nm accuracy over 100 mm. Such microcombs have been fabricated, resulting in error budget contributions from the alignment tools that are small compared to other terms in the error budget.

3.1.2.2 Grating Technology Development Plan

Strategy and Logic: Among the various technologies available to prepare and align gratings for the RGS, a few key technologies require development. These technologies are required primarily for the scaling aspects of the instrument. The deliverable gratings (~1000 per SXT) should be produced, measured, and accepted in a 2-year period, which requires a throughput of about 25 gratings per day from an industrial vendor. Since the lithographic process and anisotropic etching on the Si wafers benefit from industrial experience, technology development therefore focuses on the efficient preparation of the thin, flat, freestanding grating substrates.

Technology Development Plan: The technology development to be conducted over the next two years will focus on the key areas of grating patterning, pattern replication, substrate preparation, and assembly and alignment.

First, the capability to produce flight-size gratings using scanning beam interference lithography (SBIL) will be demonstrated by making constant groove spaced gratings (December 2003). Second, the SBIL facility will be generalized to produce variable-period SBIL (VPSBIL). Availability of VPSBIL will permit "writing" a grating pattern into a full-size grating, 100 x 200 mm, in approximately one hour. A parallel fabrication approach using UV nano-imprint technology to fabricate the gratings is being pursued for risk mitigation. This approach, if usable, will provide a substantial reduction in cost, because of combined high fidelity imprinting and zero stress cure of the emulsion. This will allow patterning of substrates using a master produced with VPSBIL and will alleviate the need to write (and etch) each grating directly. After patterning, each substrate will have a reflective coating applied to complete the grating.

Several tests will be conducted on full-size gratings on flat, flight representative substrates, to verify capability to retain flatness after application of the high-density reflective coating. The surface tension of metal coatings can distort the figure of thin optics; application of the same coating on the reverse side can mitigate this effect.

Scheduled arrival dates for higher TRLs are as follows:

- TRL 4 will be reached in March 2004. The milestone is to fabricate a nearly (70%) flight size reflection grating, 140 x 100 mm with the flight specific groove facet form and ruling density. The grating will not necessarily contain the appropriate "chirp" or ruling density gradient.
- TRL 5 will be reached in September 2004. This is the critical technology milestone for grating technology development. It will be achieved when three (or more) flight representative substrates are assembled in a flight-like structure, meeting the 2 arcsec flatness criteria both for optic flatness and for mutual alignment. The substrates will be fabricated using procedures that can be applied to mass production and experience all processing steps that are included in the plan for the final flight gratings. Stiffness and resonant frequencies will be similar to the flight module frames. Verification of flatness and alignment retention before and after environmental testing will be performed.
- Capability to fabricate variable line spacing gratings will be available in mid-2005, when the VPSBIL facility upgrade is completed.
- Arrival at TRL 6 is expected in March 2006. The milestone for this will be the successful X-ray testing of an assembled grating subassembly module (approximately 10 gratings). This will be performed as an "end-to-end" test in a finite source distance, X-ray beam facility. A converging beam will be intercepted by the grating module, and the pass-through, reflected, and diffracted beams will be measured at the focal planes.

Technology Investments to Date: Efforts to develop technology suitable for grating fabrication have been funded thus far by a combination of Constellation-X Technology and SR&T funding sources supplemented by leveraging DARPA activities. Results include the advances enumerated above, namely: development of the SBIL facility, capability to pattern and anisotropically etch the grating test rulings, testing the MRF substrate flattening process (at the MRF tool vendor), and holographic test ruling production for the off-plane grating concept described above. A Shack-Hartmann metrology facility was developed to provide input for the MRF flattening process. Micro-comb development for grating assembly has been funded largely by the SXT group, and demonstrates the synergism in the program between the technology development efforts.

Test Beds, Simulators, Flight Demonstrations of the Technology: Facilities at MIT's Space Nanostructures Lab will be used to align and assemble flat grating substrates into prototype modules. Verification of grating alignment and flatness retention will be done before and after environmental testing at either MSFC's XRCF or at Columbia's Nevis Long-beam X-ray calibration facility.

Equipment and Facilities Required for the Technology Development Effort: The technology development effort will require enhancements to existing facilities already available as part of the investments to date. Included in these are the VPSBIL upgrade to the SBIL facility for writing flight size grating patterns, an ion etching tool, an upgrade of the Shack-Hartman metrology tool to provide mid-frequency resolution, and UV nanoimprint facility for mandrel production.

Plans for Production Facilities: Production of flight gratings will be performed by industry, with technology transfer taking place more than a year before production commences. Routine alignment and performance verification of the modules can be performed either at MSFC's XRCF, Columbia's Nevis calibration facility, or at another suitable X-ray beam facility. A spare SXT mirror segment will be used to provide a converging beam. In the baseline approach, assembly of the grating modules into the final RGA will be performed by the FMA contractor.

3.1.2.3 Key Risks and Mitigations

The key technical risks during the grating technology development phase are shown in Table 3-2.

Meeting Substrate Requirements (RGA-1): The ability to produce freestanding, flat substrates of the required size.

Flight Grating Fabrication (RGA-2): The ability to direct fabricate (anisotropic etch) full-size flight gratings in graze-cut Si (111) wafers.

The probability of both risks is assessed as low, however both can be mitigated by using a similar substrate production and alignment scheme as was used for the XMM-Newton RGA (TRL 8). The higher mass per grating (and integrated mass) would result in a trade between an increased mass allowance (~100%) or a reduction in grating array effective area.

3.1.3 CCD Technology Readiness and Development Plans

3.1.3.1 CCD Technology Readiness

The RFC is an array of CCDs mounted on a common structure (Foldout 4B-12). Requirements for the RFC system are summarized in Section 1.3.1.2. The RFC consists of two separate camera systems with essentially identical requirements: the spectroscopy readout camera (SRC) and the zero order camera (ZOC). The SRC is analogous to the RFC aboard XMM-Newton[29].

Technology Description: The primary features of the CCDs include high quantum detection efficiency over the 6-50Å (0.25-2 keV) bandpass, efficient rejection of stray optical light, (dark current induced) flickering pixels and non-photon background. The required readout frequency is currently ~0.5 frames per second. The other functional requirement for the CCDs is that the pulseheight spectral resolution be sufficient to separate spectral orders in small extraction regions. Back-Illuminated (BI) CCDs are required for their superior quantum detection efficiency at low energies.

The ZOC provides an attitude solution to <1 arcsec that is required to locate the wavelength scale of the SRC. Because the zero order image is undispersed, the local count-rate is higher than in the SRC CCD and therefore the readout frequency for the ZOC CCDs is moderately higher than that of the SRC CCDs.

TRL Status: The CCDs are at a high TRL. The principal technology developments are enhancing from a mass production viewpoint, as the CCDs require no enabling technical development. New technology is required to improve production yield for BI-CCDs, reducing cost and schedule risks.

Heritage for the CCDs is drawn from ACIS (Chandra) and the Solid-state Imaging Spectrometer (SIS) onboard ASCA.

3.1.3.2 CCD Technology Development Plan

Strategy and Logic: Two technology advancements are being pursued.

- Suitable BI CCDs are currently available, but will benefit from improved production yield. To improve device yield (and as an added benefit improve low-energy efficiency), molecular beam epitaxy (MBE), a lower temperature process, will be used to thin and treat the CCD backsides.
- An unconventional, but technologically straightforward, enhancement can be made to the on-chip electronics and to the CCD analog video chain. This modification provides event driven CCD (EDCCD) capability[37]; essentially a nondestructive charge

sensor and a (CCD) serial register delay line that performs ADC conversion only when the pixels contain significant charge (see Foldout 4-B13). A conventional X-ray CCD operates by reading out the full array, and pattern recognizing the X-ray events contained in each digitized frame, though >99% of the pixels typically contain no X-ray events. By converting only the pixels containing charge detectable by the nondestructive sensor, an enormous savings is made in the energy consumption per frame readout. With a fixed power budget, a larger readout frequency may be attained in exchange for the reduced energy per readout. The current estimate of the frame readout frequency is over 10 Hz. While not a requirement for the RFC, this enhancement will vastly improve data quality, timing resolution, and background rejection for the RGS system.

Technology Development Plan: The roadmap for technology development of the MBE-BI EDCCDs includes several iterations of fabrication, packaging, tuning, and testing. Each iteration is done in "half lots" to reduce costs. The fabrication and packaging are performed at MIT/LL, while the testing is performed at MIT/CSR. The first EDCCDs (Gen.1, Lot1), were fabricated and packaged in September 2002. They feature the EDCCD on-chip electronics included in a front-illuminated (FI) device. Gen.1, Lot1 CCDs will suffice to test the predicted EDCCD power savings and assess radiation damage performance. Radiation damage testing should be complete by March 2003.

Mask design and layout for the Gen.2 Lot1 devices (including the MBE processing) began in October 2002, and their testing (quantum efficiency, resolution, background rejection, radiation damage, etc., is due for completion in October 2003. At that point, TRL 4 will be reached for the grating spectrometer EDCCDs.

Production of Gen.2 Lots 2 and 3 will start in October 2003 and October 2004, respectively, during which optimization of the MBE processed backside and optical blocking filter application will be performed. TRL 5 is scheduled for March 2005, when an engineering unit focal plane is produced, with camera electronics including field programmable gate arrays (FPGAs). TRL 6 will be reached in September 2005 following environmental testing of the prototype focal plane.

Technology Investments to Date: Technology development for BI-EDCCDs has been funded by a combination of Constellation-X technology and SR&T funding sources. In addition, the first "event drive" circuitry on a functional (frontside illuminated) Gen-1 EDCCD was produced as a piggy-back in production for the XIS CCDs on Astro-E2 (see Foldout 4-B14).

Test Beds, Simulators, Flight Demonstrations of the Technology: Gen-1 EDCCDs provide a test bed for the "event drive" concept for CCD readouts. These tests will demonstrate EDCCD technology and functionality. MBE BI CCD test devices will be produced to verify charge collection performance for the flight devices.

Equipment and Facilities Required for the Technology Development Effort: Fabrication and packaging of the test lots of CCDs will be done at existing facilities (MIT/Lincoln Labs), while GSE, including electronics and calibration facilities, will be fabricated for EDCCD testing and calibration at MIT.

Plans for Production Facilities: Plans for producing the RFCs include use of both commercial and institutional facilities. EDCCDs can be produced, tested, and screened in commercial settings. Integration and testing of the RFC system can be done either by an industrial vendor or at an academic institution.

3.1.3.3 Key Risks and Mitigations

The key technical risks during the CCD technology development phase are shown in Table 3-2.

Low MBE CCD Yield (CCD-1): To mitigate the risk of a low BI-MBE CCD yield, other low-temperature backside preparation processes will be considered, as well as procurement of back-illuminated X-ray CCDs from alternate vendors (e.g., EEV).

EDCCD Circuitry Design (CCD-2): In the case that the event driven circuitry design is not demonstrated, the mitigation will be to not use the (optional) circuitry. The EDCCD then functions as a normal CCD.

3.1.4 X-ray Microcalorimeter Technology Readiness and Development Plans

3.1.4.1 Microcalorimeter Technology Readiness

Technology Description: The XMS is a high-quantum-efficiency, imaging spectrometer with 4-eV resolution near 6 keV, 2-eV resolution near 1 keV, and the ability to function at count rates up to 1000 counts/sec/pixel. In order to meet the design requirements of efficiency and spectral resolution, a low-temperature detector must be used. Within this class of instruments, only microcalorimeters with resistive temperature sensors are sufficiently developed for the Constellation-X technology roadmap. Superconducting transition-edge sensor (TES) microcalorimeters are in development for the XMS baseline, and semiconductor thermistor microcalorimeters (specifically, neutron transmutation doped [NTD] Ge) as an alternate implementation[38].

TRL Status: At the start of the technology development effort in 1998, TES and semiconductor microcalorimeters were at TRL 3, relative to the needs of Constellation-X. This is an important clarification, as both technologies at that time were ready for less demanding applications[39]. For Constellation-X, demonstrations of fewer-pixel, lower-resolution (6 eV), and/or slower (3 msec) microcalorimeter arrays (i.e., similar to those on Astro-E2), coupled with theoretical estimates of improved performance, constitute experimental and analytical proof-of-concept, hence, TRL 3. Many component technologies, such as schemes for close-packing the XMS pixels and integrating their X-ray absorbers, were at TRL 1 at the onset, and are now at TRL 3 or higher. TES technology is presently at TRL 4 because small TES arrays (5 x 5) with pixels of size, quantum efficiency, and fill factor suitable for XMS have been demonstrated. The readout scheme also has reached TRL 4 through a recent demonstration of 2 x 12 multiplexing of TES devices on 4 separate chips, including two 8 x 8 arrays.

3.1.4.2 Microcalorimeter Technology Development Plan

Strategy and Logic: The rapid progress in TES technology, the theoretical prediction of 2 eV resolution and the potential for large scale multiplexing with supeconducting read-out combined to recommend TES development for the XMS baseline. To mitigate risks associated with a relatively new technology, the more traditional semiconductor-based microcalorimeter technology at SAO is developed in parallel. Such NTD calorimeters have attained energy resolution of 4.8 eV at 6 keV[19].

Technology Development Plan: The microcalorimeter XMS technology roadmap is shown in Table 3-4. At the beginning of the development, a very high energy resolution was obtained (e.g., 2.0 eV at 1.5 keV[40], and 4.5 eV at 5.9 keV[41]), in large, isolated TES pixels using proximity-effect bilayers (Mo/Cu and Mo/Au) on much larger silicon nitride membranes which provided the necessary thermal isolation of the TES from the 50 mK heat sink. These early devices were individual 6-mm square chips with central active areas of 0.3 to 0.6 mm^2. To meet the XMS pixel size requirement the following enabling component technologies have been pursued. (1) Compact pixels consisting of a 0.15 x 0.15 mm TES surrounded by a ~10 μm wide silicon-nitride perimeter, as shown in Figure 3-2, have been developed. The thermal conductance of this thermal link is tuned through perforating the nitride and/or choice of the nitride thickness[42]. (2) Bi/Cu mushroom-shaped X-ray absorbers (0.24 x 0.24 mm) that contact the TES in the middle but are cantilevered over the nitride

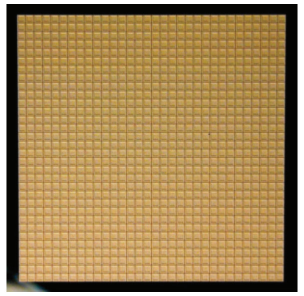
Table 3-4: Microcalorimeter Technology Roadmap

Element	Array TRL 4	Readout TRL 4	TRL 5	TRL 6	Flight Baseline
Array size	5 x 5	24 assorted pixels on 4 chips	8 x 8	32 x 32	32 x 32
Channels simultaneous readout	2	24	16	96	1024
MUX scale	None	2 x 12	2 x 8	3 x 32 goal	32 x 32 goal
Pixel size	0.25	0.4	0.25	0.25	0.25
Timescale	Q1 of FY03	Q1 of FY03	Q4 of FY04	Q4 of FY05	

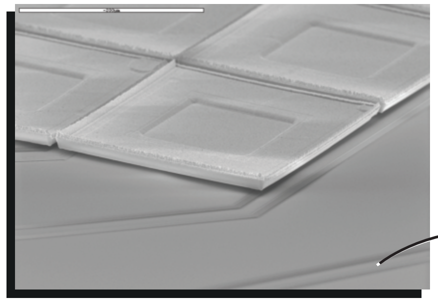
Constellation-X Focal Plane Module Instrument Technologies

A X-ray Microcalorimeter Spectrometer (XMS)

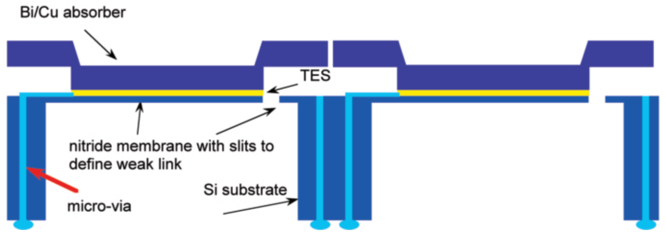
Microcalorimeter Array



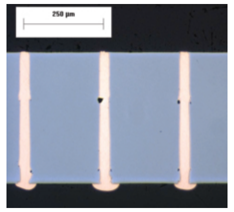
1) Top View of full 32 x 32 array of Bi/Cu X-ray absorbers.



2) SEM angled view showing 240 µm cantilevered absorbers on a fully-integrated array.

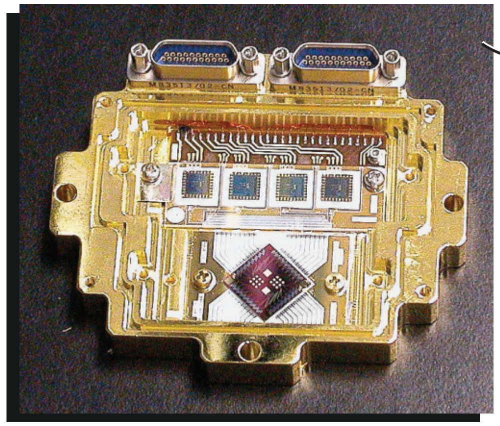


3) Concept for high-density array of X-ray microcalorimeters using overhanging absorbers and micro-via interconnects.

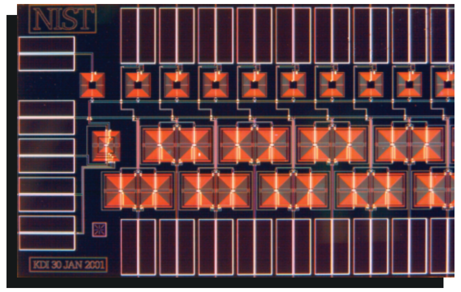


4) Cross-section of prototype Cu-in-Si micro-via interconnect prototype. The vias are 425 x 25 µm.

Superconducting Readout

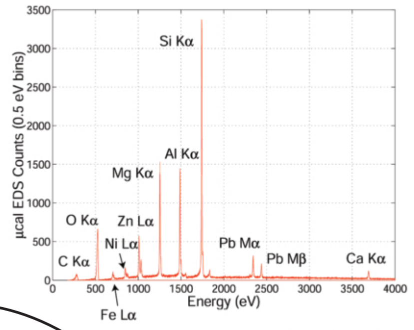


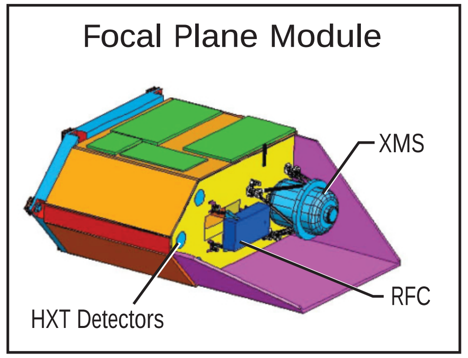
5) Four-channel test platform showing microcalorimeter arrays and first stage superconducting preamplifiers.

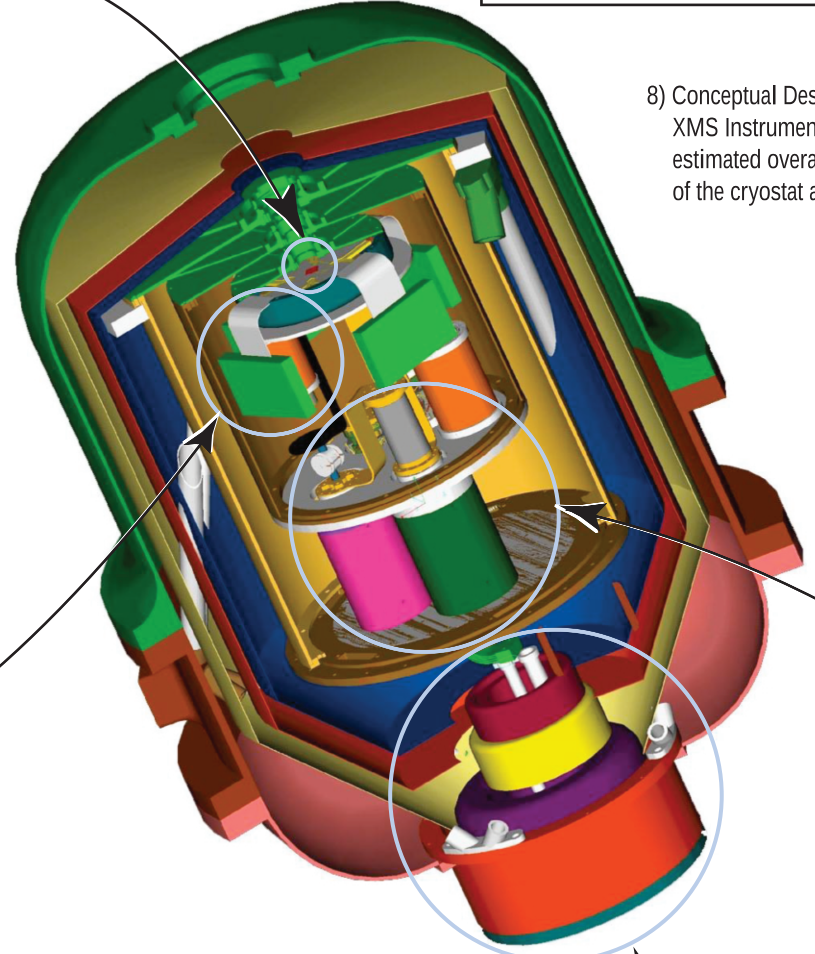


6) Portion of 32 channel superconducting multiplexer chip for low-power readout of microcalorimeter array.

7) High Resolution X-ray spectrum obtained with a superconducting microcalorimeter.

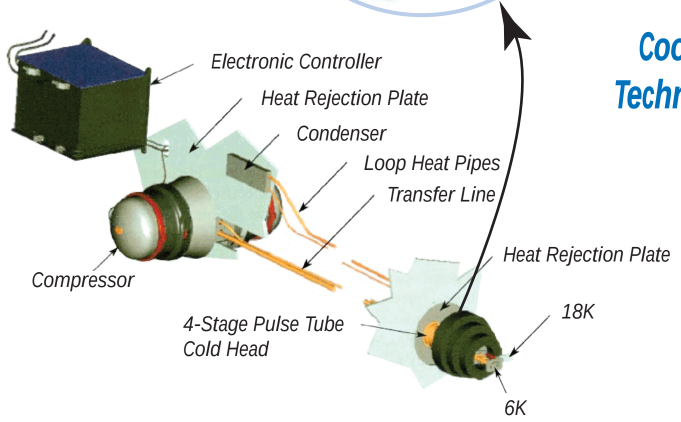






8) Conceptual Design of the XMS Instrument. The estimated overall dimensions of the cryostat are 50 x 75 cm.

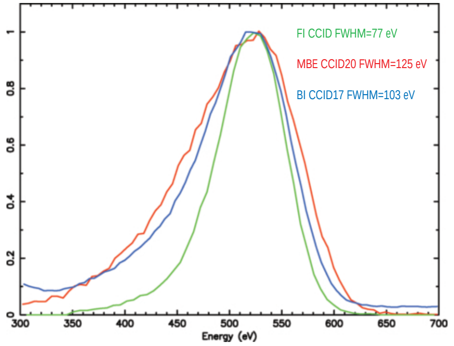
Cooling Technology



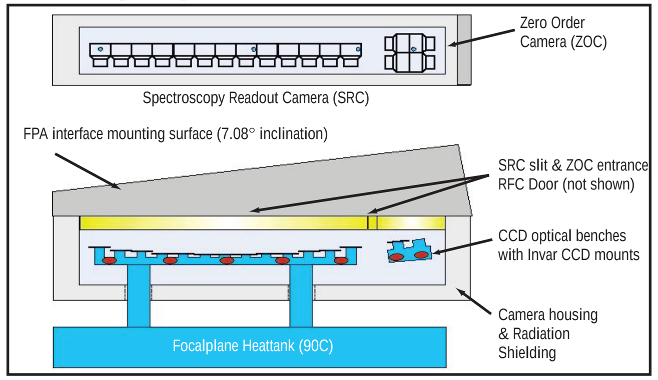
9) Lockheed Martin 6K cryocooler design from Advanced Cryocooler Technology Development Program (ACTDP).

10) Four-stage 50 mK continuous adiabatic demagnetization refrigerator (CADR) in test dewar.

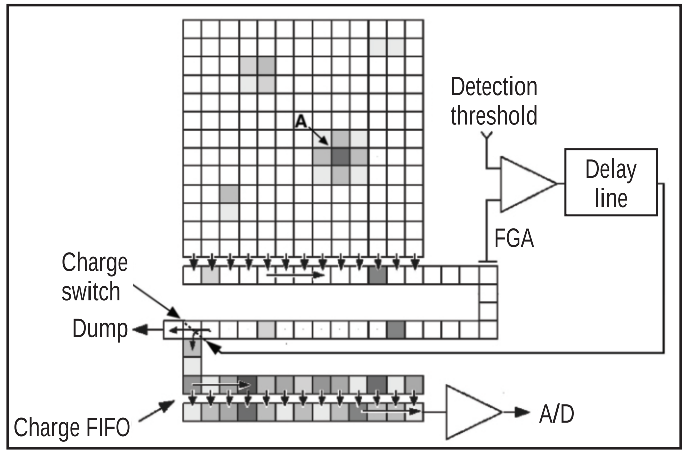
B Reflecting Grating Focal Plane Camera (RFC)



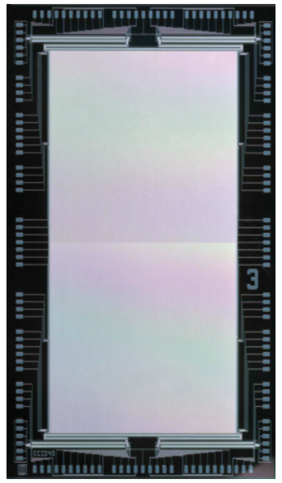
11) Energy Resolution of MBE is already comparable to best previous back-illuminated CCD.



12) Concept for RGS Focal Plane Camera (RFC).

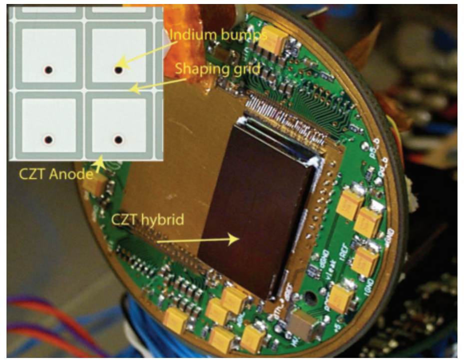


13) Event-driven CCD schematic.



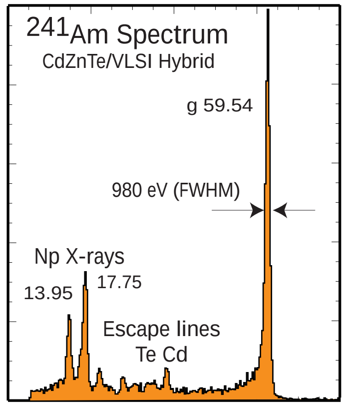
14) Generation 1 Event-Driven (frontside illuminated) CCD featuring EDCCD "event drive" electronics on each of four readout nodes (nondestructive charge sensor, analog delay line, charge dump, charge FIFO and ADC).

C Hard X-ray Telescope (HXT) Detector



15) Prototype hybrid CdZnTe detector mounted to the readout board. Two sensors placed side-by-side make up the 2.6 x 2.6 cm focal plane. (Inset): CdZnTe anode with shaping grid and indium interconnect bumps.

16) Spectrum of a ^{241}Am source fully illuminating a pixel of a HEFT detector operated at 18° C.



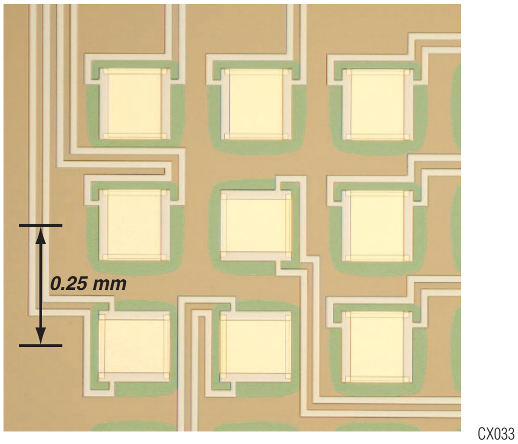


Figure 3-2: Portion of Mo/Au TES array. 0.25 mm spacing meets the XMS requirement.

border and wiring channel for maximal fill factor have been developed[43]. Both of these component technologies have been successfully demonstrated, and refinements are continuing. Spectral resolution of 2.5 eV at 1.5 keV has been demonstrated in a compact pixel without an absorber, and in the first array of compact pixels with integrated overhanging absorbers (Foldout 4-A3) 10 eV resolution has already been achieved. The performance of this device was limited mainly by parasitic resistances in the electrical contact traces. To extend these arraying concepts to 32 x 32, a further enabling component technology is needed: (3) high density array interconnects. Two approaches are being pursued to bring the electrical contacts to each pixel in a 1024-pixel array. In one, ultra-low-resistance micro-vias bring the signals out to the back of the array, where they can be bump-bonded to a fan-out board. This scheme, along with the Bi/Cu absorbers, is illustrated in Foldout 4-A3 and 4-A2. In the other, surface micromachining is used to fabricate calorimeter pixels that stand above a solid substrate, leaving the space under each pixel available for wiring tracks.

Another critical area of development has been in the superconducting read-out electronics. The resistance change in each TES is sensed by measuring the change in current in its bias circuit with a SQUID. To meet the bandwidth requirements, series-array SQUIDs must be used as one stage of the current amplification. Although a 32 x 32 TES microcalorimeter array can be read out using 1024 independent channels of electronics, reducing the number of channels through use of a SQUID multiplexer (MUX)[44] significantly reduces the heat load on the ADR, and the complexity of the front-end assembly. A time-division multiplexing scheme in which each 32-pixel column is read by one series-array SQUID is in development. Each TES pixel is sampled by its own input SQUID, which is switched on and off by the MUX controller. Figure 3-3 is a schematic of the MUX read-out. A successful demonstration of 2 x 12 multiplexed X-ray TES devices in a test at NIST has just been completed. Initial studies to quantify the performance have indicated no statistically significant degradation in resolution as the number of MUXed channels is increased.

Particle rejection for XMS is required to flag as background events those signal pulses that result from energy deposition by cosmic rays. The baseline scheme is based on detectors designed for detection of dark matter particles, and Stanford University will be funded to pursue this application of their Cryogenic Dark Matter Search (CDMS) technology. Such a detector would consist of a Ge crystal with TES sensors on its surface. The energy resolution requirement for the anti-coincidence detector is set by the required threshold energy. This will be determined after modeling the response to the expected cosmic ray environment at L2. Leveraging heavily off of the CDMS technology[17] makes the anti-coincidence detector a much more modest development effort than the spectroscopy array.

Test Beds and Simulators: These key component technologies will be integrated in separate TRL 5 and TRL 6 system demonstrations. For the TRL 5 demonstration, a 2 x 8 SQUID MUX system will be used to read out a portion of an 8 x 8 array. High density array interconnects will not be needed at this point. For the TRL 6 demonstration, a 3 x 32 SQUID MUX system will be used to read out a portion of a 32 x 32 array. The engineering model will be based on the TRL 6 demonstration unit, redesigned to meet the requirements on mass, thermal loads, and mechanical robustness. The power required per channel will be the same in the flight model as in the TRL 6 demo unit. Table 3-4 summarizes the technology roadmap.

Equipment and Facilities: Key facilities needed for the primary development effort already exist at the microfabrication laboratories at

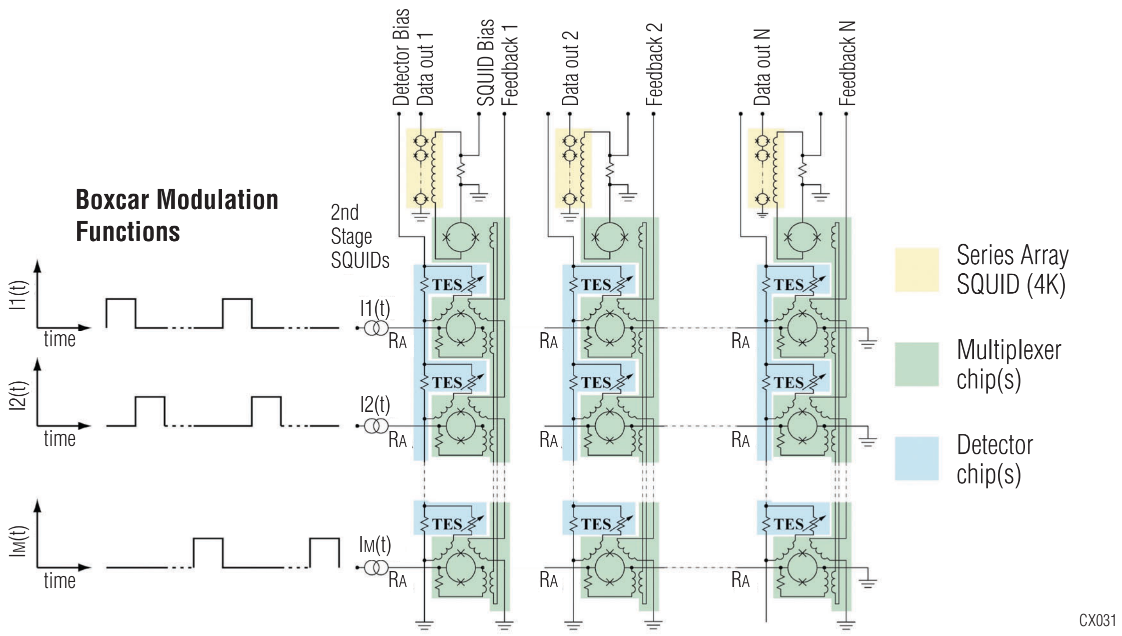


Figure 3-3: Schematic of SQUID MUX Readout

GSFC and NIST-Boulder. There are cryogenic test platforms at both institutions.

The GSFC Detector Development Lab (DDL) has sophisticated fabrication facilities including systems for photo-lithography and e-beam lithography, a 1 MeV ion implanter, several standard deep reactive ion etch (RIE) systems, and several sputtering and e-beam thin film deposition systems. A flip-chip bonder will be added in the next month. Process development and fabrication of TES arrays, high-density interconnects, and superconducting fan-outs will continue to be carried out in this facility. The NIST superconducting microfabrication facility is used for the fabrication of complex superconducting integrated circuits, including the Josephson voltage standard. Systems are available for photolithography, e-beam lithography, thin film deposition, and etching. Process development and fabrication of single SQUIDs, SQUID multiplexers, SQUID series arrays, and TES devices will continue to be carried out in this facility.

Both the NIST and GSFC calorimeter groups already have many cold test platforms for testing components and systems, including two dilution refrigerators and multiple adiabatic demagnetization refrigerators.

3.1.4.3 Key Risks and Mitigation

The key technical risks during the XMS technology development phase are shown in Table 3-2.

TES Detector Fabrication (XMS-1): The low-probability risk of not meeting the 4 eV resolution requirement during the technology development phase is mitigated in three ways: (1) developing the TES detector fabrication in two independent laboratories, (2) developing in parallel the NTD/Ge semiconductor detector, and (3) via ongoing development of TES technology by independent international groups who make their results available to the Constellation-X Program.

High Density Array Interconnects (XMS-2): The low-probability risk is mitigated by developing parallel approaches (micro-vias and surface micro machining) to development. A third alternative utilizing stacked insulated leads is also available if required. For the NTD case, the arrays are assembled from individual rows of devices with vertical fanout substrates[45]. This trades the complexity of the interconnects with the complexity of micro-assembly and is considered a low risk approach.

SQUID MUX Speed and Noise (XMS-3): The low-probability risk in developing a SQUID MUX system with adequate speed and noise performance is mitigated by trading the number of MUXed channels against heat load and design complexity. There exists a region of phase space in which the scale of the multiplexing can be traded against the thermal loads on the ADR without impacting instrument performance. Beyond that, the cost in performance results in increased dead time at a particular count rate, and not in degraded spectral resolution. Given current state-of-the-art, a MUX scale of 32 x 32 with detector fall times as fast as 0.5 ms should be achievable, with a realistic goal for 0.1 ms fall times.

3.1.5 ADR Technology Readiness and Development Plan

3.1.5.1 ADR Technology Readiness

Technology Description: The XMS detector assembly will be cooled to 50 mK using a "continuous" adiabatic demagnetization refrigerator (CADR; see Figure 3-4). This system is capable of meeting the detector cooling power requirement (6 microwatts at 50 mK) and of rejecting heat at controlled rates to a mechanical cryocooler (<20 mW at 6 K). It is based on conventional (i.e., single-shot) ADR technology but operated in a fundamentally different manner that dramatically increases its cooling power per unit mass and reduces its peak heat rejection rate.

Conventional ADRs use a discrete process in which the refrigerant is first magnetized (warming it up and allowing heat to be rejected to a heat sink), and then demagnetized to cool to low temperature. This simple single-shot technique is extremely robust and is easily implemented in space-flight instruments. The Astro-E/E2 missions use this approach.

Single-shot operation, however, is limited to heat rejection in short bursts at widely spaced intervals. An ADR sized to meet XMS cooling requirements needs to reject heat at rates far exceeding the capability of cryocoolers presently under development for the Advanced Cryocooler Technology Development Program (ACTDP). Also, because a single-shot ADR must store heat for extended periods of time, the relatively low entropy density of magnetic refrigerants translates to large system size and mass.

The CADR under development eliminates both of these problems. It uses multiple stages arranged sequentially (Figure 3-4), with each salt pill connected to the next stage (or to the heat sink) by a heat switch. The first stage acts as a heat capacity reservoir to regulate the temperature of the detectors, while the other stages cascade heat to the cryocooler. Four stages are required to produce continuous cooling at 50 mK using a 6 K heat sink. A fifth stage will be used to regulate the detector's second-stage SQUIDs at 1 K.

TRL Status: The CADR development began in 1999 with a TRL 3 demonstration of heat transfer between two stages at low temperature (50 mK). In the last two years, with funding from NASA's CETDP, the technology reached TRL 4 with the demonstration of a four-stage breadboard CADR (with nonmoving parts) operating continuously at 50 mK using a 4.2 K heat sink. Its cooling power (6 microwatts at 50 mK) and peak heat rejection rate (≤7.5 mW to 4.2 K) exceed the Constellation-X requirements. The present focus is on testing a new fourth stage that incorporates a gadolinium fluoride refrigerant that will increase its heat rejection capability into the 6K range, as required by the ACTDP coolers.

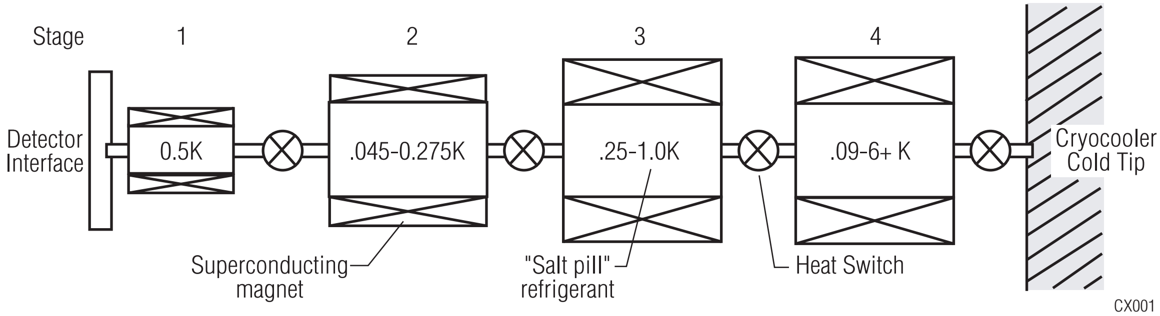


Figure 3-4: Block Diagram of 4-Stage CADR Demonstration Units

3.1.5.2 ADR Technology Development Plan

Strategy and Logic: The development strategy was to first demonstrate the components and heat transfer processes needed for continuous cooling at very low temperatures, then to develop the upper stages needed to reject heat at high temperatures. The initial focus was therefore to develop low temperature heat switches and salt pills, and to build a 2-stage demonstration unit. This was a critical step since the system's thermodynamic efficiency and heat transfer rates established the performance requirements for the upper stages. As these were produced, the 2-stage assembly was expanded to three and then to four stages, which at present has a heat rejection capability of 4.2 K. Through this process, all of the heat switches, salt pills, and control software, and some suspension components, have now been fully demonstrated, and the breadboard CADR is close to fully optimized.

Technology Development Plan: The plan for taking this technology to TRL 6 involves three main thrusts.

- Continue development of the fourth and fifth stages. This includes continued engineering of refrigerant materials with better entropy density and lower magnetic field requirements to meet the 6 K heat rejection requirement, and the fabrication of a stage to demonstrate continuous cooling at 1 K.
- Development of high-temperature magnets. The CADR's magnets (in stages 2-5) will be cooled to 6K by the cryocooler. This temperature is just beyond the practical limit for using NbTi technology. Although higher temperature superconductors like Nb3Sn will work at temperatures up to 12K, wire manufacturers do not produce the small gauge wire needed for high field, low current magnets. The plan is to begin funding industry partners that have expertise in this area. In particular, a new technique being pioneered by Superconducting Systems, Inc., for producing very fine Nb3Sn wire that can be reacted before being wound into magnets looks very promising.
- Assemble and flight-qualify a 5-stage engineering unit CADR that meets the XMS's cooling requirements. The emphasis will be on developing suspension systems that provide structural support to the low temperature components, while not degrading the CADR's thermal performance.

The development schedule aims to have this system ready for full functional testing with the prototype ACTDP cryocooler in FY06.

Test beds and Simulators: The Cryogenics and Fluids Group has a long history of developing flight ADRs, and has extensive facilities for testing ADR components and assemblies. These include several helium dewars and one cooled by a commercial pulse-tube cryocooler. These are modular and adaptable systems that will accommodate virtually any final CADR configuration. The latter will be particularly valuable as a high-fidelity simulator for the Constellation-X cryocooler's interface. Existing vibratable dewars are available for cold vibration of components and assemblies.

As part of the on-going CADR development effort, the GSFC Cryogenics Group has developed high-fidelity ADR simulators to model the performance of multi-stage systems. The simulators show excellent agreement with as-built components, and will be used to optimize the design of the 5-stage engineering unit CADR prior to beginning fabrication.

Equipment and Facilities: The Cryogenics Group has many unique facilities for producing and testing flight ADR systems, including a state-of-the-art wire electric discharge machine (EDM), equipment for growing hydrated salts, a coil winder for superconducting magnets, and an apparatus for characterizing the entropy of magnetic refrigerants. These facilities have been critical for prototyping of components for the CADR development, and will be available for production of the flight instruments.

3.1.5.3 Key Risks and Mitigation

The key technical risks being addressed during the XMS ADR technology development phase are shown in Table 3-2.

CADR Thermal Interface Requirements [XMS-4]: The ACTDP cryocoolers are required to provide a base temperature of 6K or below, with a cooling power of 20 mW or higher. The CADR already meets the cooling power requirement, but has not yet demonstrated magnet operation at 6K. In the event that higher temperature magnet technology does not mature in time for Constellation-X, it will be necessary to reduce the operating temperature of the cooler. Partially for this reason, the solicitation for

ACTDP cryocoolers specified a goal of 4 K operation. The trade off may be a reduction in cooling power, but likely not to a degree that would impact the operation of the CADR. However, if it were necessary, the CADR could be reconfigured to significantly reduce its cooling power requirements.

SQUID Magnetic Field Noise [XMS-5]: There is a potential for fringing magnetic fields to interfere with the XMS detectors and SQUID amplifiers. Two strategies are used to minimize magnetic interactions between the CADR and the XMS: (1) ferromagnetic shielding around each of the CADR's magnets provides a high degree of attenuation of fringing fields. (2) the detector assembly is physically located as far as possible from the largest magnets. It has already been verified that fields in the vicinity of the detectors will be less than 1 mT. This is well below the levels of concern, and can be totally eliminated by passive and/or superconducting shielding around the detector assembly.

3.1.6 Cryocooler Technology Readiness and Development Plans

3.1.6.1 Cryocooler Technology Readiness

Technology Description: A key component of the XMS is a mechanical cryocooler that provides several stages of active cooling inside the instrument cryostat. Its primary purpose is to provide a 6 K heat-sink stage for the ADR described in Section 3.1.5. A secondary purpose is to actively cool a stage at the 90-100 K "warm" end of high temperature superconducting ADR power leads. A tertiary requirement is for heat-sink stages intermediate to those just mentioned. All stages include actively cooled radiation shields, several of which also connect to infrared blocking filters in the optical path.

TRL Status: The space cryogenics community is transitioning from stored cryogen systems to ones incorporating mechanical cryocoolers. Several cryocooler systems employing different technologies and capable of reaching 50 K are currently at TRL 9. Cryocoolers reaching as low as 15 K exist at the TRL 5 level. Cooling to around 6 K has been achieved in the laboratory, qualifying that technology for the TRL 4 category.

3.1.6.2 Cryocooler Technology Development Plan

Strategy and Logic: Development of a cryocooler to meet the needs of Constellation-X is part of a cooperative effort within NASA's OSS. Through the JPL-managed Navigator Program and the Terrestrial Planet Finder project (TPF), OSS is funding the ACTDP. The primary users of ACTDP technologies will be NASA's Constellation-X, JWST, and TPF missions. The goal is to develop several technologies that can yield a demonstrable cryocooler design capable of realistically completing flight unit delivery in the 2007 time frame.

Members of the Constellation-X team are actively participating in the ACTDP as members of the Technical Peer Review Panel and the Programmatic Review Panel. Project involvement will increase as one of the ACTDP coolers is driven to become the TRL 6 engineering model cryocooler for Constellation-X.

Technology Development Plan: The ACTDP is divided into a Study Phase and a Demonstration Phase. The Study Phase of the program is complete and contract negotiations with three contractors for the Demonstration Phase are in progress. During the first year of that phase, each contractor will have individualized development tasks designed to retire specific technological risks identified by the ACTDP Technical Peer Review Panel. Successful completion of those tasks will lead to contract options for construction and testing of TRL 5 cryocoolers. It is expected that the transition of the cryocooler from TRL 5 to TRL 6 will be managed by the XMS IPT lead.

Test Beds and Simulators: All test beds required for the development of the TRL 5 cooler are budgeted for under the ACTDP. It is expected that these will be available for TRL 6 qualifications under Constellation-X funding. A mass model of the final cryocooler coldhead design will be required for inclusion in cryostat integration and vibration testing.

Equipment and Facilities: The contractors selected under the ACTDP have in-house facilities and equipment adequate to develop the cryocoolers through TRL 5. No additional specialized facilities nor equipment are required to transition from TRL 5 to 6.

3.1.6.3 Key Risks and Mitigation

The key technical risk during the development phase is shown in Table 3-2.

Achieving Required Cryocooler Cooling Efficiency [XMS-6]: Although the proposed ACTDP cryocoolers were primarily designed with existing technologies, there remain risks associated with the cryocooler as a system. The ACTDP technical panel identified risk items for each cryocooler in the areas of technology development, manufacturing and overall cooling efficiency. The first stage of risk mitigation is within the ACTDP itself. The approach is to contract with the three remaining vendors for one year of development directed individually toward retirement of identified risks. Contract options will then be exercised for vendors succeeding during that period.

Constellation-X is base-lining the pulse tube cooler being designed by Lockheed-Martin (LM) under the ACTDP for its applicability to the XMS system. Should LM have difficulties in retiring its risks over the next year, the project would initiate a second-stage of risk mitigation with one or both of the other ACTDP contractors, and fund an accommodation study of another ACTDP technology would be required. A third stage of risk mitigation could be considered a case where Constellation-X required the hardware of an ACTDP vendor other than LM.

The fourth mitigation stage would be the use of a hybrid cryocooler/stored-cryogen system with an inner radiation shield of the cryostat cooled by an existing 35 K cryocooler. Such TRL 6-7 cryocoolers have the heritage of the 50 K flight coolers being used on Atmospheric Infrared Sounder (AIRS) and Tropospheric Emission Spectrometer (TES). Achieving the mission science requirements with this approach will incur a mass penalty, as well as possible cost and schedule penalties.

3.1.7 Hard X-ray Telescope Mirror Technology Readiness and Development Plans

3.1.7.1 HXT Mirror Technology Readiness

The HXT mirror requirements are described in Section 1.3.1.4. An individual HXT mirror module must have an angular resolution <1 arcmin HPD, an effective area of >1500 cm^2 from 6-40 keV, and an 8 arcmin FOV across this energy band. Each satellite carries three co-aligned HXT telescope modules each with 10 m focal length, whose mass must not exceed 150 kg.

Technology Description: The HXT technical approach is based on depth-graded multilayer-coated conical approximation or Wolter-I optics. The optics are high-throughput, low mass, and highly nested, smooth (RMS <0.4 nm), and have a thin film of alternating high and low index of refraction materials (multilayer) applied. The multilayer films typically have 100-300 layer pairs of Tungsten and Silicon, with bilayer thicknesses ranging from 20- 200 Å.

Two optics approaches are being considered: nickel and glass (see Table 3-5). In the former, each shell is an integral unit, while in the latter, each shell is assembled from a number of segments. The integral nature of the Ni shells gives them the advantage of mechanical integrity, with fewer pieces requiring precision alignment. The primary disadvantage of integral shells is that the multilayer coatings are more difficult to apply, and the estimated mass will be 30% larger. For integral shells, the multilayers must either be applied to the interior surfaces or must be replicated from the same mandrel as the shell. The former is not easily done with standard magnetron sputtering systems (the technique of choice for growing large-areas of smooth, thin films), and the latter requires development in more complex steps in the replication process, including appropriate release layers. In contrast, application of high-quality multilayers of design applicable to the HXT has already been demonstrated for segmented shells.

TRL Status: The general approach of segmented conical optics has been demonstrated in flight on BBXRT, ASCA, and Astro-E and InFOCμS balloon payloads. The thermally

Table 3-5: Nickel vs. Glass Mirror Dimensions

	Segmented	Integral
Substrate	Thermally formed Glass	Electroformed Nickel
Thickness	0.2 – 0.3 mm	0.1 – 0.15 mm
Shells/module	150	82
Inner radius	4 cm	6 cm
Outer radius	20 cm	20 cm
Mass target/ satellite	95 kg	150 kg

formed glass development draws largely from the HEFT balloon experiment, which has developed substrates, multilayer coatings, and substrate mounting technique, all of which have now demonstrated the HXT performance requirements, except on the smallest radius shells. Glass optics fabricated for HEFT achieve 45 arcsec HPD resolution for shell radii greater than 10 cm (see Foldout 3-C14). Epoxy replication of the substrates (as described in Section 1.3.1.4) is being pursued to improve the figure on small radius shells. Glass substrate production benefits from the SXT mirror technology development, as SXT reflectors exceed the HXT figure requirement, overlap between the HXT and SXT fabrication approaches offers potential economies during implementation. Depth graded multilayers of the HXT design have been applied to formed substrates, and the required reflectance has been demonstrated (see Foldout 3-C13). Multilayers replicated onto glass substrates show comparable X-ray efficiencies.

Nickel replica mirrors with the requisite resolution and similar dimensions to the HXT were demonstrated in flight on XMM-Newton. Substrates of requisite thickness have been produced and tested as part of the HERO balloon experiment. Depth-graded multilayers with the required reflectance have been fabricated, but the application to nickel shells either through deposition onto a mandrel and subsequent replication onto the mirror, or through direct application using a specialized coating system needs to be demonstrated.

Based on the above discussion, the glass mirrors are at TRL 4-5, while the component technologies are at TRL 5-6. The nickel optics are at TRL 3, with the component technologies at TRL 4 (multilayers) and TRL 6 (Ni shells).

3.1.7.2 HXT Mirror Technology Development Plan

Strategy and Logic: Both HXT mirror approaches have already demonstrated technologies at the component level. A parallel development track is followed as late as possible into the program. Small prototypes of Ni and glass mirrors are being constructed for performance evaluations. One technology will then be selected in FY03 to proceed to a full prototype for both performance and environmental testing. Technology selection includes consideration of the production processes capable of meeting the required volume of reflectors.

Technology Development Plan: The HXT mirror technology development steps are outlined below:

1. Fabricate nickel and glass prototypes for demonstration/performance comparison.
2. Test prototypes at MSFC for X-ray reflectance, and angular resolution. (TRL 4)
3. Fabricate prototype with full range of mirror shell dimensions and flight-design multilayers. (TRL 5)
4. Evaluate X-ray reflectance, throughput, and angular resolution.
5. Test full prototype for vibration tolerance and thermal tolerance. (TRL 6)

Technology Investments to Date: Most of the HXT mirror technology is leveraged from NASA SR&T programs. For the HXT program, this has supported the development of glass mounting schemes, glass shell production, and prototypes at Columbia University, completion of a multilayer deposition facility for shell mirrors at SAO, comparative studies of candidate multilayers by SAO, and development of mandrels for prototype shells and segment product, by MSFC and GSFC, respectively.

Test Beds and Simulators: The small prototypes under development serve as test beds for the two approaches to the optics technologies. The facilities listed below serve as a test beds for mirror fabrication, coatings, and alignment.

Equipment and Facilities for Technology Development: The HXT mirror program takes advantage of facilities developed for other programs. The glass mirrors utilize facilities developed for HEFT, including metrology stations developed at Columbia, mounting and alignment fixtures developed at Colorado Precision Products, Inc., a multilayer deposition chamber at the Danish Space Research Institute (Foldout 3-C12). Also utilized, are the glass forming and replication facilities at GSFC developed for the SXT mirror. The Ni mirrors utilize the mandrel machining facilities at OAB, Ni electroforming facilities at MSFC, and a multilayer deposition chamber at SAO. The later two facilities were developed in part with Constellation-X funding. Both mirror approaches will use the MSFC X-ray calibration facilities.

Plans for Production Facility: As for the SXT, the HXT mirror production facilities can be modeled after existing and previous production efforts. The glass mirror production and coatings can be based on the GSFC facility that produced the InFOCμs mirror, along with the Astro-E/E2 mirrors. A Ni mirror facility can be modeled after the Media-Lario facility used for XM, or the MSFC facility used for HERO. A reasonable option for the glass mirror option is to set up the HXT production as a parallel line in the SXT production facility to accommodate the glass forming; multilayer deposition would require a separate facility.

3.1.8 HXT Detector Technology Readiness and Development Plans

3.1.8.1 HXT Detector Technology Readiness

The HXT focal plane performance requirements and physical detector requirements are described in Section 1.3.1.4. The detector must operate over the 6-40 keV band with better than 90% quantum efficiency, with a threshold at 6 keV, and with a resolving power of 5 (DE/E = 20%). In addition, the background must be low enough to guarantee that signal dominates noise for a 10^5 s observation. Each satellite carries three co-aligned telescopes with independent focal planes consisting of a solid state pixel sensor surrounded by an active shield.

Technology Description: The baseline option for the Constellation-X HXT focal plane detectors is a large bandgap semiconductor pixel detector. Sensor materials are CdTe or CdZnTe. These provide low-leakage current (and therefore low noise), are mechanically robust, and the high atomic number provides quantum efficiency near unity over the HXT bandpass.

The requirements of low threshold (to allow sufficient overlap with the SXT for cross calibration) and good spatial resolution dictate a pixel geometry with the sensor bump bonded to a low-noise custom ASIC readout. In this architecture, each pixel is connected to a separate readout channel on the ASIC chip by a small (25-micron) indium bump. The readout chip has identical dimensions as the sensor, with one channel occupying an area equivalent to the pixel size. The shield will consist of an inorganic scintillator (CsI or BGO) in a well configuration, read out by a photomultiplier tube operated in anticoincidence with the CdZnTe detector.

TRL Status: The development of the Constellation-X pixel sensors is largely supported by SR&T under the HEFT balloon program. The HEFT program has invested seven years in developing a high-performance, custom low-noise ASIC and in CdZnTe pixel sensors with geometry essentially identical to that required for the HXT. Flight detectors have been fabricated and tested and will be deployed in Fall 2003. A large CdZnTe array will soon fly on the Swift mission. Although the detectors are of different architecture than planned for Constellation-X, the sensor material was flown on InFOCμS and EXITE and has been extensively tested for radiation tolerance (for monolithic rather than pixel sensors) and background properties.

The design of the low-noise custom ASICs is derived from the ACE CRIS/SIS instruments, and the logic and support processing system will fly on STEREO. Active scintillator shields have flown on numerous missions over the last 20 years, including GRO/OSSE, HEAO A-4, and Integral.

Based on the above discussion, the CdZnTe sensor material is at TRL 5, the pixel hybrid detector at TRL 4-5, and the shielding and other required systems at TRL 6.

3.1.8.2 HXT Detector Technology Development Plan

Strategy and Logic: Several areas require targeted development for HXT. The readout developed for HEFT has demonstrated that the low-noise required to achieve 1 keV spectral resolution at 6 keV is possible, the threshold on the current electronics is limited to ~10 keV by systematic noise. To operate as an imaging detector at 6 keV, individual pixel thresholds must be below 3 keV so that events with charge split between pixels can be reconstructed. Given the complexity of the readout architecture, this will take some iteration on the current design.

A second important area of development is in the sensor and contact fabrication. Large uniform CdZnTe crystals are difficult to obtain, and surface and bulk leakage currents vary by almost an order of magnitude sensor to sensor. Some of these problems may be solved with continued development of new growth techniques, new contacts, and new materials. It is therefore important to continue to evaluate new materials and contacts, such as CdTe with blocking contacts, and CdZnTe grown by high-pressure Bridgeman (HPB) techniques. This latter process produces very uniform material, albeit with high leakage current. The development of blocking contacts may allow both CdTe and HPB to be used for the HXT sensors.

Further work is required to evaluate the performance of both CdZnTe and CdTe in a radiation environment and to develop space-qualified packaging techniques. In particular, activation as well as changes in electrical properties resulting from increased charge trapping could be problematic. Mitigation may require incorporating a heating system to anneal the sensors periodically.

Development Plan: The planned technology development steps are outlined below:

- **Detector Threshold–**Evaluate limits on current readout threshold; modify design and fabricate small prototype ASIC chip; fabricate full-sized chip.
- **Sensor Material–**Evaluate leakage currents and sensor performance for combinations of contacts and materials; evaluate charge trapping resulting from radiation exposure for different sensor/contact combinations.
- **System–**Fabricate flight-sized prototype; evaluate performance; test response to radiation environment, vibration tolerance, thermal response.

Technology Investments to Date: Essentially the entire HXT detector technology development program has been funded through SR&T. This includes the development of a custom, low-noise readout, interconnect technologies, and CdZnTe sensor development, and evaluation of prototype detectors.

Test Beds and Simulators: A prototype will be developed to serve as a test bed for the detector technologies. The fabrication steps will be carried out in facilities appropriate for flight production.

Equipment and Facilities for Technology Development: The HXT detector program utilizes existing facilities at Caltech and GSFC. Caltech has developed an ASIC design and test facility, and laboratories for sensor packaging and hybridization. GSFC has an extensive facility for CdZnTe sensor material processing, contacting, and evaluation.

Plans for Production Facility: No additional production facilities are required beyond those already in place for the technology development effort.

3.1.8.3 Key Risks and Mitigations

The key technical risks during the HXT development phase are shown in Table 3-2.

Low-energy threshold [HXT-1] systematic noise currently limits threshold to ~10 keV. Mitigation is to redesign the electronics architecture (see Section 3.1.812).

3.2 Other Program Formulation Activities

The Constellation-X Project will successfully complete the formulation phase of the mission life cycle while complying with the NASA Procedure and Guideline (NPG) 7120.5B, NASA Program and Project Management Processes and Requirements, and the Goddard Directives for project management. The purpose of the formulation subprocess is to refine the preliminary mission concepts into an affordable program and plan that meet mission objectives and technology goals that are consistent with the NASA and Enterprise Strategic Plans. The Formulation Authorization Document (FAD), authorized by the Enterprise Associate Administrator, is the formal initiation of formulation.

The Constellation-X Project will perform the specific set of formulation activities in an iterative manner until mature products are delivered, appropriate information is baselined, and all requirements are met to successfully pass the established control gates, i.e., reviews. These major reviews serve as natural milestones for go/no-go decisions for proceeding onto the next step. As each step through formulation is completed, this process ultimately leads to the successful transfer into implementation.

Table 3-6 shows the list of Constellation-X formation products mapped to the major elements of the mission. The strategy for completing formulation is discussed in Section 4.1.1.6.

Table 3-7 lists the documentation to be prepared by the Project with references to the applicable reviews and governing management directives. Appendix B, page B-7 lists the major reviews that are held during formulation to assess levels of planning and readiness in order to proceed to the next formulation activity. A brief description of the major activities during formulation are described next. Project planning defines detailed program requirements and establishes program controls to manage the formulation subprocess. Systems analyses and life-cycle costing are conducted

Table 3-6: Constellation-X Formulation Products

<table>
<tr><th colspan="2">Management Concept</th></tr>
<tr><td>• Responsibilities
• LOA (as required)
• International Management Agreement (as required)
• NASA/Partner/MOU (as required)
• Technology Investments
• Integrated Schedules
• Updated Staffing Plan
• Draft Science Management Plan
• Acquisition Strategy including make/buy of significant acquisitions</td><td>• Developmental Strategy
• Flight Assurance/Safety Approach
• Integrated Financial Management
• Configuration Control Approach
• Reserves Management Approach
• Independent External Reviews
• Outreach Strategy
• Updated Budgets including Life Cycle Cost
• Project Plan Outline</td></tr>
<tr><th colspan="2">Constellation-X Requirements</th></tr>
<tr><td>• Level 2 Requirements Draft
• Mission Success Criteria
• Minimal Mission
• Flight Segment Preliminary Performance Reqs</td><td>• Ground Segment Preliminary Performance Reqs
• Launch Segment Preliminary Performance Reqs
• Facility Requirements
• Verification Concept
• Calibration Plan</td></tr>
<tr><th colspan="2">Advanced Technology</th></tr>
<tr><td>• Technology Readiness Assessment</td><td>• Required Performance for each Advanced Technology</td></tr>
<tr><th colspan="2">System Engineering Management Concepts</th></tr>
<tr><td>• Software Development Strategy
• Draft Spacecraft Concept
• Draft Payload Concept
• Launch Vehicle Options
• Integrated Modeling
• Draft Verification Matrix</td><td>• Resource Allocation Process
• Draft Resource Allocations to Demonstrate Feasibility
• Interface Descriptions/ICD Outlines
• Technical Documentation Approach
• Draft Documentation Tree
• IV&V of Flight Software
• Traceability Methodology</td></tr>
<tr><th colspan="2">Mission Design and Operations Concept</th></tr>
<tr><td>• Data Reduction Plan
• Organizational Approach of Ground Segment
• Communications Strategy
• Orbital Parameters</td><td>• Data Collection Strategy
• Ground System Sizing
• Data Policy</td></tr>
</table>

on concepts and options to meet program objectives. Technology assessment reviews the program concepts and technology requirements for feasibility, availability, security, technology readiness, opportunities for leveraging research and new technologies. Technology and commercialization planning identify technology, partnering, and commercialization options that satisfy the identified needs of the candidate concepts. Business partnership opportunities are identified in the development and operations elements of the program to satisfy program requirements. An assessment of the infrastructure, and a plan for upgrades/development are made to minimize program life cycle cost (LCC) by utilizing existing or modified infrastructure of NASA, other national and international agencies, industry, and academia where possible. Finally, the Project will perform knowledge capture which collects and evaluates process performance and also identifies process lessons learned.

Table 3-7: Formulation Documentation

Document Title	Description	Referenced By	Due By	Update
Risk Management Plan	Provides a description of how risks will be identified, assessed, tracked, mitigated, and documented.	NPG 7120.5B	SRR	PDR/NAR
Software Management Plan	Describes the work to be performed and the resources needed to accomplish the goals and objectives established in the customer agreement. The Software Management Plan includes the design planning information and the process management information.	Flt Proj PM H/B dated 8/94, page A-2; NPD 2820.1, NASA Software Policies; GPG-8700.5, In-house Development and Maintenance of Software Products (pending release)	MDR	PDR
Configuration Management Procedure	Defines how Configuration identification Control Status Accounting and Auditing will be performed for a program or project.	NPG 7120.5B (paragraph 3.1.1.j)	SRR	PDR/NAR
Environmental Assessment	Document that ensures that environmental impacts have been considered in project planning and decision-making.	NASA Systems Engineering Handbook dated 6/1995, pp. 112-114; NASA Regulations (14 CFR Part 1216 Subpart 1216.3); NPG 8580.1, Implementing The National Environmental Policy Act and Executive Order 12114	NAR	N/A
Mission Assurance Requirements	Present the safety and mission assurance (SMA) requirements that may be necessary for project.	300-PG-7120.2.2A	PDR	CDR
Orbital Debris	Debris assessment addresses orbital debris generation that result from normal operations, malfunction conditions, and on-orbit collisions. Addresses provisions for post mission disposal.	NPD 8710.3, NASA Policy For Limiting Orbital Debris Generation; NSS 1740.14, Guidelines and Assessment Procedures for Limiting Orbital Debris	PDR	CDR
Program Commitment Agreement	Agreement between the Administrator and Enterprise Associate Administrator that documents the Agency's commitment to execute the program requirements within established constraints.	NPG 7120.5B, 2.1.1.2	NAR	Annually validate
Program Plan	Approach and plans for formulating, approving, implementing, and evaluating the project.	NPG 7120.5B, 2.1.1.2	PDR/ NAR	---
Project Plan	Product of Project Formulation; describes implementation of a project.	NPD 7120.4B (para 1.e.1) NPG 7120.5B	NAR	---
Safety Data Packages	Safety Data Packages are developed to demonstrate a payload's compliance with launch range requirements. For GSFC projects, Code 302, the Systems Safety and Reliability Office will either prepare or review the SDP's.	302-PG-7120.2.1A, Systems Safety Support to GSFC Missions and Other Organizations	Mission Definition Review (MDRs)	CDR
Software Requirements Document	This document forms the basis for software design.	Flt Proj PM H/B dated 8/94, page A-2	PDR	Contract Award and PDR
Software Test Plan	This document lists the procedures used to test and validate software.	Flt Proj PM H/B dated 8/94, page A-3	PDR	CDR
System Engineering Management Plan	This document contains trade studies, technology studies, system verification and test plans, and interface requirements.	SEU Program Office Requirement	PDR	CDR
Technology and Commercialization Plan	This plan describes the establishment of partnerships to transfer technologies, discoveries, and processes with potential for commercialization.	NPG 7120.5B (para 2.1.4)	PDR/ NAR	NA

4.0 MANAGEMENT, SCHEDULE, AND BUDGET

4.1 Management

The key features of the Constellation-X Project are clear interfaces and a direct, proven management structure. The management approach was designed to provide clear and uncomplicated lines of authority with one Project Manager (PM) in charge, while utilizing the strengths of the SAO/GSFC collaboration and honoring NASA HQ direction for GSFC to perform the management of Constellation-X as a facility-class mission. Constellation-X will build on the experience gained from the successful Chandra model, where SAO teamed with MSFC in a fashion similar to that proposed for Constellation-X. Both GSFC and SAO have extensive flight experience and have worked together on several previous missions (e.g., SWAS, SOHO, Spartan, U.S. ROSAT Data Center). They have successfully collaborated on Constellation-X for the past 6 years.

The management approach for Constellation-X has been successfully used at GSFC for many years. Throughout its history, GSFC has launched more than 250 space missions and has a proven track record of utilizing its resources, from engineering support to upper management, to ensure mission success. The interfaces and relationships among GSFC, SAO, and the other organizations, both in the technology development and in the implementation, are very clean and well understood, as described in the following paragraphs.

The SAO contribution to the Project makes maximum use of its experience with Chandra, both in telescope and instrument development, and in operations. Much of Chandra's design and analysis experience will be used for Constellation-X, and SAO's management experience will be invaluable in supporting the overall management of the Project. In many cases, Constellation-X key individuals will be those who worked on Chandra.

4.1.1 Mission Formulation

In 1996, following selection of their independent proposals in response to NASA's solicitation for new concepts, GSFC (Dr. Nicholas White) and SAO (Dr. Harvey Tananbaum) combined similar ideas into a collaborative program. They requested and received approval from NASA HQ to form the FST for this joint endeavor, and that group continues to provide scientific guidance. Given the anticipated performance improvement compared with previous missions, the technology needed to be extended and proven. Hence, the Project was started as a technology development effort. Since then, several organizations have been developing the technologies to TRL 6, according to the technology development schedules in Foldouts 8 and 9. In addition, the other formulation activities needed to develop a mission concept were initiated and are proceeding. All technology and formulation work is geared toward meeting the mission requirements.

4.1.1.1 Organization

The Constellation-X formulation organization (Figure 4-1) shows the integrated nature of the Project, while retaining clear lines of authority. The Project Management is seated in the NMP/SEU Program within the FPPD at GSFC. The NMP/SEU theme, led by an experienced Program Manager, Dr. Bryant Cramer, provides program-level support and guidance. The Project presents a status monthly to the Director of FPPD and the GSFC Executive Council, which is headed by the Deputy Center Director and includes the heads of each Directorate. The guidance and support from these two groups is of great value in obtaining Center resources and in getting the high-level attention needed to resolve Project issues. Quality Assurance and System Safety support is supplied using the resources of the long-established Quality organization at GSFC. The OSSMA Directorate personnel work on the Project, but retain an independent reporting path to the Center Director. The Project must respond to issues raised through the OSSMA. As an example of added value, the materials group at GSFC has been actively engaged in selection of a workable epoxy for the SXT reflector development. Both GSFC and SAO provide additional scientific leadership and support drawing from more than 35 years of experience in X-ray astronomy. Other directorates at GSFC supply matrixed support, including discipline engineering, systems engineering (including the lead Mission Systems Engineer [MSE]), Instrument Managers, business and procurement management, and ground system and operations support. SAO supplies system engineering, operations and ground system design support, and engineering support.

In the science area, GSFC supplies the Project Scientist, Deputy Project Scientist, and one of the

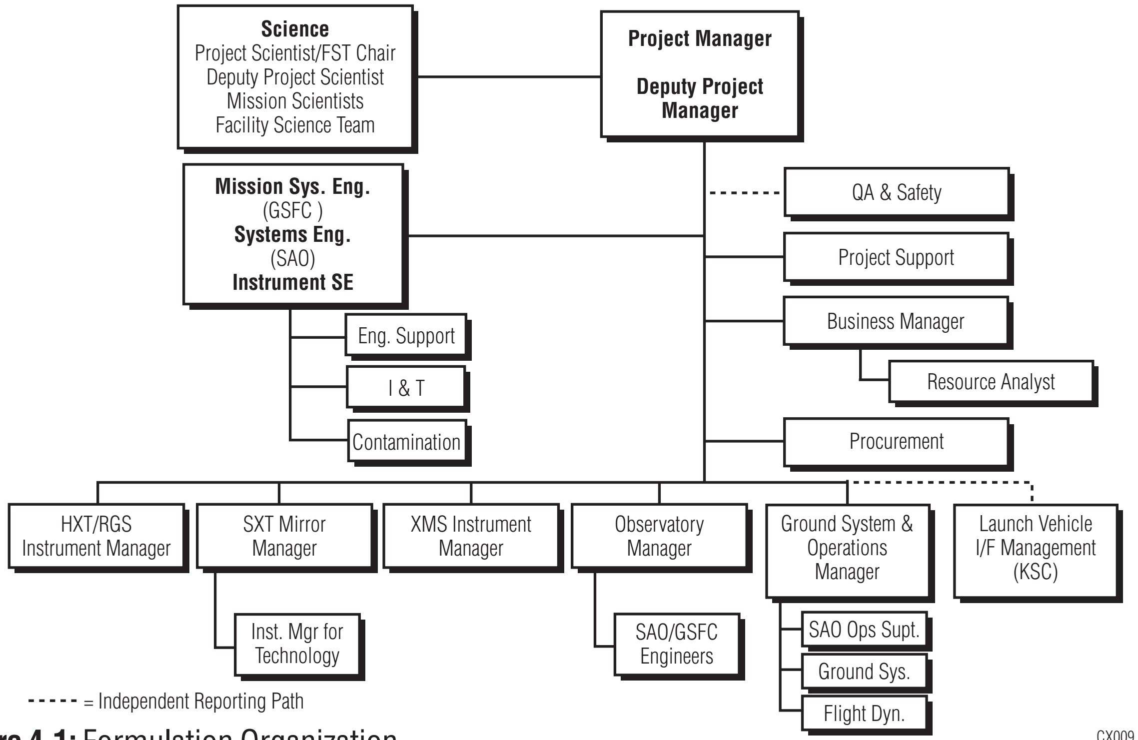


Figure 4-1: Formulation Organization

Mission Scientists. SAO supplies the FST Chair and the other Mission Scientist. The FST is an international group of scientists recognized as experts in the field of X-ray astronomy, brought together to provide science guidance and requirements development during the formulation phase. Technology development activities are led by their respective IPT lead, with a cognizant manager on the Project staff. Due to the complexity of the SXT FMA development and the need for an early start, an SXT FMA Manager is identified now, in addition to the Instrument Manager for technology development. The FMA manager will oversee the SXT mirror production activities, including phasing from technology development to production, procurement of mandrels, and soliciting vendor interest for flight production.

4.1.1.2 Teaming Arrangement and Institutional Commitments

The Constellation-X Project in the formulation phase is a collaboration among several institutions. GSFC and SAO form a core science and management group to oversee the concept development of the mission elements. The GSFC/SAO collaboration has been a strong one, as evidenced in the progress made in the last 6 years including development of the mission concept and the documenting of mission requirements. There has been a synergistic relationship, utilizing the best of both organizations to advance the Project. Both organizations are committed to the technology development phase, as illustrated in the organization chart. A Cooperative Agreement held by GSFC for SAO is the legal mechanism for transfer of funds and establishment of institutional commitment.

Institutions were selected through a 1998 NRA to develop the required technologies for the X-ray Microcalorimeter, the RGS CCDs and Gratings, and the HXT. Upon selection of the technology developers, IPTs were formed, combining the best expertise of the various organizations for specific technologies. From the selected proposals, an IPT lead was assigned to manage each technology effort and report to the Project. While the major activity of each group is to develop the key technology, they also perform the formulation activity of defining the instrument concept. SXT mirror technology work was deemed so critical to mission formulation and implementation that an IPT lead was assigned at GSFC, with support from SAO and MSFC.

All of the organizations performing the technology development activities have had extensive experience in the areas for which they are responsible. Table 4-1 lists the organizations, their technology being developed, and relevant experience.

Each of these organizations is funded according to the funding profile shown in Section 4.3. Grants for the universities and funding commitments for the government organizations are sized to enable a technology development program to reach the TRLs as indicated in the technology development schedules, Foldouts 8 and 9.

Teaming relationships and commitments within each IPT are detailed in Section 4.1.1.5.

Table 4-1: Teaming Arrangements

Organization	Lead Personnel	Responsibility	Relevant Experience
Project Level			
GSFC	Nick White, Kim Weaver, Robert Petre, Scott Lambros, Jean Grady	Project management; science management; mission design and engineering	RXTE, CGRO, MAP, IMAGE, Astro-E, HST, GLAST, Terra
SAO	Harvey Tananbaum, Jay Bookbinder, Robert Rasche	Project management support; science management; mission design and engineering	Chandra, ROSAT, Einstein, UHURU, TRACE, Solar-B, NICMOS
Technology Developments			
SXT Mirror			
GSFC	Robert Petre*	Management; reflector development; structure and alignment; optical design	BBXRT, ASCA, Astro-E
SAO	Bill Podgorski	Systems engineering; analysis	Chandra, Einstein
MSFC	Steve O'Dell	X-ray testing; mandrel procurement	Chandra, Einstein
MIT	Mark Schattenburg	Si alignment structures	Chandra
RGS			
Columbia U.	Steve Kahn* Andrew Rasmussen	Management; optical design; structure design; alignment	XMM-Newton, RGS
MIT	Mark Schattenburg	Grating and substrate production; alignment; module design	Chandra, HETG
Colorado U.	Webster Cash	Off-plane diffraction grating (alternate design)	FUSE
MIT	George Ricker	CCD readout array	Chandra ACIS; Astro-E CCD; ASCA SIS; HETE
XMS			
GSFC	Richard Kelley* Caroline Stahle	Management; calorimeter development; TES; ADR; Cooler Oversight	Astro-E/E2, XQC suborbital
NIST	Kent Irwin	TES; SQUID readout	SCUBA-2
SAO	Eric Silver	NTD technology (alternate design)	SRRT, B-MINE
JPL	Ron Ross	Cryocooler ACTDP management	many years cryocooler research
HXT			
Caltech	Fiona Harrison*	Management; CdZnTe detectors; ASIC readout	HEFT, ACE, STEREO
Columbia U.	Charles Hailey	Glass optics	HEFT, XMM
DSRI	Finn Christensen	Multilayers on glass	SODART, HEFT
GSFC	Jack Tueller, Will Zhang	CdZnTe material, contacts; Glass mirror substrates	Astro-E, InFOCμS, Swift
LLNL	William Craig	Glass optics mechanical design	HEFT, XMM
MSFC	Brian Ramsey	Nickel optics	HERO, Chandra
SAO	Paul Gorenstein	Multilayers on nickel	Chandra, Einstein, Apollo
U. Brera	Oberto Citterio	Nickel optics	SAX, XMM, JET-X
*IPT Leads			

4.1.1.3 Decision-Making Process

The final authority for all decisions is the GSFC Project Office, headed by the PM. The PM is ultimately responsible for all decisions made on the Project. While all inputs from the collaboration are considered and an attempt is made to reach decisions by consensus, particularly with the Senior Management Team (defined below), the PM is ultimately responsible and accountable for the successful completion of the Project. The PM, in turn, reports to GSFC upper management and to NASA HQ and must abide by decisions made at those levels. This process has been successful for developing the technology programs and mission architecture for the last 6 years.

A Senior Management Team has been established to support major decisions that affect project direction. This group includes the PM, Deputy Project Manager, Project Scientist, Deputy Project Scientist, FST Chair, and Mission Scientists (from GSFC and SAO). This group communicates continuously by regularly scheduled status meetings and by phone, email, and ad-hoc meetings.

The Project Scientist and the FST Chair are responsible for defining the science requirements and performance. They must consider inputs from the FST, other inputs from the science community and scientific review panels, and mission feasibility. Once agreed upon, requirements are configuration controlled by the Project. Any changes require concurrence by the Project Scientist, FST Chair, and the PM. Any science decisions which affect mission feasibility require input from the Project, with final authority from the PM.

The MSE is accountable to the Project Management for technical decisions made on the mission architecture. The MSE oversees this development and generates technical allocations for each element. If requests are made to change technical allocations, the MSE is responsible for making recommendations, but the final decision for all allocation changes lies with the PM. The lead MSE resides at GSFC.

Each IPT lead has the responsibility to develop their technology to TRL 6 within the allocated budget and schedule, and is responsible for the day-to-day decisions on their program. They are accountable to the Project Office and report status on a regular basis. Much of this reporting is made in a larger group, consisting of GSFC and SAO key personnel and often the other IPT leads. For example, status is given at FST meetings that occur twice yearly; open team meetings/telecons occur on a bi-weekly basis. Yearly executive meetings with the IPT leads review and discuss the funding for each technology for the following year. All budget requests are discussed by the group, with the overall Project schedule and performance as the context for recommendations. In this way, IPT leads have input into project decisions that may impact their technology program, or instrument concept development.

One of many examples that illustrates the success of the decision-making process is the decision to baseline segmented technology, instead of shells, for the SXT mirror. This decision involved the SXT IPT, and discussions with the GSFC and SAO management team. The technology development results along with cost and schedule projections were considered as a group and a decision was made by the PM, which was acceptable to everyone.

Another example involves the decision to baseline Event Driven CCDs for the RGS development. In addition to the process previously described, an independent panel of CCD experts was convened in a peer review to formalize the review and decision process.

4.1.1.4 Responsibilities and Experience of Team Members

Table 4-1 lists the organizations involved in technology development and formulation activities, their responsibilities, and relevant experience. All lead organizations have outstanding records for cost and schedule performance for flight deliveries as indicated in the table.

GSFC has built space flight instrumentation since its establishment in 1959 and is respected internationally for its accomplishments in Space and Earth Sciences. GSFC recent mission development experience includes RXTE, CGRO, COBE, MAP, HST, EOS-Terra and Aqua. GSFC has launched more than 250 missions, continually refining a proven management system and mission and instrument development capability, and generating corporate knowledge that is available to Constellation-X.

SAO has also participated in many successful missions. Chandra is the most similar to Constellation-X, and several people who have worked on Chandra are participating in Constellation-X. SAO team members have built the first orbiting X-ray astronomy satellite, UHURU; the first orbiting X-ray telescope to observe objects other than the Sun, Einstein; and the High Resolution Imager that flew on ROSAT. SAO shared responsibility for the U.S. ROSAT Data Center with GSFC and had responsibility for the Einstein General Observers and Data Center. SAO now managers the Chandra Operations and Science Center.

Project Management resides at GSFC. Systems Engineering is a combined effort between GSFC and SAO. The MSE located at GSFC concentrates on the overall mission elements and has also been acting as the Observatory Manager during much of the early development phase. This includes managing the observatory concept development, utilizing the engineering staff for concept development and conducting trade studies. The engineering staff is matrixed from the Applied Engineering and Technology Directorate (AETD) at GSFC and includes all the major disciplines needed to design a spaceflight mission, as learned from the many missions built at GSFC. The SAO Systems Engineering effort has concentrated largely on supporting the TM concept development, in particular SXT development and the TM architecture. The structural engineering of the TM is being performed at GSFC. The thermal engineering has been shared between GSFC and SAO, which illustrates the integrated effort between the two organizations. Requirements flowdown has been a major systems engineering activity during the formulation phase. The operations concept development has been centered at SAO, as was the case with Chandra, with the intention that SAO will perform mission operations after launch, as well as the science operations in conjunction with GSFC.

4.1.1.5 Technology Development Management

This section describes the relevant experience of the organizations involved in each of the technology development areas.

SXT Mirror: The SXT mirror technology development team has members from several institutions, each with well-defined responsibilities (see Table 4-1). The team is highly integrated and takes advantage of the strengths of the contributing organizations. Industry consultants have included Bauer Associates, RJH Scientific, and Zeiss. All participating organizations are fully committed to supporting the SXT development. Currently all development is funded by the Constellation-X Project. In prior years the GSFC, MIT, and MSFC X-ray groups made substantial institutional contribution to the SXT development via SR&T, CETDP, IR&D and facilities funds.

The GSFC X-ray group is the world leader in the development and production of segmented X-ray mirrors for flight experiments. The segmented mirror was invented at GSFC approximately 25 years ago. Since then, the group has supplied mirrors for BBXRT, ASCA, Astro-E, and suborbital programs. It is currently building five segmented mirrors for Astro-E2. SAO provides the systems engineering and analysis expertise it supplied for the Chandra mirrors as well as its extensive involvement in the fabrication, assembly, and calibration of the Chandra and Einstein X-ray optics. MSFC has unique X-ray test facilities, and together with SAO, organized and implemented the Chandra calibration. The MIT group has pioneered the development of Si microcombs for use in the SXT and Constellation-X gratings.

RGS: The IPT Lead is at Columbia University and is responsible for optimizing the design of the spectrometer. The MIT group is responsible for grating technology development for production improvements such as substrate flattening and assembly concepts. Another group at MIT is responsible for development of the BI EDCCDs, their characterization and design. The University of Colorado is responsible for examining alternate optical design concepts, including novel, high ruling density, off-plane gratings. All participants in the technology development are fully committed to supporting the RGS development. Development is supported by Constellation-X technology development and leveraging activities with SR&T and DARPA, for example.

The IPT lead has experience relevant to all project phases with the RGS aboard XMM-Newton. MIT planned and built the HETG grating spectrometer aboard Chandra and has the capability to devise new precision structures and fabricate them. MIT also has more than 35 years of experience in other X-ray missions, including 0S0-2, -7, SAS-3, HEAOs 1 and 3, Einstein, RXTE, and HETE. The Colorado group has experience designing and building astronomical instrumentation as a co-investigator for Lyman-FUSE. The MIT CCD group has extensive experience in designing and building CCD array cameras and their associated electronics, including CCD instruments for Chandra, ASCA SIS and Astro-E.

X-ray Microcalorimeter Spectrometer (XMS): XMS technology team members have extensive experience in all facets of microcalorimeter array development and readout as well as low temperature systems for space flight use. The GSFC Laboratory for High Energy Astrophysics is a world leader in inventing and developing state-of-the-art detector systems for high energy astrophysics, with experience dating back to the 1960s on suborbital payloads and orbiting observatories since then that include OSO-8, Ariel-V, HEAO-1, HEAO-2, BBXRT, ASCA, Astro-E, and Astro-E2. GSFC developed the X-ray microcalorimeter with both implanted Si arrays starting in the early 1980s, and TES arrays starting in the mid 1990s. The GSFC Cryogenics Branch has developed a number of space flight cryogenic instruments and ADRs. They are also experts in space cryocooler systems and have worked with a number of companies to develop this technology for a variety of NASA programs. Lockheed-Martin, TRW, and Ball Aerospace are cryocooler developers working on this project. The Cryogenic Branch's work on Astro-E/E2 is particularly relevant, and the GSFC team is well qualified to develop and carry out a technology plan with a high degree of cost certainty.

The NIST group pioneered and developed the TES thermometer for microcalorimeters and are world leaders in TES fabrication and SQUID readout. In addition to the work they are doing on X-ray TES arrays, they are responsible for an ambitious multiplexed TES 6400-pixel submillimeter array for the James Clerk Maxwell Telescope. They have also developed laboratory TES systems for materials analysis.

SAO is developing an alternate calorimeter concept using NTD technology. Utilizing their experience of building microcalorimeter arrays, they have been proving this technology through laboratory astrophysics experiments. SAO is partnering with the Lawrence Berkeley National Laboratory, which has long experience of building flight instruments. The decision of which technology to move forward will be made in 2004.

HXT: The HXT technology development program is being carried out by an international team of experts in X-ray optics, multilayer coatings, and detector development consisting of the leading groups in hard X-ray astrophysical instrumentation who are currently involved in major efforts to develop focusing capability for the hard X-ray band.

The HXT team includes members from institutions that have developed major facilities for Chandra, XMM, ASCA, Astro-E, Swift, STEREO, and ACE. Therefore, the collaboration has access to major production, calibration, and processing facilities both at NASA Centers and universities that have been committed to carrying out the Constellation-X HXT development program.

4.1.1.6 Mission Architecture Development

During the early formulation phase, mission architecture studies have already helped to define the spacecraft concept, the TM concept, the ground systems and operations concept, the launch vehicle capabilities, orbit, initial I&T flow, and assignment of technical resource allocations to each element. systems engineering studies, such as determining alignment concepts and examining realism of pointing error allocations and performance have also been conducted. In 1998, through a Cooperative Agreement Notice to perform an architecture study, TRW and Ball Aerospace designed independent solutions to the Constellation-X requirements. This information was reviewed and used as input, along with a third input from GSFC and SAO engineering to design a "Reference Mission Description[24]" document. The reference configuration used the instrument concepts that were developed by the technology development IPTs, along with the GSFC and SAO engineers. This reference configuration was used to demonstrate the validity of the Constellation-X concept, to provide a starting point for designing the instrument concepts, and for costing. The reference configuration shows that the required performance can be met.

These studies will continue through the formulation phase. As results of further studies and trades become available, the reference configuration will be updated accordingly. In particular, the following are planned:

Mission Phase A and B : The Phase A studies will be multiple contracts to industry. Multiple contracts will ensure independent technical designs, so the best available technical solutions are incorporated into the mission architecture. The Phase A studies will be for the observatory architecture: the combined spacecraft and TM. Following completion of Phase A, an open competition will result in selection of one vendor to perform a Phase B study (this prime contractor will follow-on with Phase C/D). The Phase B activities will continue to develop the preliminary design.

Science and Operations Center: Led by SAO, the Operations Concept Document[25] will be baselined, leading to the definition of the ground system architecture and the process for integrating CXSOC planning and development activities with the existing Chandra Operation Center. Activities include specification of the mission data system and archive architectures, refinement of the calibration plan, and development of the data management plan.

4.1.1.7 Risk Management

The principal risks during the formulation phase are the risks associated with the development of the optics and instruments. All technologies have heritage from previous designs which reduce their risk level. However, given that the technologies are an extension of what has been done before, and development is required, there is necessarily an element of risk. The technology development program is the first line mitigation for this risk. That is, the program is in place to develop the required technologies to the required performance for Constellation-X, before moving into the instrument development phase. Technology investigations also address process development. For example, the SXT mirror fabrication and assembly process is being studied and tested extensively to ensure that it can be done within the required schedule and cost.

The Project carries margin in performance, cost, schedule, and technical resources such as mass and power, in order to make trades to optimize the mission and to manage problems such as insufficient progress in technology development, unexpected system interactions, or changes in cost/schedule requirements. Technology development progress is monitored on a regular basis, and backup options are discussed and investigated as part of the technology developments.

Specific risk areas for each technology are discussed in the technology development sections, including mitigations, alternate designs and decision points for invoking back-up options. These are summarized in Table 3-2.

4.1.1.8 Transition from Technology Program to Flight Project

The Constellation-X Project plans ensure a smooth and seamless transition into the implementation phase. Moving toward implementation, the staff level will increase until it is at the full organization shown in the implementation organization chart (Figure 4-2). Project controls will be added at the appropriate phase (e.g., documents and requirements will be put under formal configuration control in Phase A). Changes will only be allowed if approved by a formal control board, chaired by the PM. Schedule control will continue throughout formulation and implementation, becoming more formalized after the flight contracts are awarded. Technical reserves requirements will be established in formulation and monitored and controlled during implementation. The approval process for moving into the implementation phase will use the NASA approach of an independent NAR. This is a rigorous approach to certify the readiness of the Project for the next phase.

The general approach for the Constellation-X Project to enable a smooth transition from formulation to implementation is as follows: The technology and mission concepts are developed in the formulation phase. Most of the elements are then competed with issuance of a NASA solicitation (see Table 4-2 for the Constellation-X acquisition strategy for each element). The Project then oversees the development by the element-providers during the implementation phase. The Project oversees the entire process and provides the management, systems engineering, and science direction and requirements.

4.1.1.8.1 Acquisition Strategy

Following is a strategy that will allow a smooth transition into the implementation phase. It is used for baseline planning, and must be approved by NASA HQ before being implemented.

Instruments: Each of the flight instruments (XMS, RGS, HXT) will be solicited with a

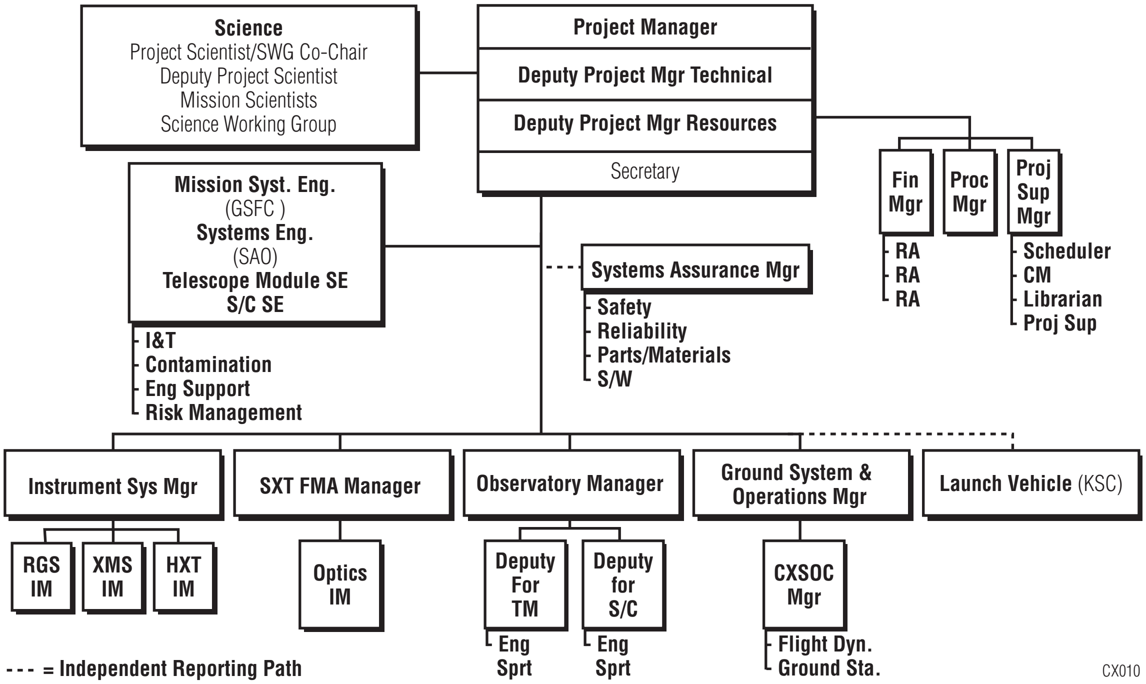


Figure 4-2: Implementation Organization

NASA HQ issued AO. A Principal Investigator with supporting institution and proposed teaming arrangements will be selected to deliver the flight-qualified instrument. It is anticipated that proposing organizations will make use of the technology development. However, the AO will be open to alternative concepts if they are mature enough to meet the Constellation-X requirements within the allotted schedule and cost. While it is recognized that the technology development teams have an advantage for the flight selection, there will still be sufficient competition, given that there are multiple teams within the Project who are capable of applying the technologies developed, as well as industry partners who are following the technology developments, by attending open science meetings, and conducting discussions with the technology teams.

Table 4-2: Acquisition Strategy

System	Procurement Strategy	When Contract Required
Instruments	AO	Phase B start
SXT optics	GSFC managed; RFP for vendor; RFP for major procurements	Phase A
Observatory	RFP	Phase B start
Mission Operations Center	Provided by SAO	PDR
Science Operations Center	Provided by SAO ; shared with GSFC	PDR
Ground stations	Leased commercial	Observatory I&T
Launch vehicle	KSC procurement	L -30 months
General Observers	SAO call for proposals	L +4 months

SXT Flight Mirror Assembly: The mirror assembly development will be managed at GSFC, with engineering and science support from GSFC and SAO. A contractor will be selected via an RFP to produce the FMA. This includes producing the mirror segments, all the systems engineering and integration, with the PI developed gratings provided for integration as government-furnished equipment (GFE). Prior to vendor selection, a study contract will allow two potential vendors to further refine the fabrication and assembly process (Phase A activity). This will be accomplished by an RFP. The flight forming mandrels and replication mandrels will be provided to the vendor as GFE. This will also be a GSFC competitive procurement. The vendor will be selected early enough to work hand-in-hand with the technology development organizations, to facilitate technology transfer, and to make use of the lessons learned. The schedule for the SXT acquisition activities is shown in Appendix B, page B-4.

Observatory: The vendor for the combined spacecraft and TM will be a prime contractor who will have responsibility for both elements, the interfaces between them, the instruments and mirrors, and the I&T, after receiving fully qualified instruments and SXT FMA. Using a prime contractor will ensure ownership and responsibility for the integrated systems design and interface management for the entire observatory. There has been, and will continue to be, active vendor involvement; there has already been a response to a CAN for mission design, an RFI for spacecraft design and cost, and unsolicited design work from several potential vendors.

An RFP will be released to industry for a 9-month Phase A study per the schedules shown in Appendix B, pages B-24 and B-25 (described in Section 4.1.1.6). It is likely that two vendors will be selected. Toward the end of the formulation contract, a separate RFP will be generated to solicit vendors for a final design and implementation contract (essentially a Phase B/C/D contract). The timeline for selection of this contract is shown in Appendix B, Page B-24 and B-25. This method has been utilized successfully on contracts such as the Advanced Technology Microwave Sounder. This RFP will be an open solicitation, not limited to the vendors who performed the formulation studies. The contract will be structured such that continuing into the implementation phase is contingent on NASA HQ approval.

Ground System: The CXSOC will be located at SAO, co-located with the Chandra X-ray Center, making maximum use of NASA's investment in the Chandra experience, personnel, and infrastructure. The Science Operations Center will be a partnership between the SAO Chandra X-ray Center and GSFC (HEASARC and its co-located science centers), with SAO as the lead. The exact roles and responsibilities between SAO and GSFC will be determined after selection of the instruments. The ground stations will be leased commercial sites.

Launch Vehicle: This procurement will be managed by the Kennedy Space Center, as per NASA practice.

General Observers: A robust GO program will be managed from the Science Operations Center. Calls for Proposals will be issued, and selected proposers will be awarded grant funding to perform their science investigations using Constellation-X data.

4.1.1.8.2 Transition Activities

Specific activities will enable a smooth transition from formulation to a flight project.

Concept Development: Beginning in formulation, concepts for the instruments and observatory are developed and used for design, proof-of-concept, and costing. These concepts will be refining the reference configuration and are developed by the GSFC and SAO engineering teams, with input from industry, and the IPTs for the instrument concepts. A manager on the Project (e.g., IM, OM, SE) is assigned to each element to manage the concept as it matures into flight designs.

Requirements Development and Configuration Control: Requirements development began early in the Project (evidenced by the Top-Level Requirements Document[4]) and will continue during the transition phase. Traceability will ensure consistent monitoring of requirements from the beginning of the Project to final design and verification. Configuration control will be in effect *before* flight contracts are awarded.

Reference Mission Description Document: This is used to keep track of one particular architecture that can satisfy the Constellation-X requirements. Responses to solicitations will be compared against this reference, to verify their validity.

Systems Engineering: Requirements flowdown and traceability ownership, technical resource ownership, system studies, such as TM concept and associated pointing performance, all systems engineering activities, will be carried through the transition phase.

Mission Studies: Phase A studies will refine the overall mission architecture and solicit inputs from industry. This will inject a broader array of technical ideas and solutions that will be used in the final design.

Science: Science support is based on internationally recognized leadership and early definition of science requirements configuration controlled through the transition process.

Management: The organization is consistent with GSFC organizations used on many successful projects. The GSFC/SAO collaboration has proven to work well and follows experience from other similar space projects.

Risk Management: This activity will carry on throughout the formulation and implementation phases, ensuring feasibility and making informed decisions at pre-defined trigger points.

Cost Control: Many of the activities during this time period will be in an effort to find the most cost effective designs and processes. Cost will be a factor in the trade studies and architecture studies performed during this time.

4.1.2 Mission Implementation

4.1.2.1 Organization

The Constellation-X Implementation organization shown in Figure 4-2 is consistent with GSFC Project organizations that have successfully managed many missions. The formulation organization staff has increased to provide the level needed to manage the implementation, consistent with the size of the Constellation-X Project. Specific changes from the formulation phase are as follows:

The PM for the implementation phase will be chosen approximately one year before moving into the implementation phase. The Director of the FPPD will select the person most appropriate for this position, who may or may not be the same as the formulation PM. The year lead time allows the PM to come up to speed, have an impact on project direction, and ensure a smooth transition before coming into the full swing of implementation.

A complete Systems Assurance Program will be in place. As in the formulation phase, this support will come from the Office of Systems Safety and Mission Assurance Directorate, and will include system assurance, safety, reliability, software assurance, software IV&V from the West Virginia facility, as well as parts and materials engineering from the AETD.

The systems engineering staff will be augmented, and formal risk management will be added to the systems engineering duties.

An added Instrument Systems Manager is responsible for the successful delivery of all instruments, and manages the team of Instrument Managers, one for each instrument, to accomplish this task.

The Observatory Manager becomes the Technical Officer on the Prime Contractor contract. Given the magnitude of the job, two deputies, one for the TM and one for the spacecraft, will be added to oversee their respective developments. A TM and spacecraft SE will be added for support.

A manager for the Constellation-X Science Operations Center will be selected by the time of implementation.

The business function of the Project will be expanded to be commensurate with the size of the Project.

As has been done on other projects (e.g., GLAST, Chandra), the FST will be disbanded by this point, having served its purpose of initially defining the Constellation-X science requirements. It will be replaced with a Science Working Group (SWG). The SWG will be selected through the instrument AOs and will consist, as a minimum, of one or two representatives from each team. It is anticipated that the co-chairs of the SWG will be the Project Scientist and the former Chair of the FST. The SWG exact makeup will be determined by NASA HQ at the time of AO release.

During implementation, all contracts to hardware developers will be in place. Each element will have a SE, which will be part of a Systems Engineering IPT, led by the MSE. In addition, since the Observatory will be the responsibility of a Prime Contractor, they will have significant systems engineering responsibilities for the complete observatory, including interfaces to the instruments, mirrors, and ground system. This is an advantage of using the Prime Contractor model, with a systems engineering cadre on the Project.

4.1.2.2 Teaming Arrangement and Institutional Commitments

As in the formulation phase, the Project is a collaborative effort between GSFC and SAO, with the Project Management performed at GSFC. The institutional commitments of the two organizations will continue throughout the implementation Phase. It is planned that the science management team, specifically the Project Scientist, the SWG Co-Chair (the FST Chair in formulation), and the Mission Scientists (one from GSFC and one from SAO) will remain the same.

The organizations which will develop the flight hardware will be solicited during formulation, and so they are not currently known. However, as a risk mitigation activity industry sources have been extensively pursued to verify that there is interest and capability to provide what is needed.

4.1.2.3 Decision-Making Process

The decision-making process during the implementation phase will carry over from the formulation phase. The PM is still accountable for the entire mission success and has the authority and responsibility for all Project decisions. The Senior Management Team consisting of GSFC and SAO personnel will continue to be used and to make the best use of the experience of the personnel from the two organizations. The leads (Project Scientist and SWG Co-Chair) will be the same people as during the formulation phase: Dr. Nicholas White, GSFC, and Dr. Harvey Tananbaum, SAO, and will represent the science inputs to the Project.

During implementation, the Level 1 Requirements will be finalized and will be a guiding document from NASA HQ to the Project. Decisions will be measured against meeting those requirements. If those requirements cannot be met, or if they require a funding level greater than the allowable guideline, HQ will be made aware of the situation and will make the final decision on how to proceed. Options include an increased funding level, implementation of descopes (including stretching the schedule), or, in a severe case, cancellation of the Project.

4.1.2.4 Responsibilities and Experience of Team Members

Senior team members for the Project Management, Science Management, and SXT management for the formulation phase are transitioned to the implementation phase with similar roles and responsibilities (see Section 4.1.1.4).

4.1.2.5 Instrument Development Management

The organizations that will develop the flight instruments will be solicited during Phase A, as described in Section 4.1.1.8.1 Acquisition Strategy, and so they are not currently known. However, as a risk mitigation activity potential sources have been extensively pursued to verify that there is interest and capability to provide what is needed. At the very least, it is expected that the institutions currently working the technology development activities will propose for the flight instrument development. Each instrument development will have an Instrument Manager to oversee the development, ensure interfaces with other systems, and monitor progress and risk management.

The management team for the SXT optics will look similar to the organization during the technology development phase. The team will continue to be led by the GSFC X-ray Astrophysics Branch, and involve in a highly integrated way participants from the GSFC Optics Branch and Mechanical Systems Center, SAO, MIT, and MSFC. All participants in the technology development program are committed to the flight development. For those major activities that are contracted out, the relevant technology development team lead will remain the point of contact within the team, taking responsibility for technology transfer and overseeing the outside effort. For those areas remaining within the team, the team lead will continue with lead responsibility.

4.1.2.6 Mission Elements Management

A Project Plan will be developed during Phase B to delineate the details of how the Project will manage each element of the Project.

The observatory contract will be managed from GSFC. The AETD will provide discipline engineers (systems, mechanical, thermal, C&DH, communications, electrical, power, propulsion, guidance, navigation and control, software, integration and test, and flight dynamics) to oversee the observatory development. This is a very deep base of support, and additional engineering support can be brought in if needed. This is the normal way GSFC operates and has proven to be a very successful approach. SAO will also provide systems engineering, and some discipline engineering support, for example thermal and structural analysis for the TM, where they have extensive experience from Chandra.

The Office of Systems Safety and Mission Assurance Directorate at GSFC will provide the QA support, and will have an independent reporting chain outside the Project Office. This ensures an independent quality review function.

The ground system and operations function during implementation will be led by SAO.

Ground system expertise from GSFC will also be utilized, and the flight dynamics function will come from GSFC, making use of unique experience with launches to the L2 libration point. The Chandra operations system at SAO will be configured to support Constellation-X in time to support I&T. Chandra is expected to still be operating when Constellation-X is launched, and so facilities, infrastructure, and experienced personnel will be shared without impact to Chandra. The launch vehicle interface will be provided by KSC.

4.1.2.7 Risk Management

During the implementation phase, risk management will be an ongoing activity. A risk management plan will be generated during Phase A, and will detail the activities to aggressively pursue the identification, characterization, mitigation planning (including resource liens, use of project margins, alternate designs and processes), and tracking of progress and decision points, for each identified risk. Each risk will be assigned a risk manager on the Project to regularly monitor its status. Any person on the Project can identify a risk at any time. The status of all risks and potential new ones will be reviewed on a regular basis and reported to the PM for necessary action.

The most significant mission risks for the implementation phase identified at this point and their mitigations to reduce or eliminate the risk are included in Table 4-3 in priority, along with an assessment for criticality (how serious the problem is) and likelihood (the probability of occurrence if no mitigation activities are implemented). Criticality and likelihood levels are defined in Section 3.1. The technology development risks summarized in Table 3-2, and the implementation risks listed in Table 4-3 give the complete picture for all mission phases.

4.1.2.8 Management of Reserves

Technical resources, such as mass, power and volume, are managed by the MSE. Allocations are established, and are continually monitored by the Project. Sufficient mass and power contingency plus project margin will be held so that 30% remains at the time of the AO/RFP release, and with configuration control established at that time. While the MSE is responsible, these resources are also monitored by the

Table 4-3: Top Mission Risks

Risk	Mission Impact	Criticality	Likelihood if no Mitigation	Mitigation
Production and alignment of large number of mirror segments may cause schedule slip	Potential launch delay	High	Medium	• Early studies identifying process and production issues; currently ongoing • Early involvement of potential contractors; discussions in process now; 5 vendors interested • Alignment techniques studied in technology development • Parallel processing as much as possible; in implementation plan • Vigilant management with involvement of scientific and technical staff • Use of schedule/cost contingency
Default of single source for key components	Schedule delay	Medium	Low	• Continue to identify potential back-ups; talking with other vendors • Get commitment from top management; site visits have begun • Use of FFP contract where feasible • Potential funding of back-up vendors during Phase A
Atlas V launch vehicle configuration is not ready (this refers to fairing size, number of solids, etc.)	Schedule delay	Medium	Low	• Use architecture and design that is tailorable for both Atlas V and Delta IV; trigger point is end of Phase B
Loss of XRCF for X-ray testing	Cost	Low	Medium	• Use alternate facilities, e.g., MSFC stray light facility, PANTER (European); trigger point end of Phase B

PM to determine if action is necessary to keep within the required limits. The current amounts of mass and power reserve are shown in Section 2.4.1.3. Performance margins are also monitored and are used to trade off for other parameters (e.g., mass), as long as the minimum science requirements are maintained.

GSFC experience has shown that, for a Constellation-X class mission, schedule contingency of 1 month of funded reserve per year during Phase C/D, is appropriate. Constellation-X holds more reserve than this, as shown on Foldout 5.

After selection of the instrument, mirror and observatory contractors, a percentage of the project reserves–technical, cost and schedule–will be allocated to the developers, to manage with their own team as contingency, with knowledge of the cognizant manager on the Project as contingency. Nominally, this will be 25% of the total reserves and will be the uncertainty applied to the current best estimate. The exact amount will be tailored according to the specific risks for each development, during formulation. For example, the SXT mirror may require more schedule contingency, while the mass may be easier to determine and require less contingency. These values will be documented in an interface agreement with the Project.

The remaining reserve (nominally 75%) is managed at the project level as unallocated margin. Any requests to use more than the nominal 25% for any element must be endorsed by the SE for technical elements, and by the manager (e.g., Instrument Manager) for cost or schedule, submitted to the CCB, and approved by the PM. In addition, the resource usage will be monitored by phase. Allowable values of reserve usage will be determined by major milestone, and documented in the interface agreement with the Project. Monitoring of actual contingency usage compared to these values will be used to establish the health of the development progress. Monitoring will be done by the Project on a regular basis, including monitoring of a developer performance measurement system, and monthly reporting of contingency usage. PM approval is required to increase an allocation for a given phase.

Figure 4-3 shows an example of a time-phased allocation strategy. Past experience has shown that approximately 25% of the technical reserves will be allocated by PDR. Schedule and cost contingency allocations should be minimal at PDR. An additional 25% of the technical reserve and approximately 15-25% of the cost reserves and very little schedule reserve should be allocated by CDR. The remaining technical assets, and cost and schedule for each delivery will be used from CDR through delivery, with a small amount retained for possible workarounds after delivery, during integration and test.

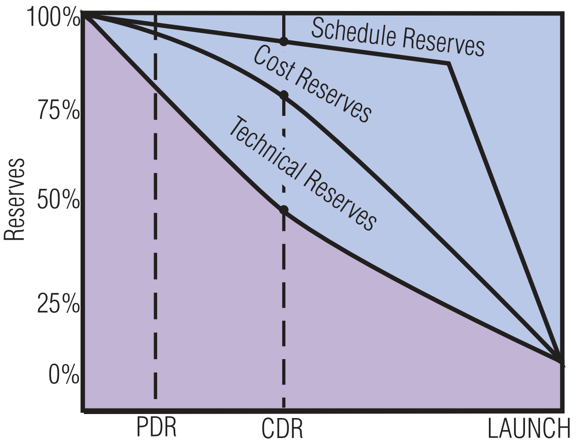


Figure 4-3: Typical Resource Allocation

If resource allocations are exceeded, the following options exist: the first defense is reprogramming, replanning, optimizing work, and checking for areas that can be reduced. When necessary, independent technical teams will be brought in to assist in assessing the situation. The next stage is for the Project to allocate additional reserves. If this is not possible or appropriate (i.e., not enough project reserves, or trend shows no confidence that the situation will improve), descope options developed during formulation will be considered. Any descope option that does not affect Level 1 science requirements can be invoked with PM approval. If Level 1 science requirements are affected, NASA HQ approval is required. The effective monitoring, management, and use of reserves will give high confidence that the Project's goals are met within the allocated reserves. In addition, the experienced technical management, along with an early defined risk and descope plan will minimize the need for use of reserves.

4.2 Schedule

Foldouts 5 through 9 show schedules for Mission Summary, Mission Formulation, Mission Implementation, and Technology Development (two), respectively. Appendix B contains detailed schedules, indicated by WBS element. All schedules were generated in accordance with the WBS, and are tied to funding levels. The detailed schedules in the appendix were used to create the two Technology Development schedule foldouts, which are summarized in the Formulation Foldout. The Formulation and Implementation Foldouts, which capture all mission activities, are summarized in the Constellation-X Summary Schedule Foldout.

All schedules were generated by personnel experienced in their respective activities. The technology development schedules were generated by the IPTs, and have been refined over the past several years. The IPTs also generated the instrument and SXT FMA implementation schedules, using their depth of experience with other similar projects. The observatory schedule was generated by the Project, again using a wealth of experience in other similar projects, and corroborated by information received in the spacecraft RFI. The MO&DA schedule was generated also using the experience of other projects, particularly Chandra, which is the model for Constellation-X MO&DA.

Of particular note is the fact that much effort went into planning for the four observatories. For all flight elements, as much parallel processing will be done as possible, to allow the best schedule advantage. The SXT FMA development makes maximum use of parallel processing to develop the large number of mandrels and reflectors required. This development is on the critical path as shown on the Mission Implementation Schedule (Foldout 7). The technology critical path shown on Foldout 8 includes the mirror development that precedes initiation of mandrel production. Because the SXT FMA is on the critical path, special attention has been given to details of the development and production of the mirrors, as can be seen in the nine pages of SXT FMA detailed schedules in Appendix B. The observatory I&T is generated based on staggering the separate builds. This allows for lessons learned from the first observatory to alleviate problems in observatories 2-4, as well as easing the planning for facility use during environmental test. It is assumed there will be separate teams for each observatory, with overlap where possible to take advantage of the experience gained which can be applied to later builds. The staggering of the first and second observatory builds also creates an additional 3 months of contingency for the first observatory, as shown on the first observatory I&T schedule (Appendix B, page B-26). These two observatories will be placed in orbit on the first launch, December 2010. The same is true for the third and fourth observatories, which will be placed in obit on the second launch 1 year later.

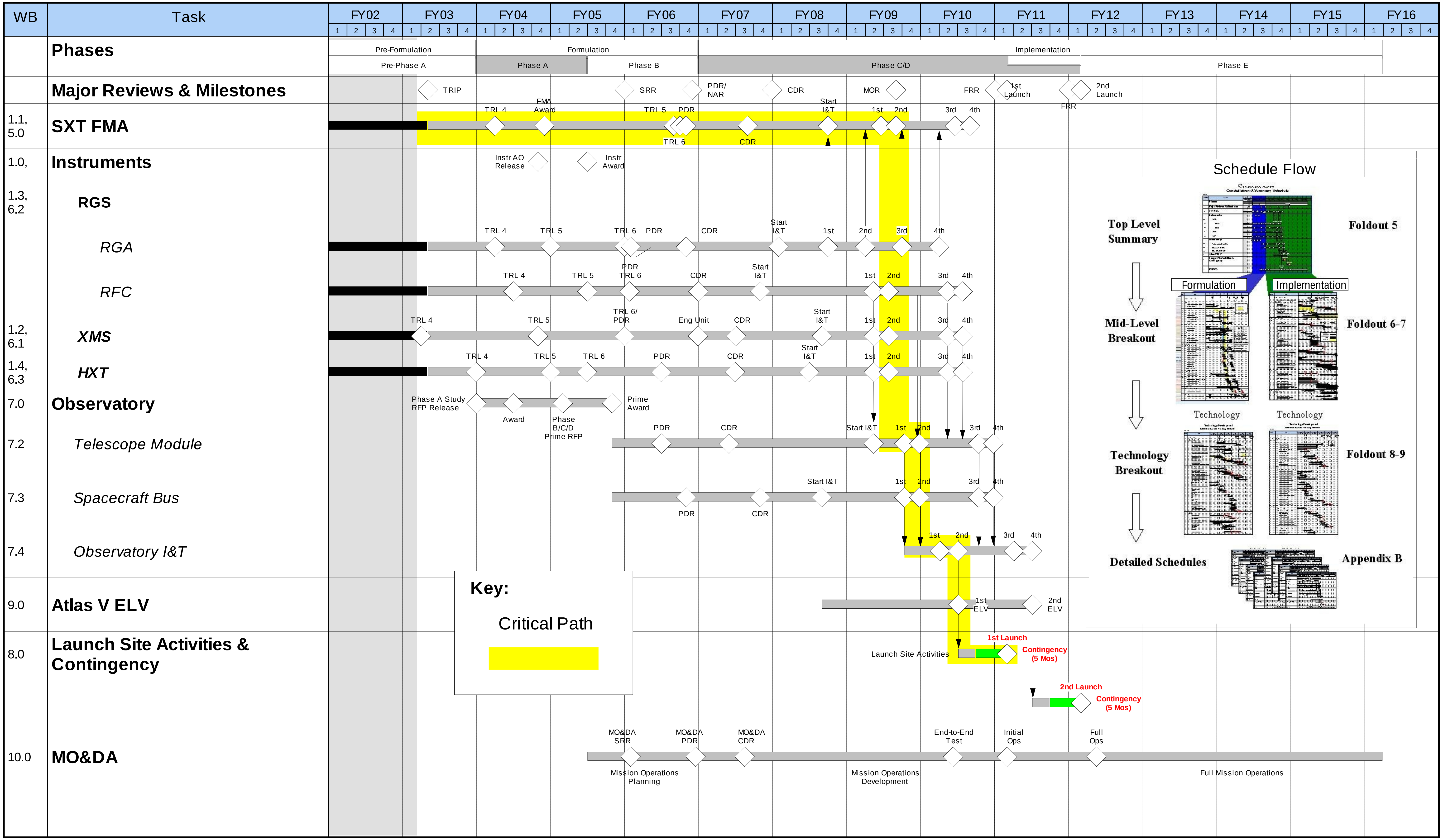
Each technology development as well as all flight elements have slack built into their schedules, as shown in Appendix B and summarized in the table on Foldout 7. This slack is funded and is controlled by the provider of each element. In addition, the Project holds 5 months of funded contingency placed at the end of the development phase, as shown in the Summary Foldout 5. This contingency is controlled by the PM, as described in Section 4.1.2.8.

The Project retains a scheduler to generate and review current schedules. The technology development schedules are reviewed at least monthly, and major milestones are tracked. Detailed schedule networks and analysis, and monthly status reviews will carry through the implementation phase.

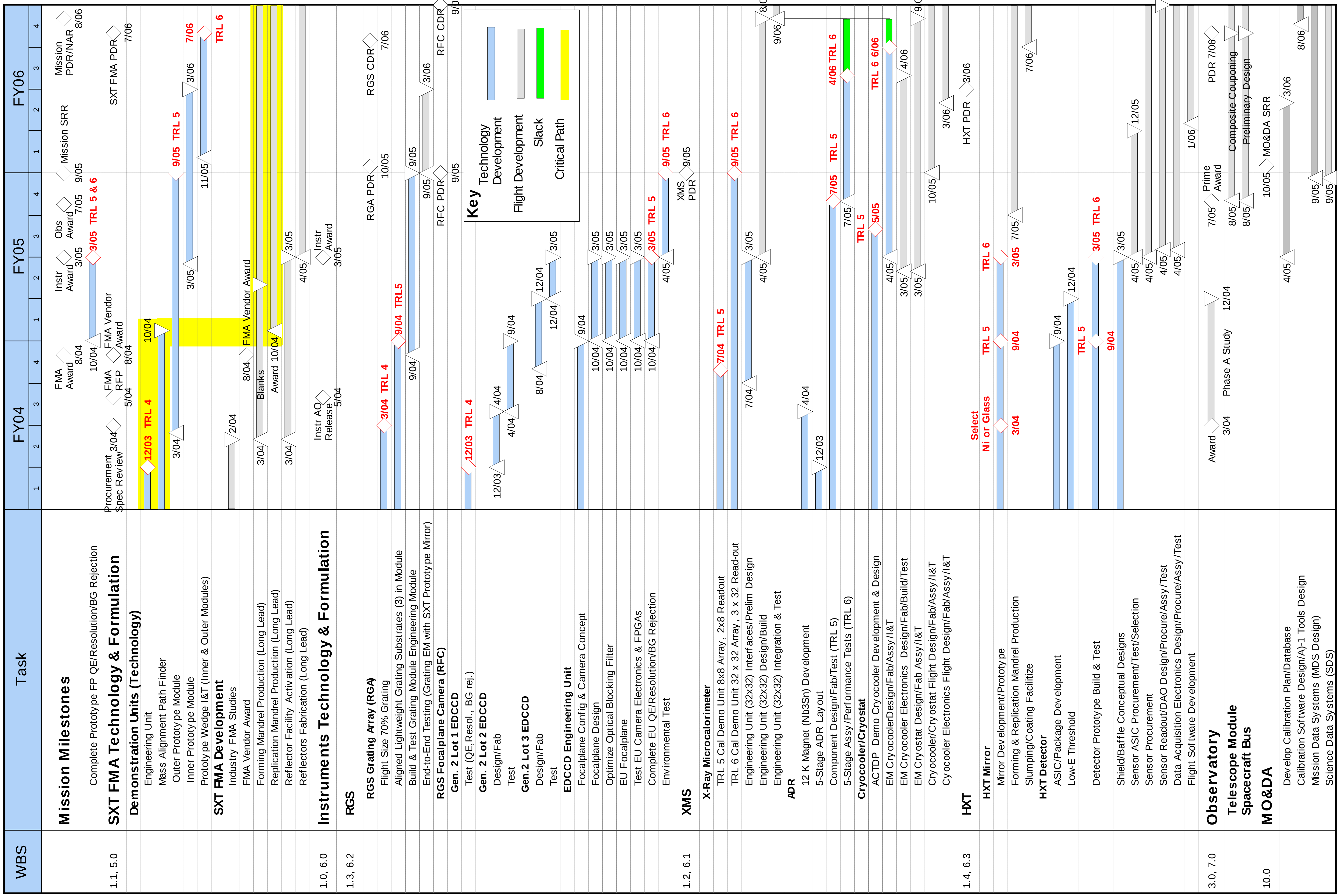
4.3 Budget

This Section Omitted

Constellation-X Summary Schedule

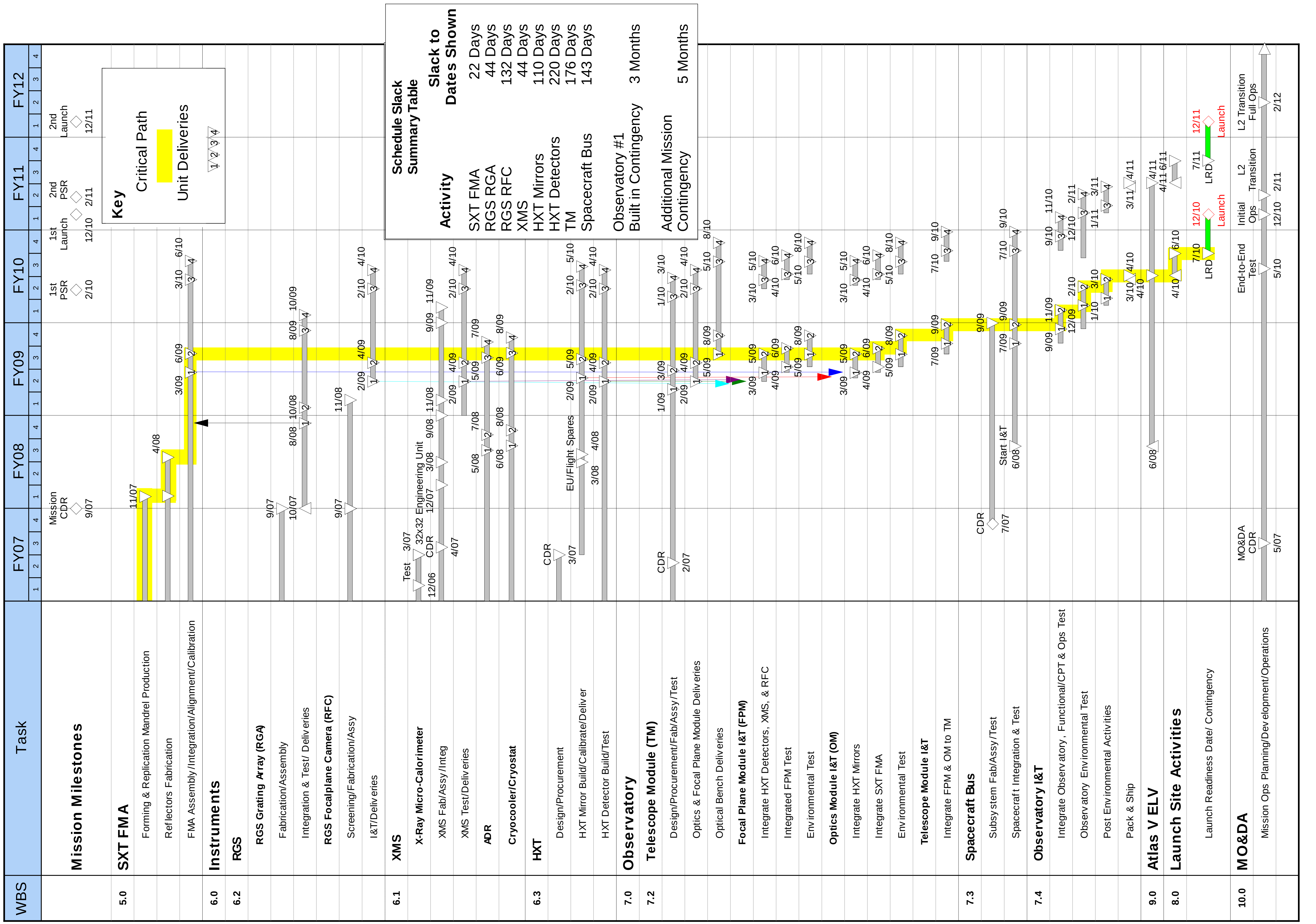


Constellation-X Mission Formulation Schedule



FOLDOUT 6

Constellation-X Mission Implementation Schedule

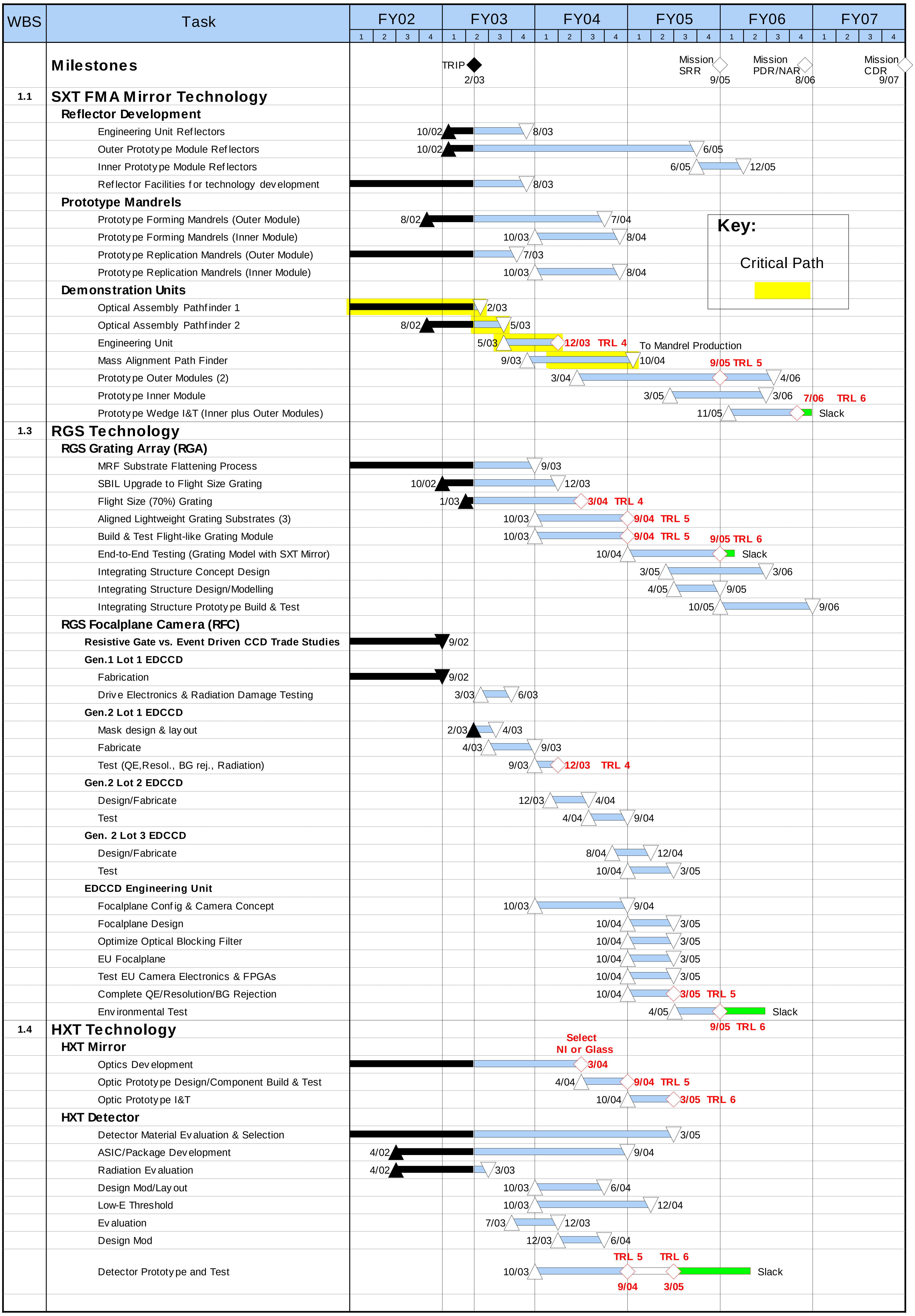


Schedule Slack Summary Table

Activity	Slack to Dates Shown
SXT FMA	22 Days
RGS RGA	44 Days
RGS RFC	132 Days
XMS	44 Days
HXT Mirrors	110 Days
HXT Detectors	220 Days
TM	176 Days
Spacecraft Bus	143 Days
Observatory #1 Built in Contingency	3 Months
Additional Mission Contingency	5 Months

Constellation-X Technology Development Schedule

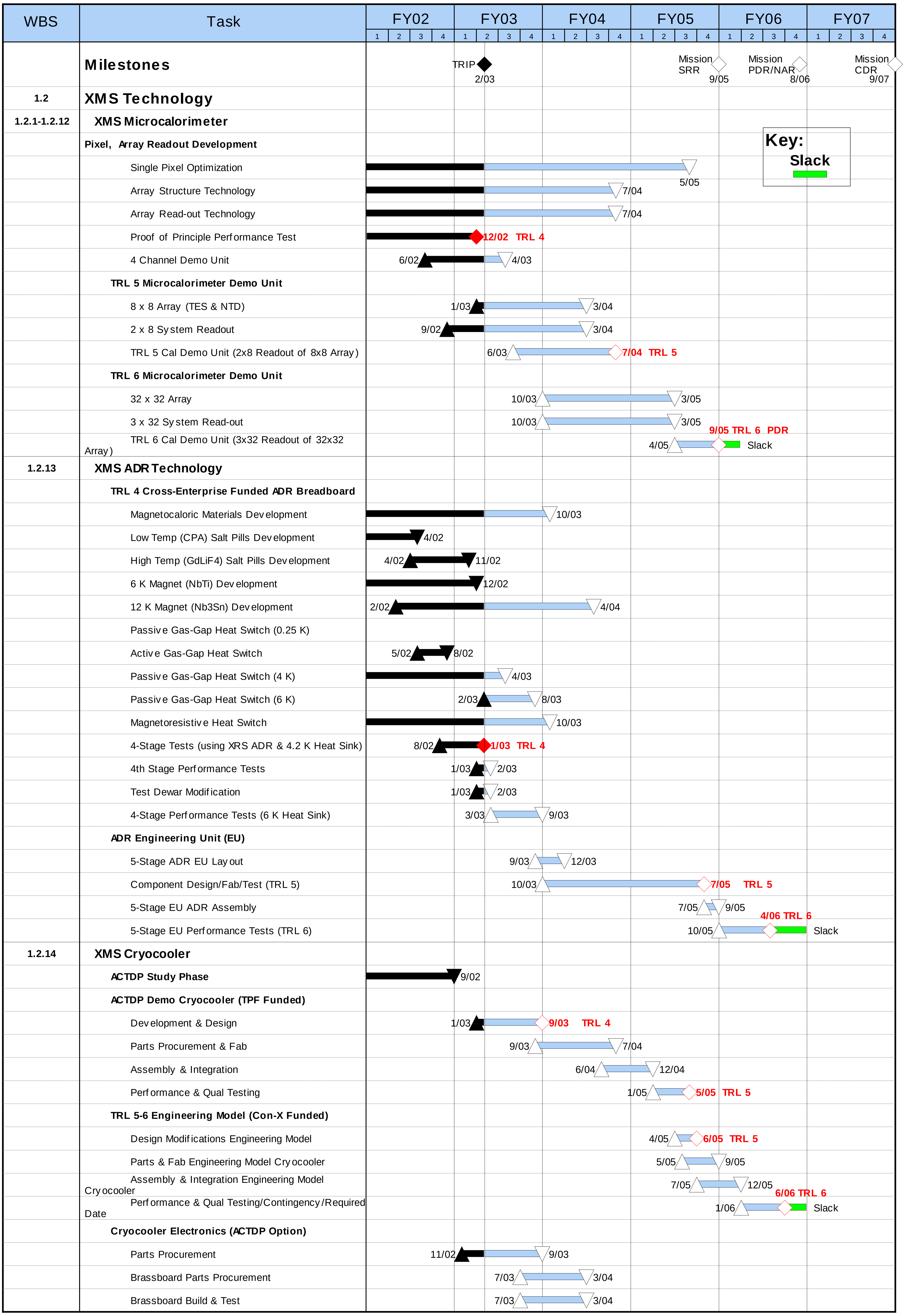
Critical Path to Achieve Technology Readiness



(Page 1 of 2)

FOLDOUT 8

Critical Path to Achieve Technology Readiness



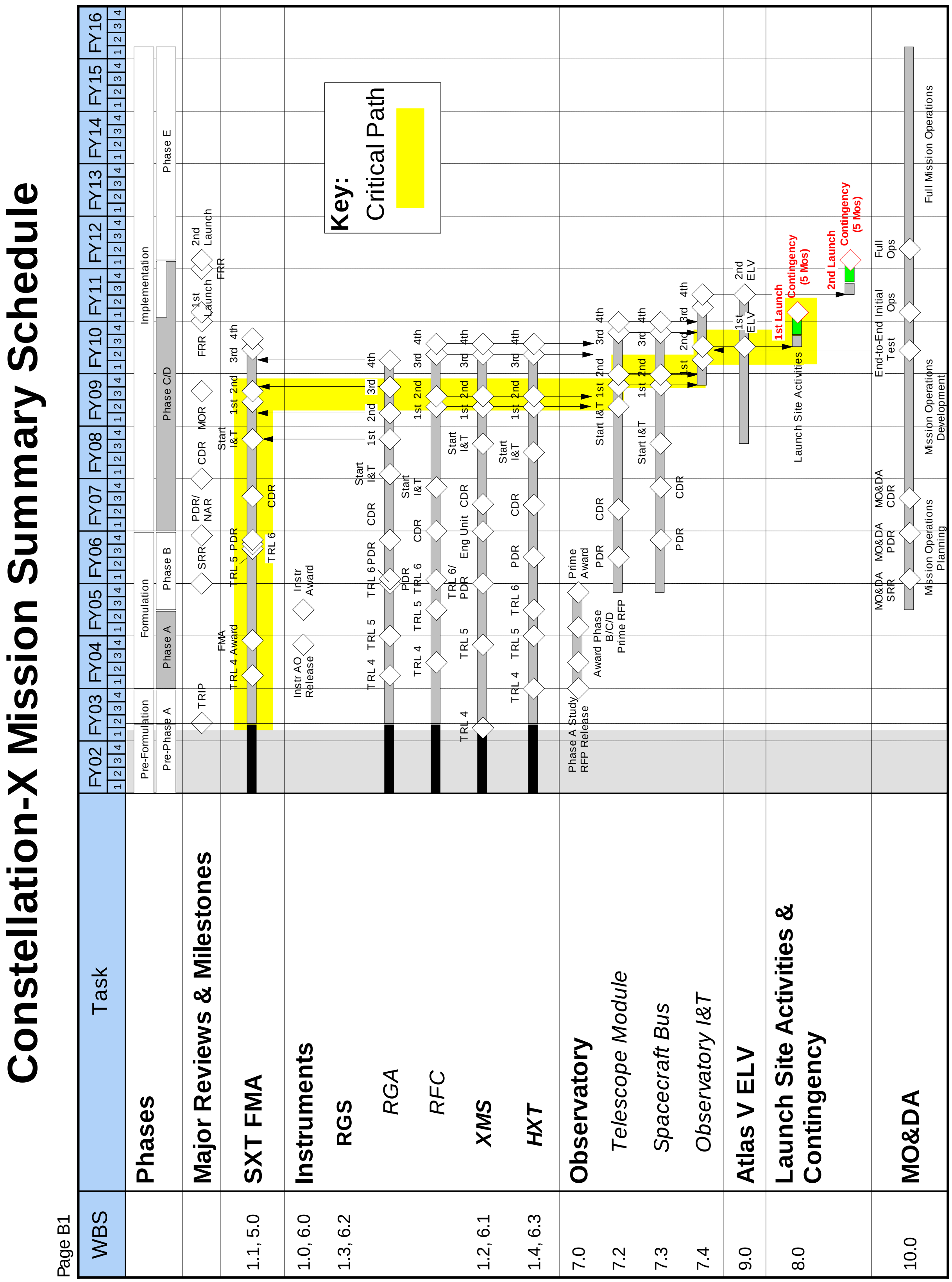
FOLDOUT 10 OMITTED

Appendix A - Detailed Budget

OMITTED

Appendix B - Supporting Detailed Schedules

Appendix B - Supporting Detailed Schedules



Major Mission Review Schedule

Page B2

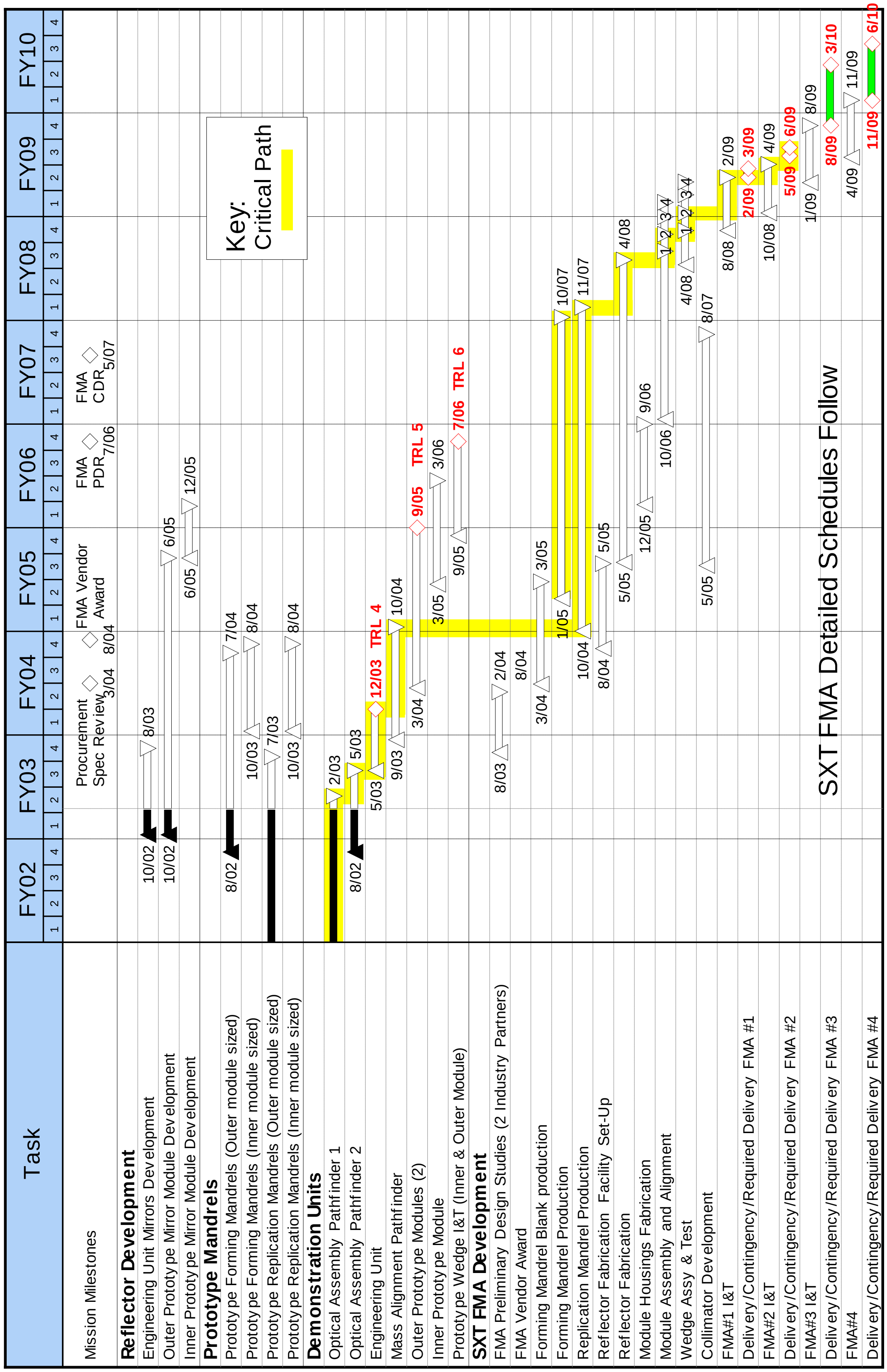
Task	FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12
	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4
Technology Readiness and Implementation Plan (TRIP)		2/03 ◇ TRIP									
Mission Definition Review (MDR)				2/05 ◇ MDR							
Systems Requirements Review (SRR)				9/05 ◇ SRR							
Preliminary Design Review (PDR)					8/06 ◇ PDR						
Non-Advocate Review (NAR)					8/06 ◇ NAR						
Critical Design Review (CDR)						9/07 ◇ CDR					
Mission Operations Review (MOR)								6/09 ◇ MOR			
1st Observatory Pre-Environmental Review (PER)								7/09 ◇ 1st PER			
2nd Observatory Pre-Environmental Review (PER)									10/09 ◇ 2nd PER		
1st Launch Pre-Ship Review (PSR)									3/10 ◇ 1st PSR		
Operations Readiness Review (ORR)									4/10 ◇ ORR		
1st Launch Flight Readiness Review ,(FRR)										10/10 ◇ 1st FRR	
1st Launch Readiness Review (LRR)										11/10 ◇ 1st LRR	
3rd Observatory Pre-Environmental Review (PER)									7/10 ◇ 3rd PER		
4th Observatory Pre-Environmental Review (PER)										10/10 ◇ 4th PER	
2nd Launch Pre-Ship Review (PSR)										3/11 ◇ 2nd PSR	
2nd Launch Flight Readiness Review											2nd FRR ◇ 10/11
2nd Launch Readiness Review (LRR)											2nd LRR ◇ 11/11

SXT Flight Mirror Assembly (FMA) Development

Technology Development & Flight Build

WBS 1.1 (Technology) & 5.0 (Flight)

Page B3

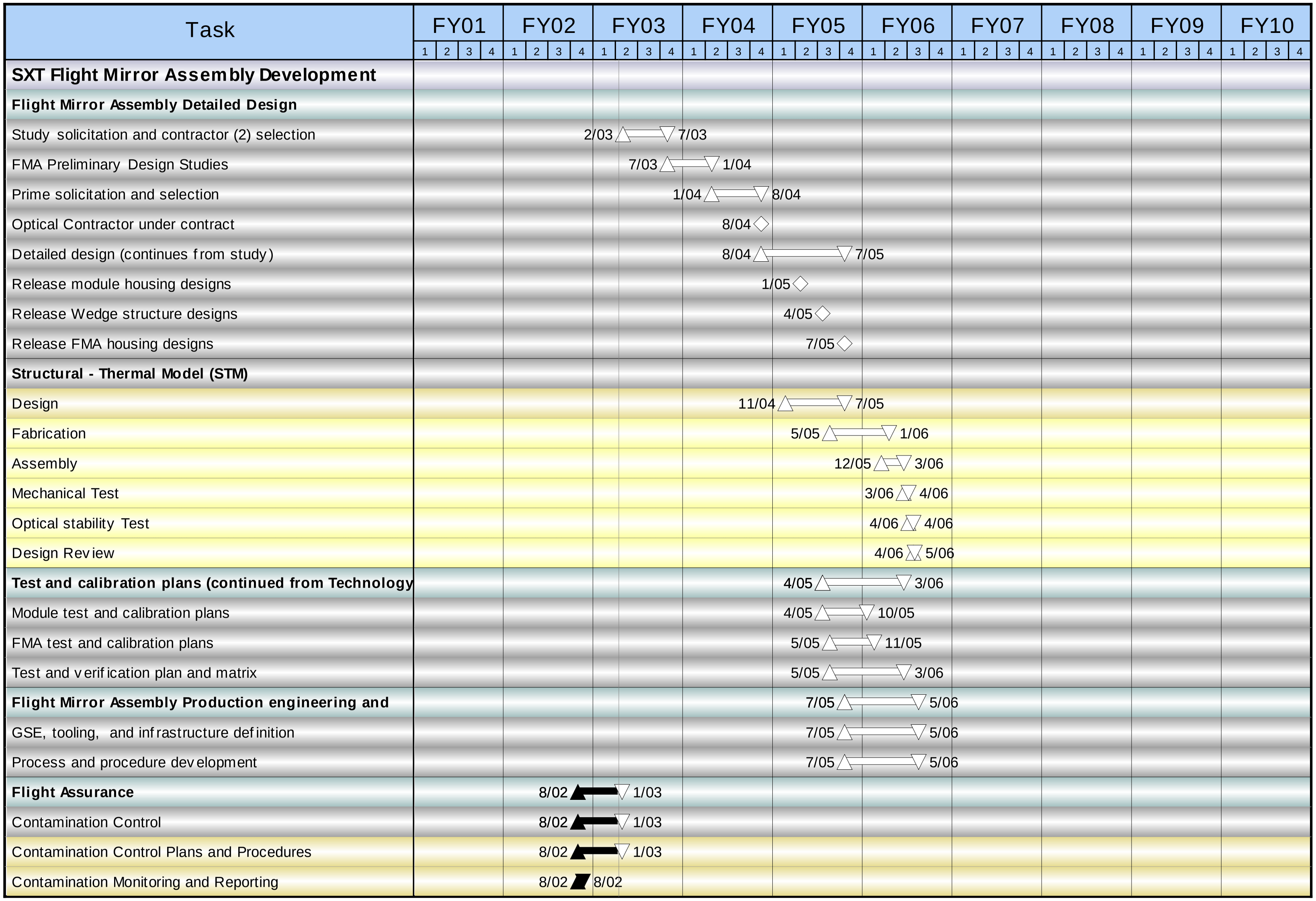


SXT FMA Flight Development

WBS 1.1 (Technology) & 5.0 (Flight)

Detail 1 of 9

Page B4



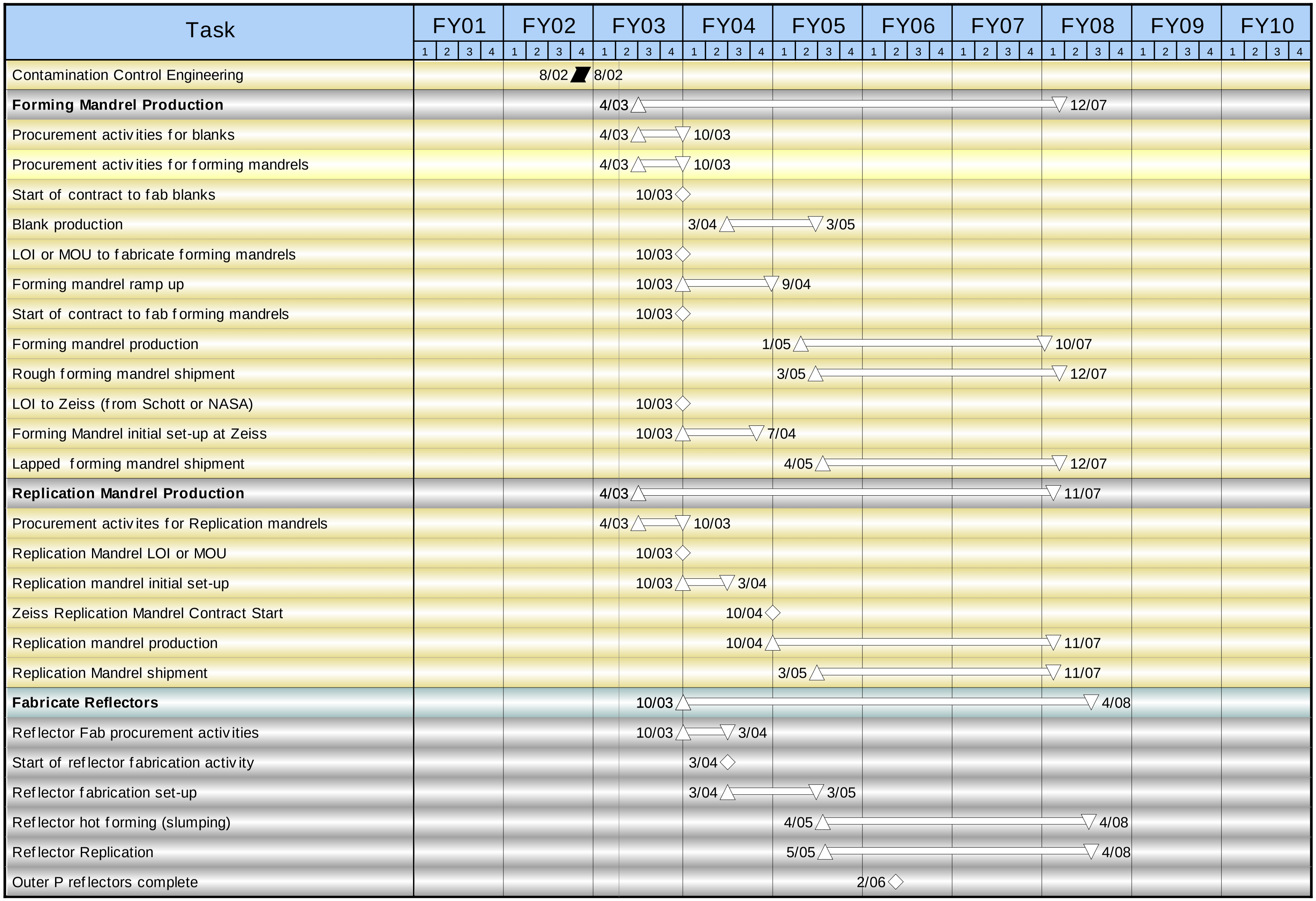
Appendix B - Supporting Detailed Schedules

SXT FMA Flight Development

WBS 1.1 (Technology) & 5.0 (Flight)

Page B5

Detail 2 of 9



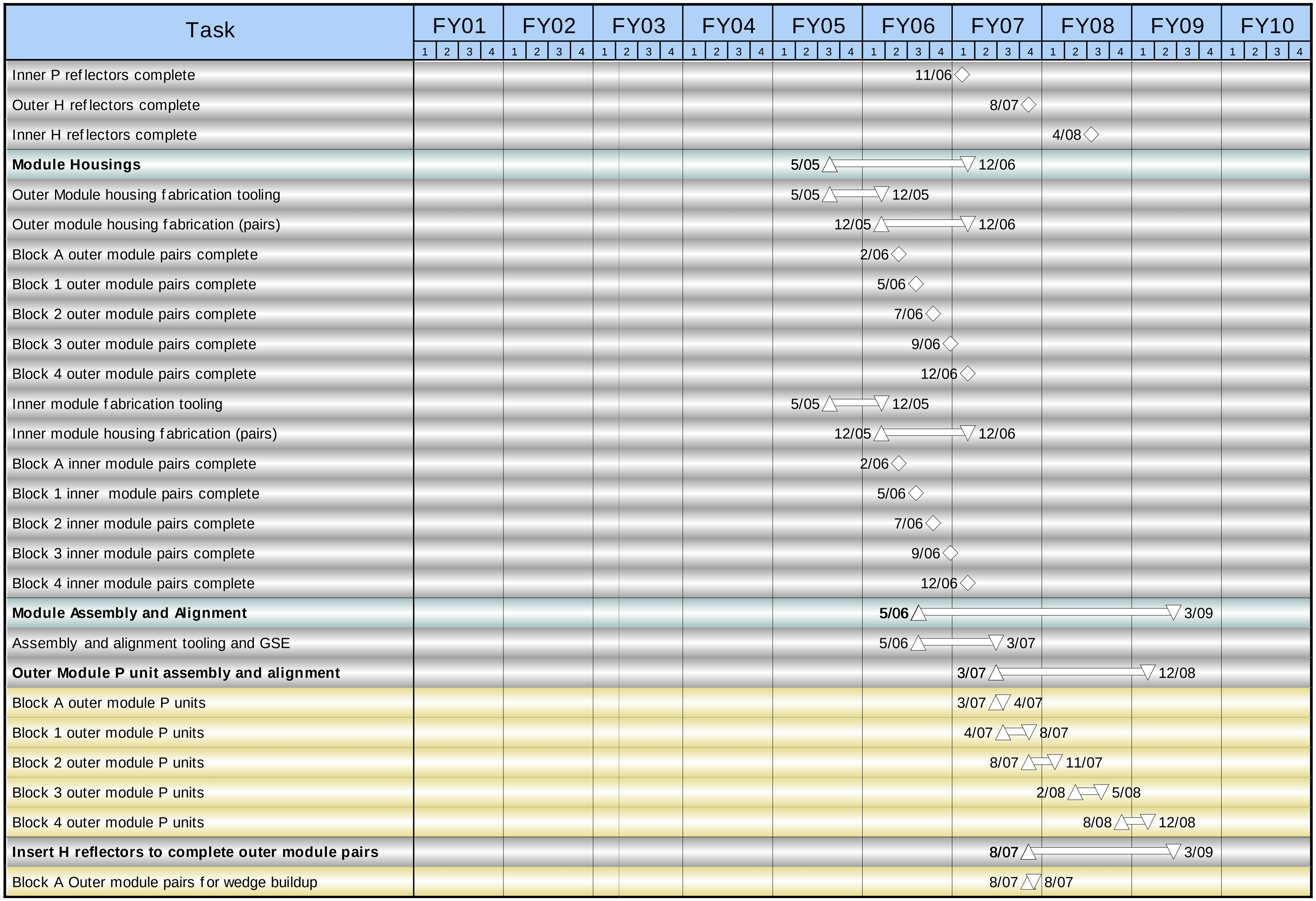
Contamination Control Engineering	8/02	8/02
Forming Mandrel Production	4/03	12/07
Procurement activities for blanks	4/03	10/03
Procurement activities for forming mandrels	4/03	10/03
Start of contract to fab blanks	10/03	
Blank production	3/04	3/05
LOI or MOU to fabricate forming mandrels	10/03	
Forming mandrel ramp up	10/03	9/04
Start of contract to fab forming mandrels	10/03	
Forming mandrel production	1/05	10/07
Rough forming mandrel shipment	3/05	12/07
LOI to Zeiss (from Schott or NASA)	10/03	
Forming Mandrel initial set-up at Zeiss	10/03	7/04
Lapped forming mandrel shipment	4/05	12/07
Replication Mandrel Production	4/03	11/07
Procurement activites for Replication mandrels	4/03	10/03
Replication Mandrel LOI or MOU	10/03	
Replication mandrel initial set-up	10/03	3/04
Zeiss Replication Mandrel Contract Start	10/04	
Replication mandrel production	10/04	11/07
Replication Mandrel shipment	3/05	11/07
Fabricate Reflectors	10/03	4/08
Reflector Fab procurement activities	10/03	3/04
Start of reflector fabrication activity	3/04	
Reflector fabrication set-up	3/04	3/05
Reflector hot forming (slumping)	4/05	4/08
Reflector Replication	5/05	4/08
Outer P reflectors complete	2/06	

SXT FMA Flight Development

WBS 1.1 (Technology) & 5.0 (Flight)

Page B6

Detail 3 of 9



Task	
Inner P reflectors complete	11/06
Outer H reflectors complete	8/07
Inner H reflectors complete	4/08
Module Housings	5/05 – 12/06
Outer Module housing fabrication tooling	5/05 – 12/05
Outer module housing fabrication (pairs)	12/05 – 12/06
Block A outer module pairs complete	2/06
Block 1 outer module pairs complete	5/06
Block 2 outer module pairs complete	7/06
Block 3 outer module pairs complete	9/06
Block 4 outer module pairs complete	12/06
Inner module fabrication tooling	5/05 – 12/05
Inner module housing fabrication (pairs)	12/05 – 12/06
Block A inner module pairs complete	2/06
Block 1 inner module pairs complete	5/06
Block 2 inner module pairs complete	7/06
Block 3 inner module pairs complete	9/06
Block 4 inner module pairs complete	12/06
Module Assembly and Alignment	**5/06** – 3/09
Assembly and alignment tooling and GSE	5/06 – 3/07
Outer Module P unit assembly and alignment	3/07 – 12/08
Block A outer module P units	3/07 – 4/07
Block 1 outer module P units	4/07 – 8/07
Block 2 outer module P units	8/07 – 11/07
Block 3 outer module P units	2/08 – 5/08
Block 4 outer module P units	8/08 – 12/08
Insert H reflectors to complete outer module pairs	**8/07** – 3/09
Block A Outer module pairs for wedge buildup	8/07 – 8/07

SXT FMA Flight Development

WBS 1.1 (Technology) & 5.0 (Flight)

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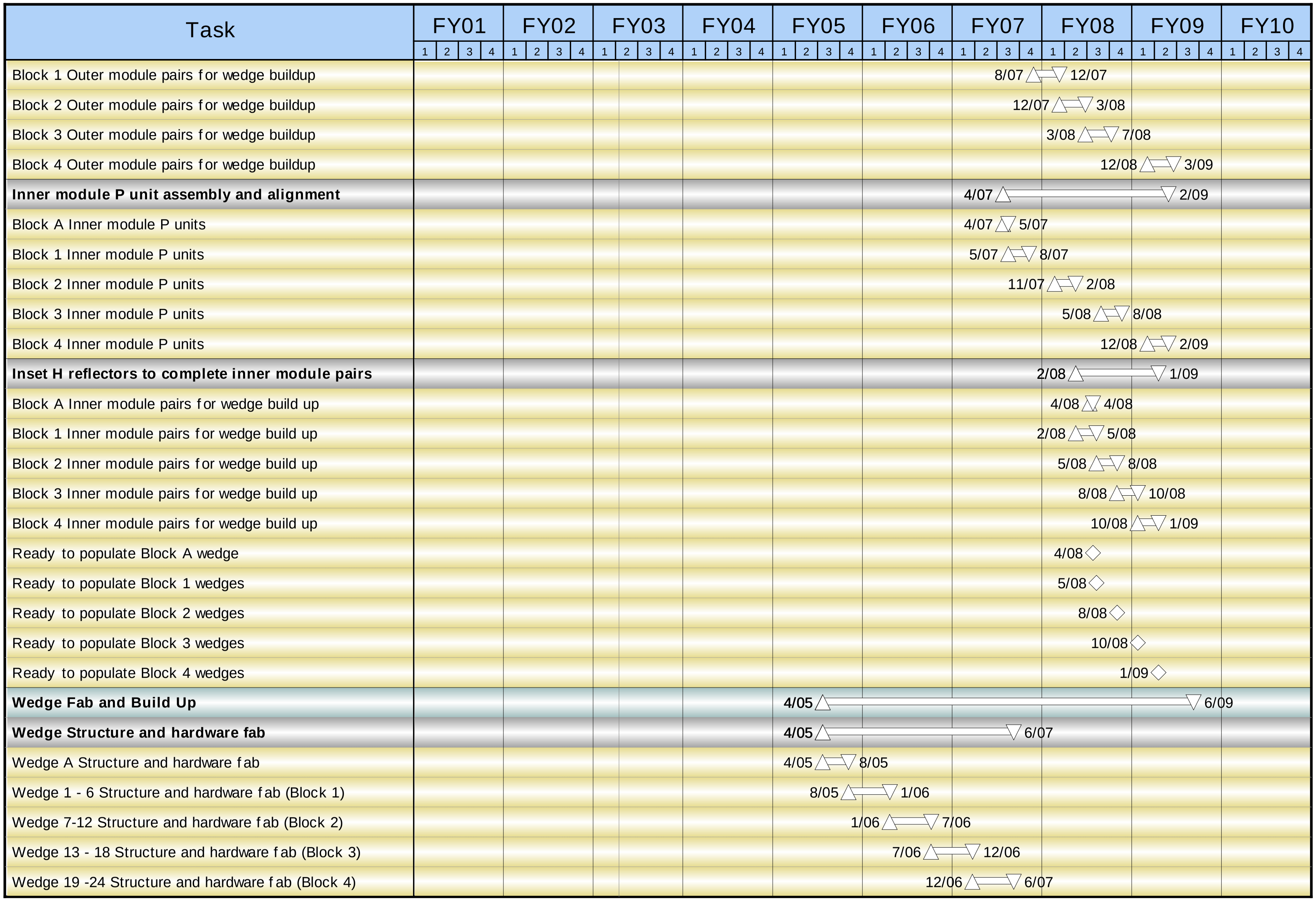
Detail 4 of 9

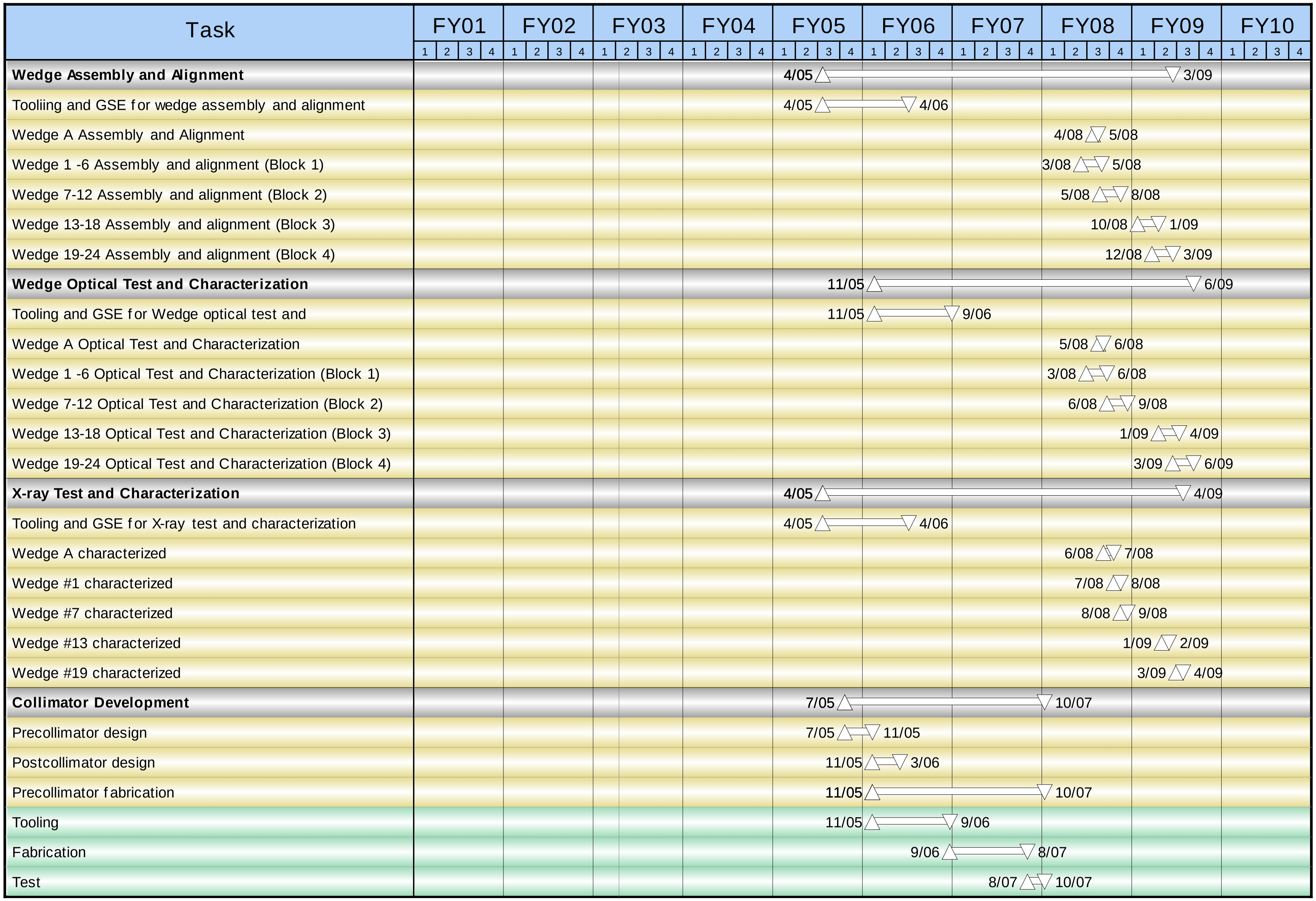


SXT FMA Flight Development

WBS 1.1 (Technology) & 5.0 (Flight)

Page B8

Detail 5 of 9



Appendix B - Supporting Detailed Schedules

SXT FMA Flight Development

WBS 1.1 (Technology) & 5.0 (Flight)

Detail 6 of 9

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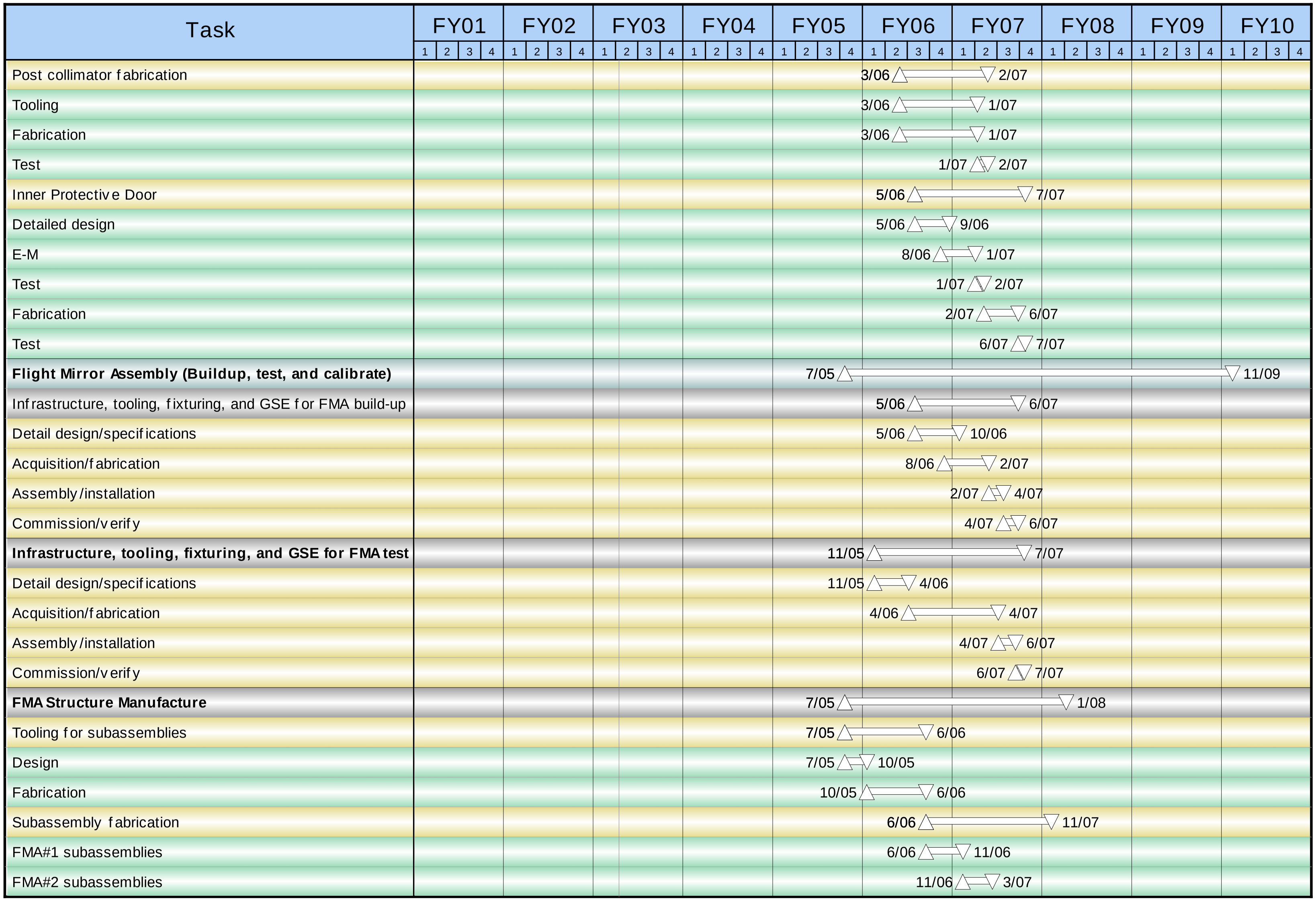
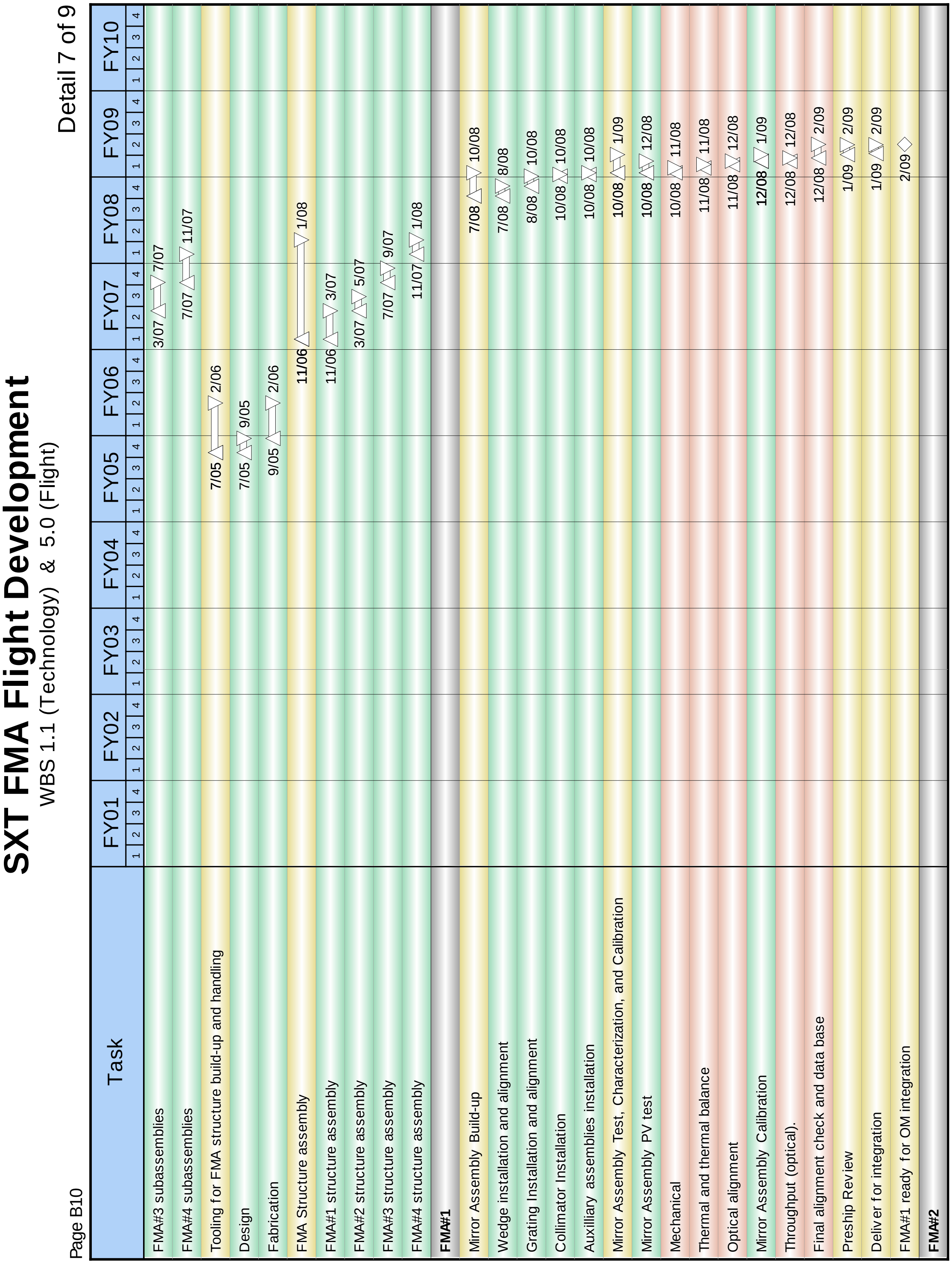


Appendix B - Supporting Detailed Schedules

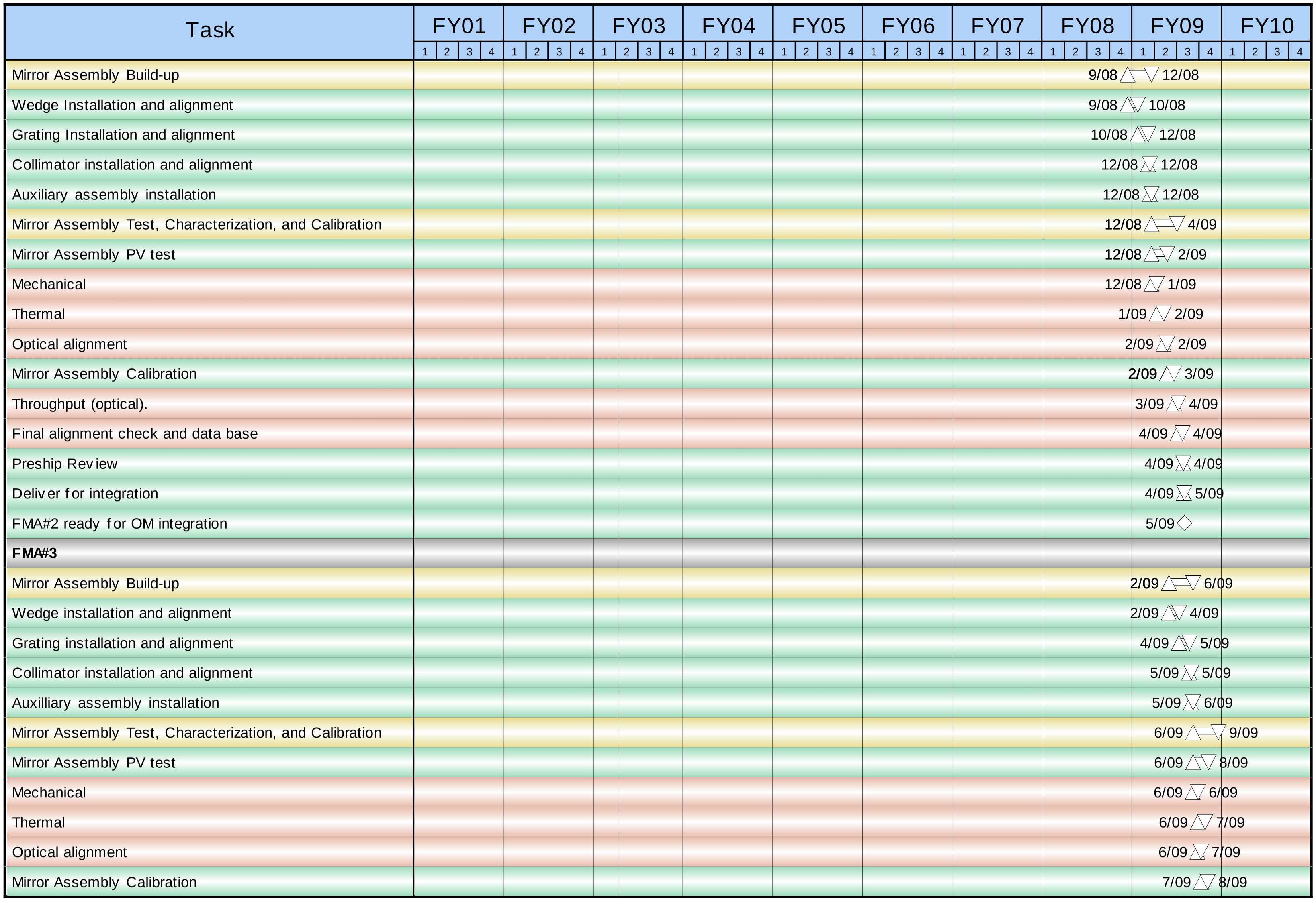


SXT FMA Flight Development

WBS 1.1 (Technology) & 5.0 (Flight)

Page B11

Detail 8 of 9



Task		
Mirror Assembly Build-up	9/08	12/08
Wedge Installation and alignment	9/08	10/08
Grating Installation and alignment	10/08	12/08
Collimator installation and alignment	12/08	12/08
Auxiliary assembly installation	12/08	12/08
Mirror Assembly Test, Characterization, and Calibration	12/08	4/09
Mirror Assembly PV test	12/08	2/09
Mechanical	12/08	1/09
Thermal	1/09	2/09
Optical alignment	2/09	2/09
Mirror Assembly Calibration	2/09	3/09
Throughput (optical).	3/09	4/09
Final alignment check and data base	4/09	4/09
Preship Review	4/09	4/09
Deliver for integration	4/09	5/09
FMA#2 ready for OM integration	5/09	
FMA#3		
Mirror Assembly Build-up	2/09	6/09
Wedge installation and alignment	2/09	4/09
Grating installation and alignment	4/09	5/09
Collimator installation and alignment	5/09	5/09
Auxilliary assembly installation	5/09	6/09
Mirror Assembly Test, Characterization, and Calibration	6/09	9/09
Mirror Assembly PV test	6/09	8/09
Mechanical	6/09	6/09
Thermal	6/09	7/09
Optical alignment	6/09	7/09
Mirror Assembly Calibration	7/09	8/09

SXT FMA Flight Development

WBS 1.1 (Technology) & 5.0 (Flight)

Page B12

Detail 9 of 9

Task		
Throughput (optical)	7/09	7/09
Final alignment check and data base	7/09	8/09
Preship Review	8/09	8/09
Deliver for integration	8/09	8/09
FMA#3 ready for OM integration	8/09	
FMA#4		
Mirror Assembly Build-up	4/09	8/09
Wedge Installation and alignment	4/09	6/09
Grating Installation and alignment	6/09	7/09
Collimator installation and alignment	7/09	7/09
Auxiliary assembly installation	7/09	8/09
Mirror Assembly Test and Calibration	8/09	11/09
Mirror Assembly PV test	8/09	10/09
Mechanical	8/09	8/09
Thermal	8/09	9/09
Optical alignment	9/09	10/09
Mirror Assembly Calibration	10/09	11/09
Throughput (optical)	10/09	10/09
Final alignment check and data base	10/09	11/09
Preship Review	11/09	11/09
Deliver for integration	11/09	11/09
FMA#4 ready for OM integration	11/09	

RGS Grating Array (RGA) Technology & Flight Development

WBS 1.3 (Technology) & 6.2 (Flight)

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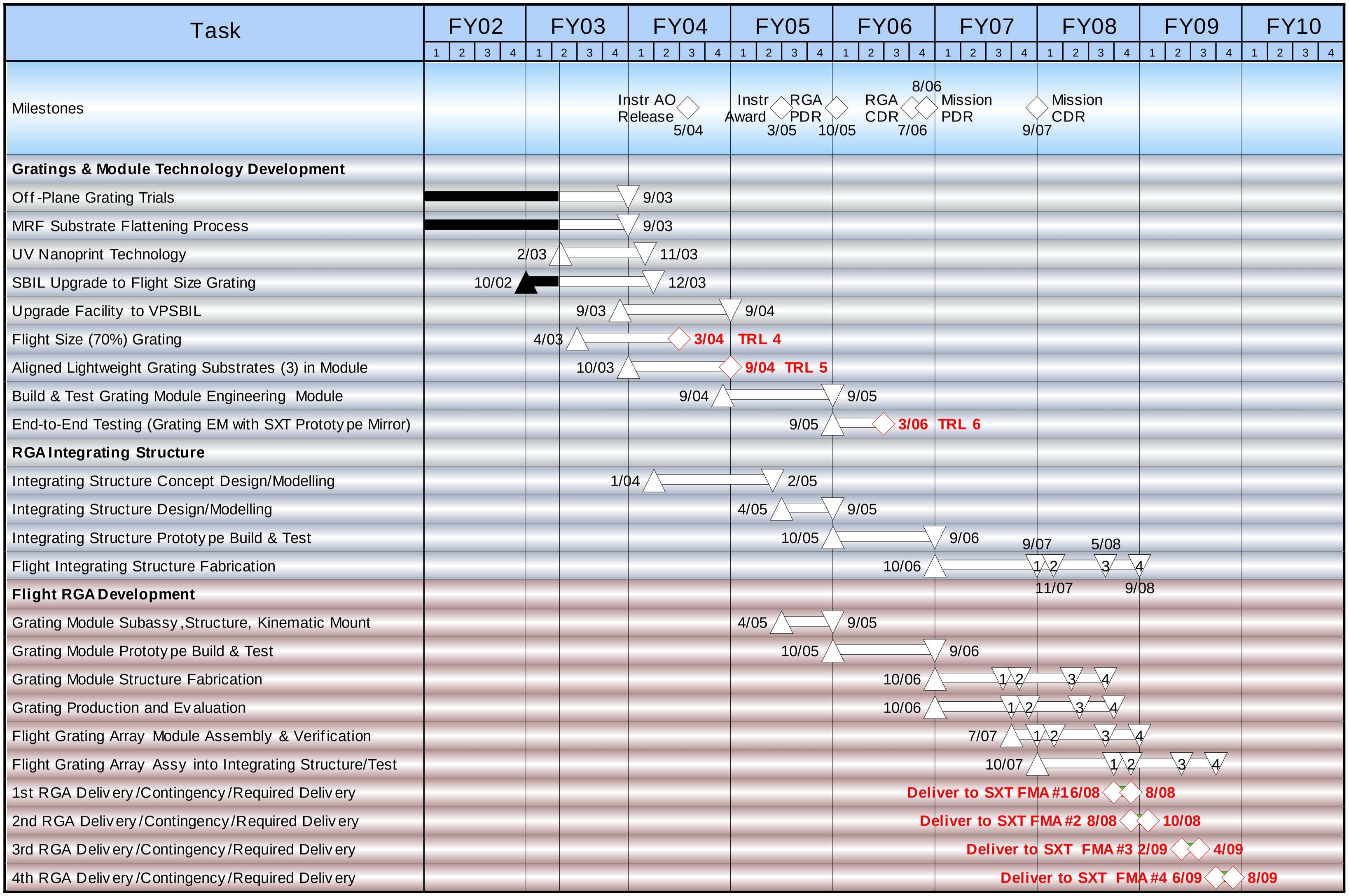

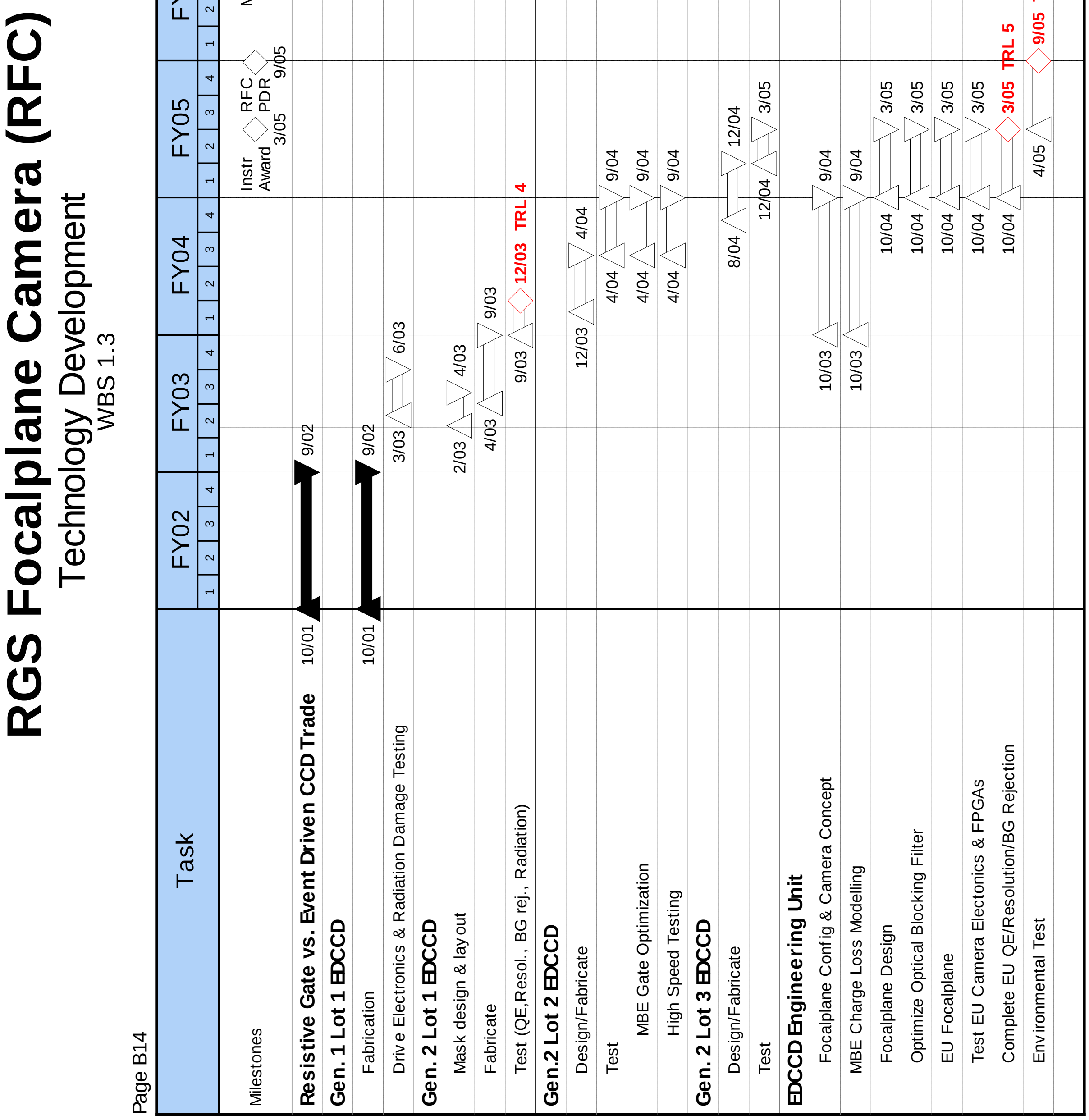
RGS Focalplane Camera (RFC)
Technology Development
WBS 1.3
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Task
FY02
FY03
FY04
FY05
FY06
FY07
FY08
1 2 3 4
Milestones
Instr Award 3/05
RFC PDR 9/05
Mission PDR 8/06
RFC CDR 9/06
Mission CDR 9/07
Resistive Gate vs. Event Driven CCD Trade 10/01 9/02
Gen. 1 Lot 1 EDCCD
Fabrication 10/01 9/02
Drive Electronics & Radiation Damage Testing 3/03 6/03
Gen. 2 Lot 1 EDCCD
Mask design & layout 2/03 4/03
Fabricate 4/03 9/03
Test (QE,Resol., BG rej., Radiation) 9/03 12/03 TRL 4
Gen.2 Lot 2 EDCCD
Design/Fabricate 12/03 4/04
Test 4/04 9/04
MBE Gate Optimization 4/04 9/04
High Speed Testing 4/04 9/04
Gen. 2 Lot 3 EDCCD
Design/Fabricate 8/04 12/04
Test 12/04 3/05
EDCCD Engineering Unit
Focalplane Config & Camera Concept 10/03 9/04
MBE Charge Loss Modelling 10/03 9/04
Focalplane Design 10/04 3/05
Optimize Optical Blocking Filter 10/04 3/05
EU Focalplane 10/04 3/05
Test EU Camera Electonics & FPGAs 10/04 3/05
Complete EU QE/Resolution/BG Rejection 10/04 3/05 TRL 5
Environmental Test 4/05 9/05 TRL 6

RGS Focalplane Camera (RFC)

Flight Development

WBS 6.2

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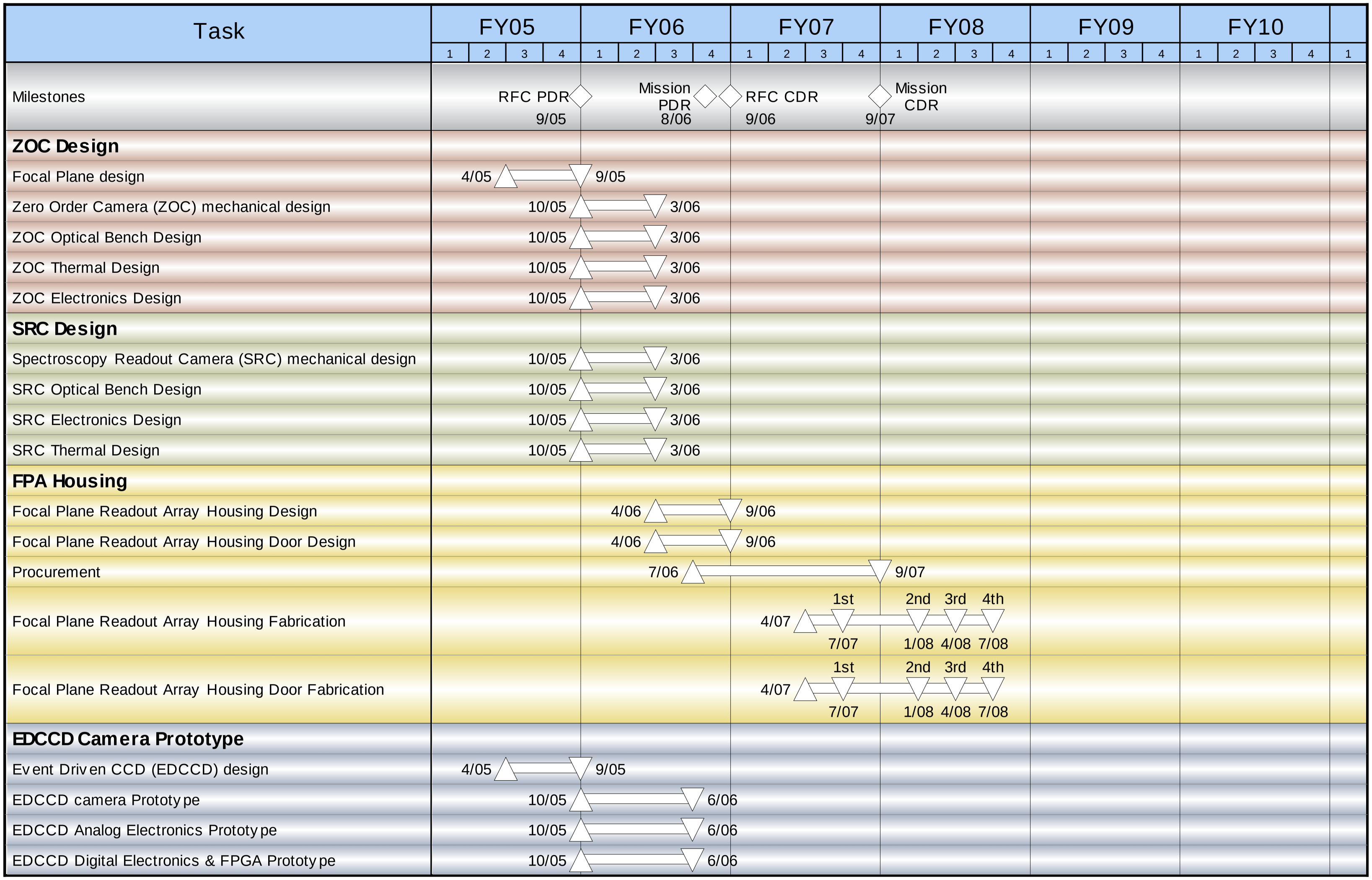
Detail 1 of 2



Appendix B - Supporting Detailed Schedules

RGS Focalplane Camera (RFC)

Flight Development

WBS 6.2

Detail 2 of 2

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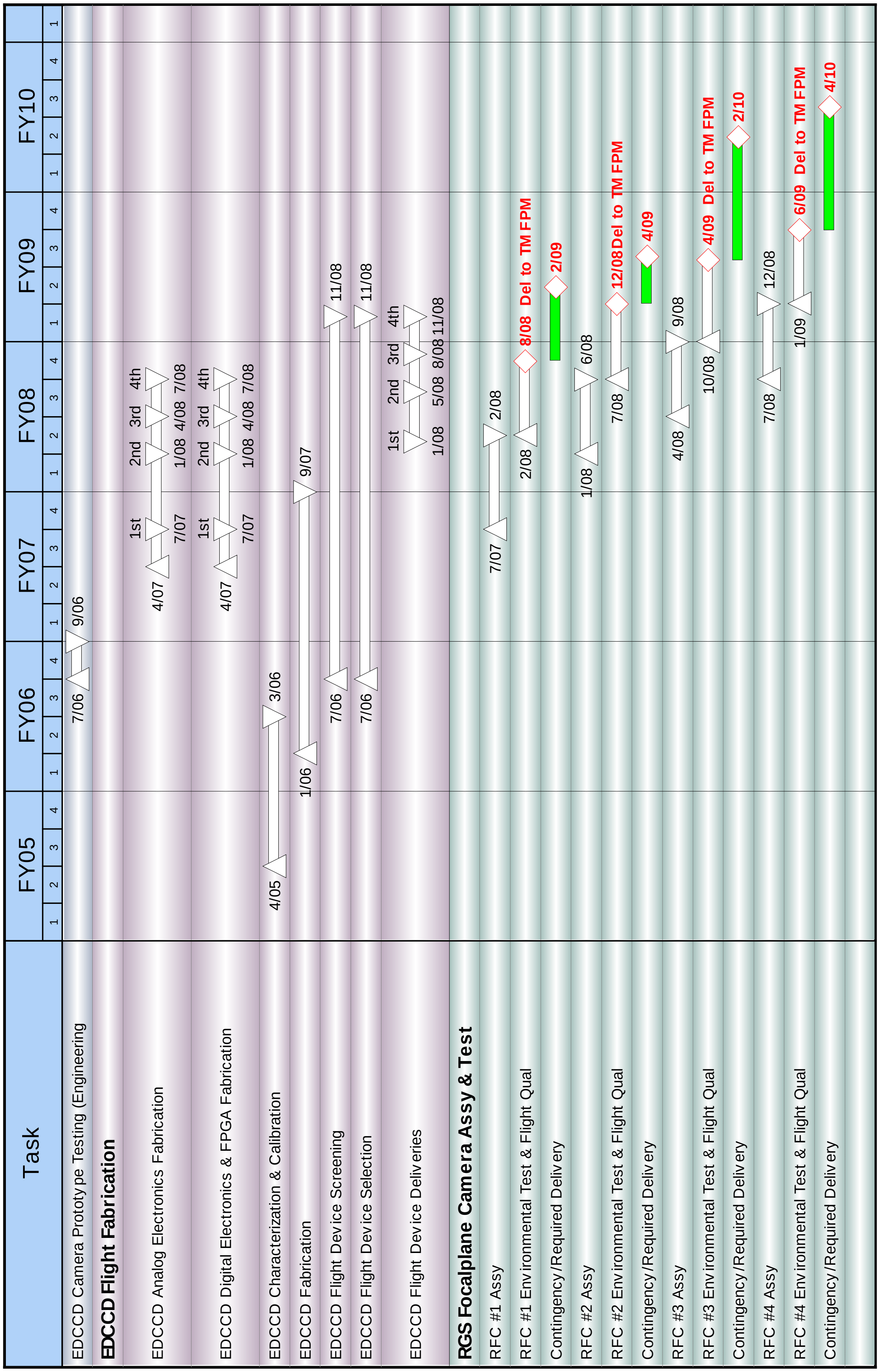
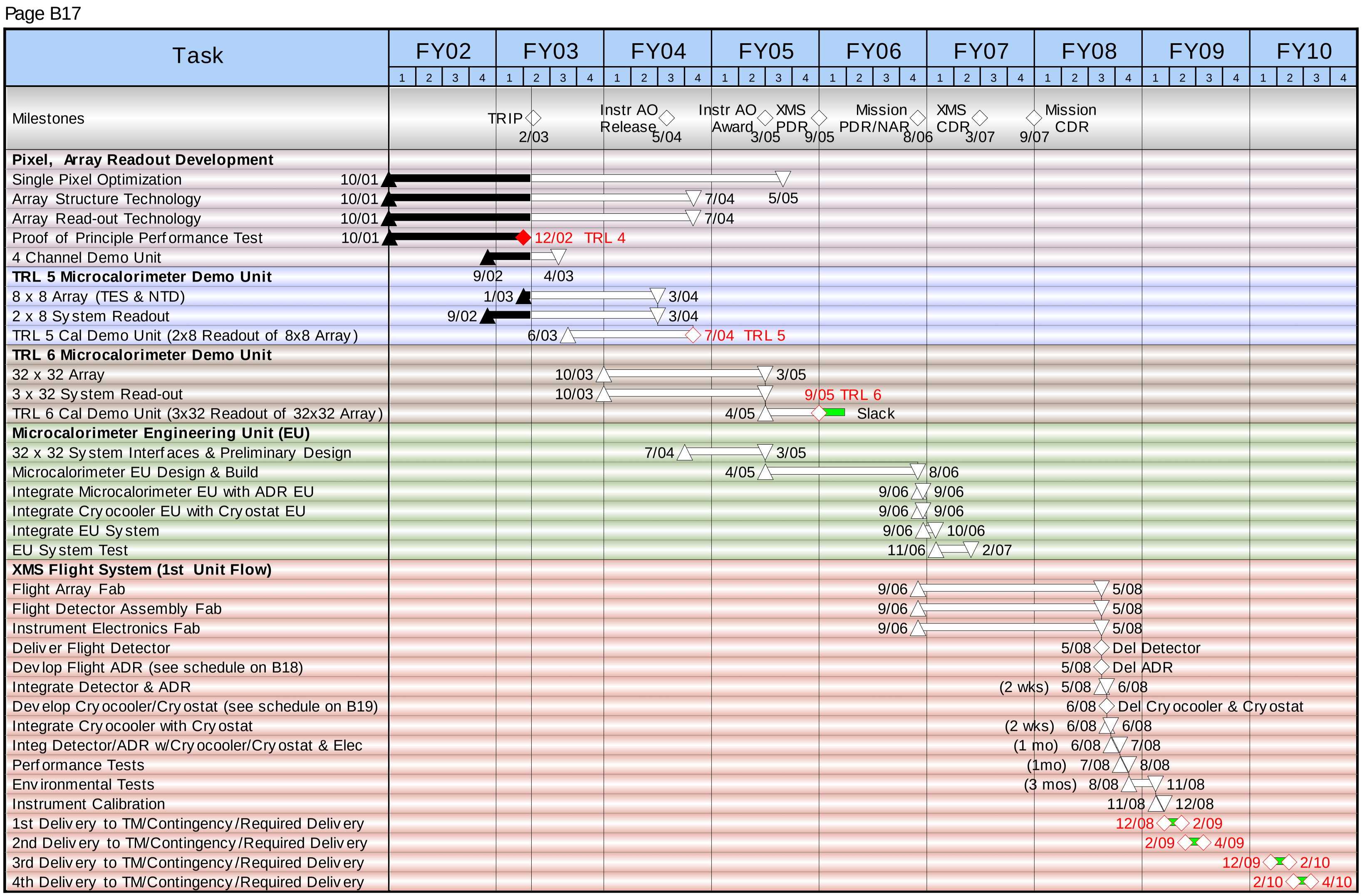


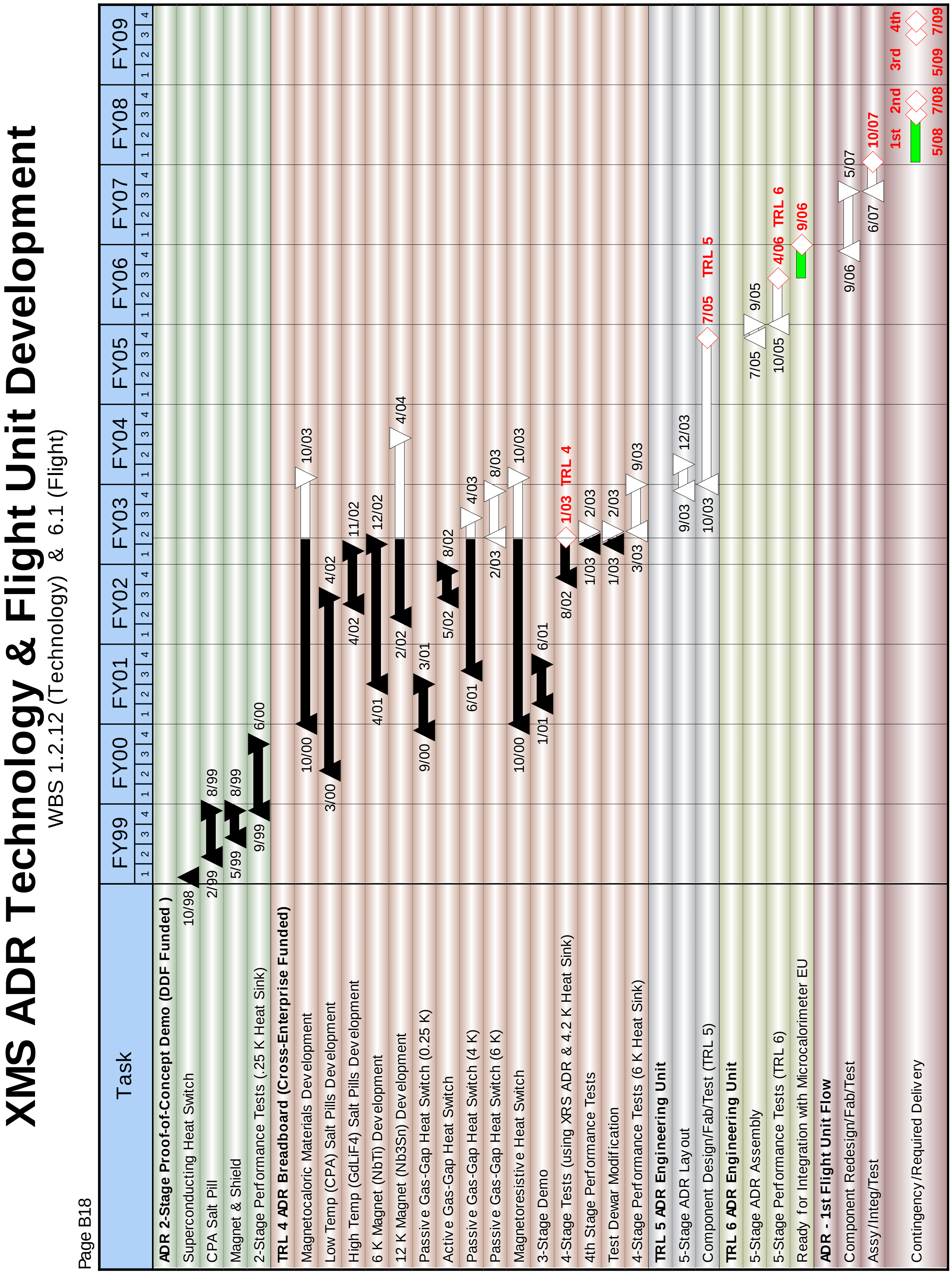
XMS X-Ray Microcalorimeter

Technology & Flight Instrument Development

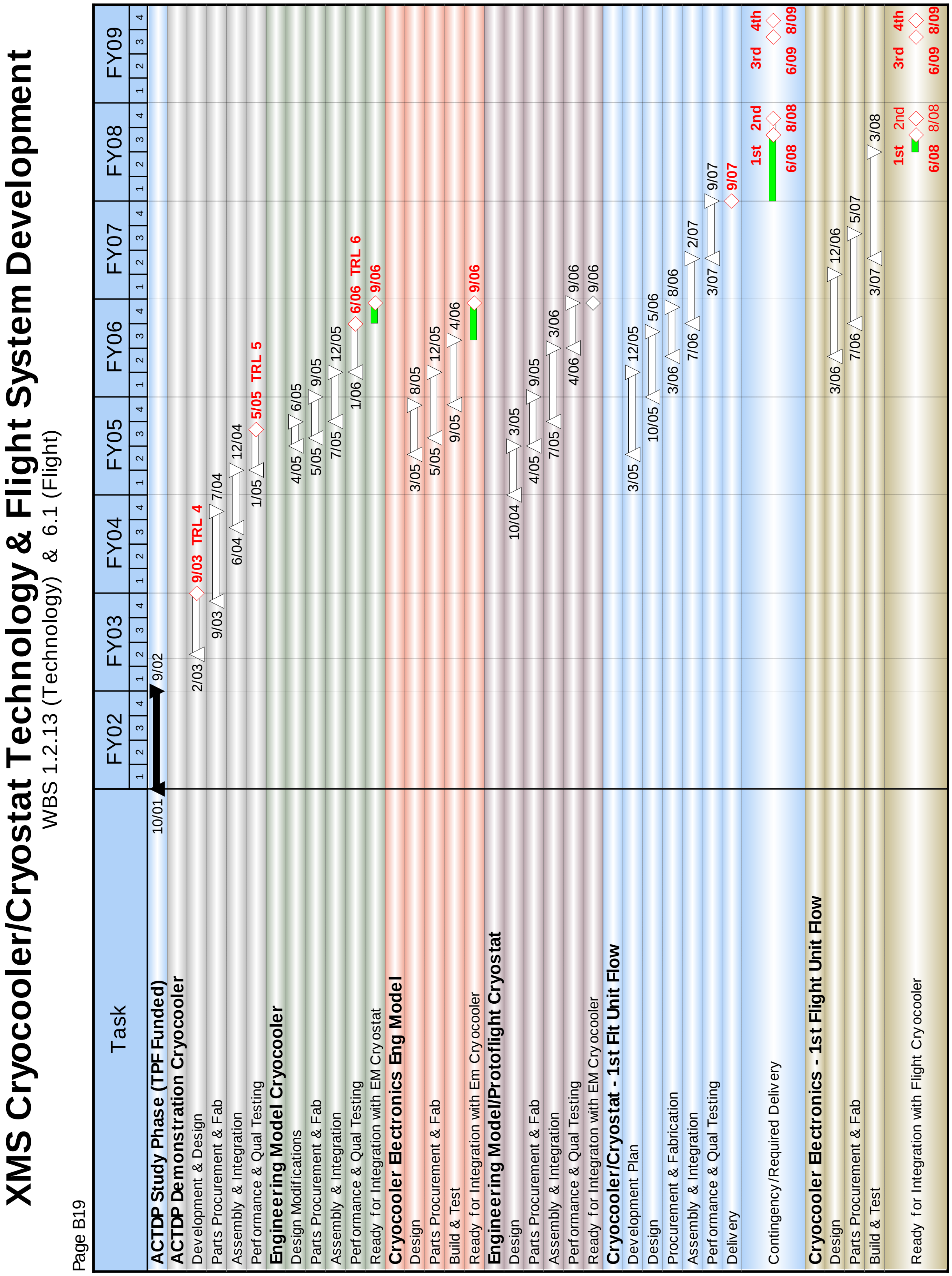
WBS 1.2 (Technology) & 6.1 (Flight)



Appendix B - Supporting Detailed Schedules



Appendix B - Supporting Detailed Schedules



HXT Technology Development

WBS 1.4 (Technology) & 6.3 (Flight)

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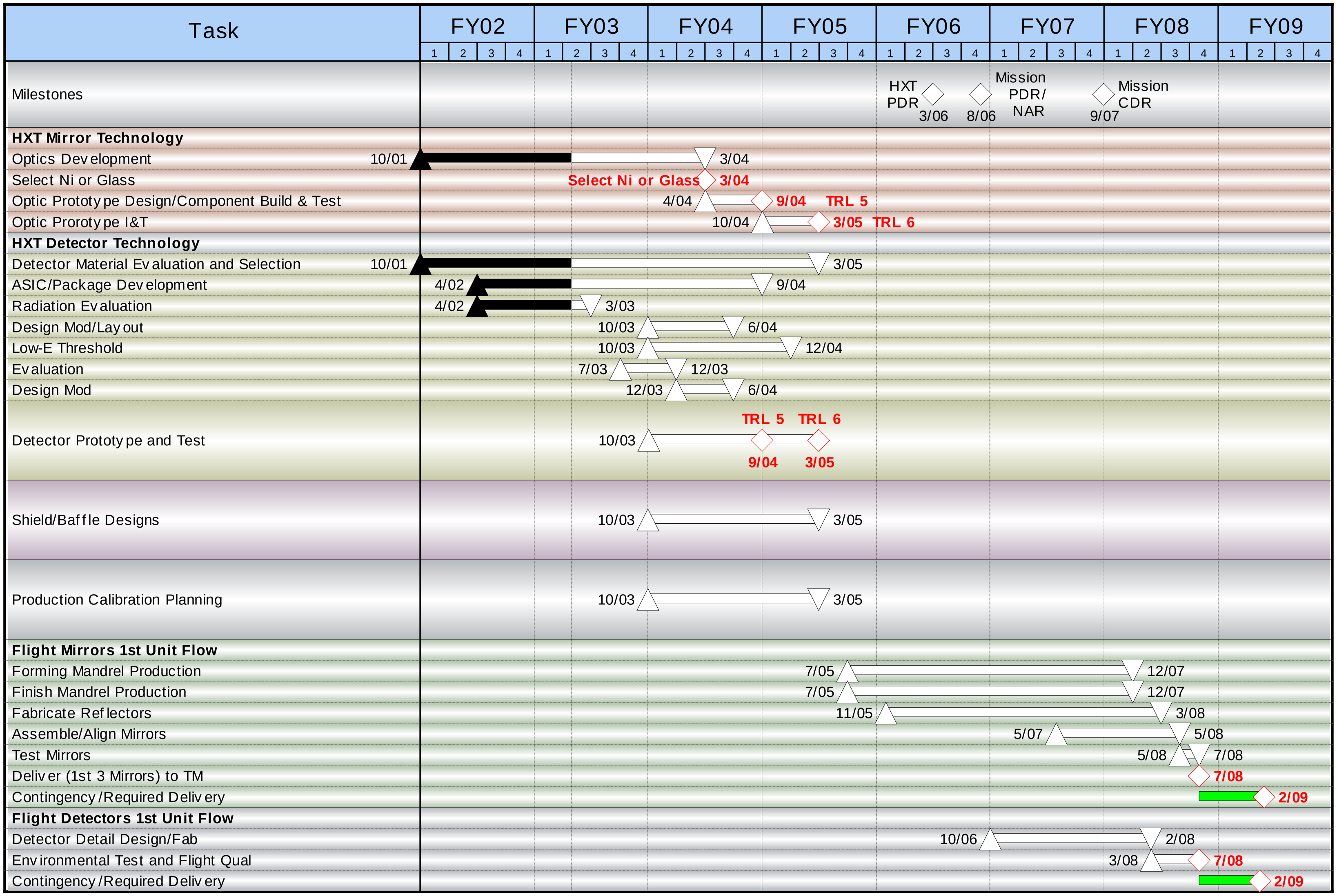

Appendix B - Supporting Detailed Schedules

HXT Mirror Flight Development

WBS 6.3

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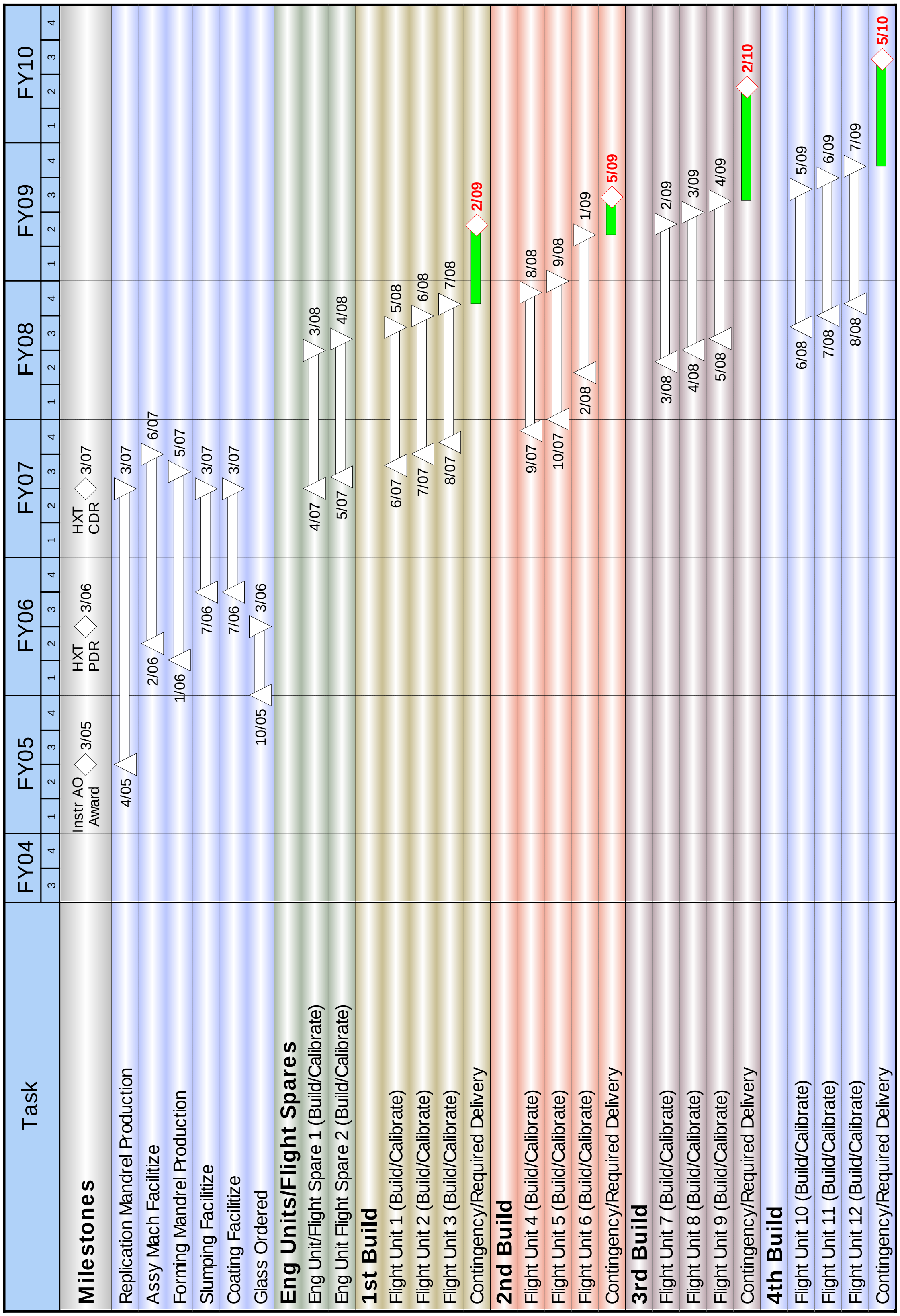

HXT Detector Flight Development

WBS 6.3

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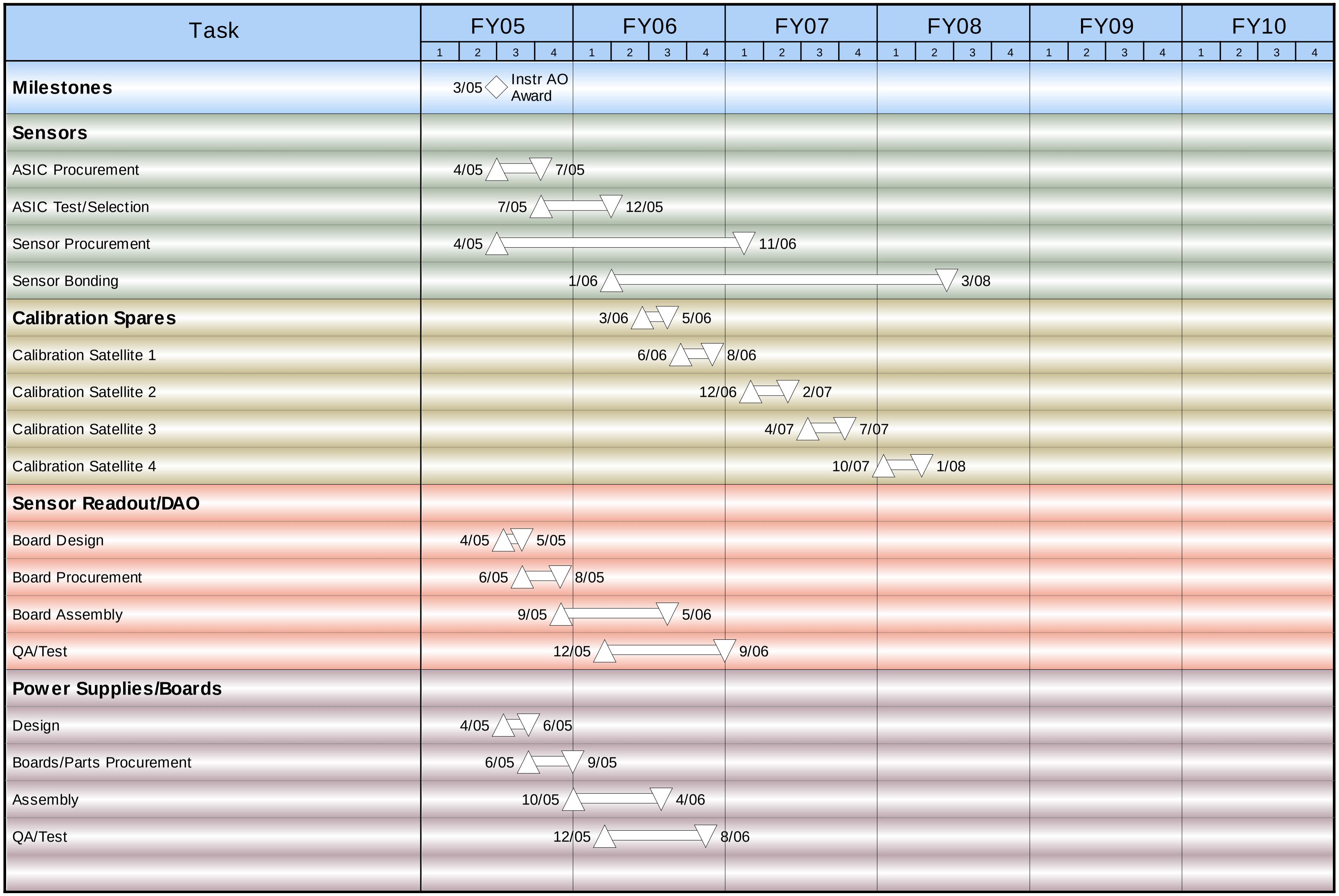
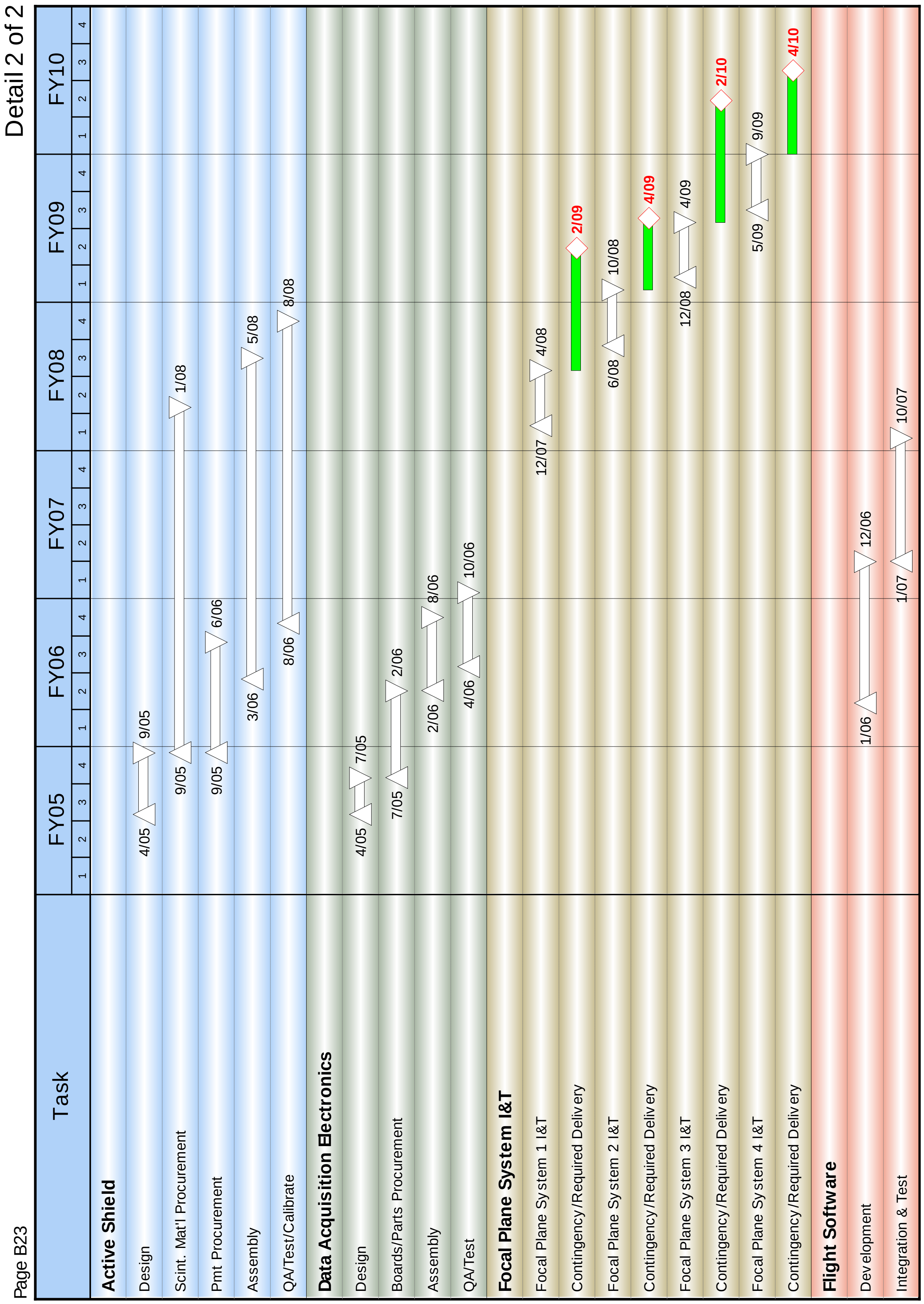
Detail 1 of 2



HXT Detector Flight Development

WBS 6.3



Appendix B - Supporting Detailed Schedules

Observatory Structures

WBS 7.2 & 7.3

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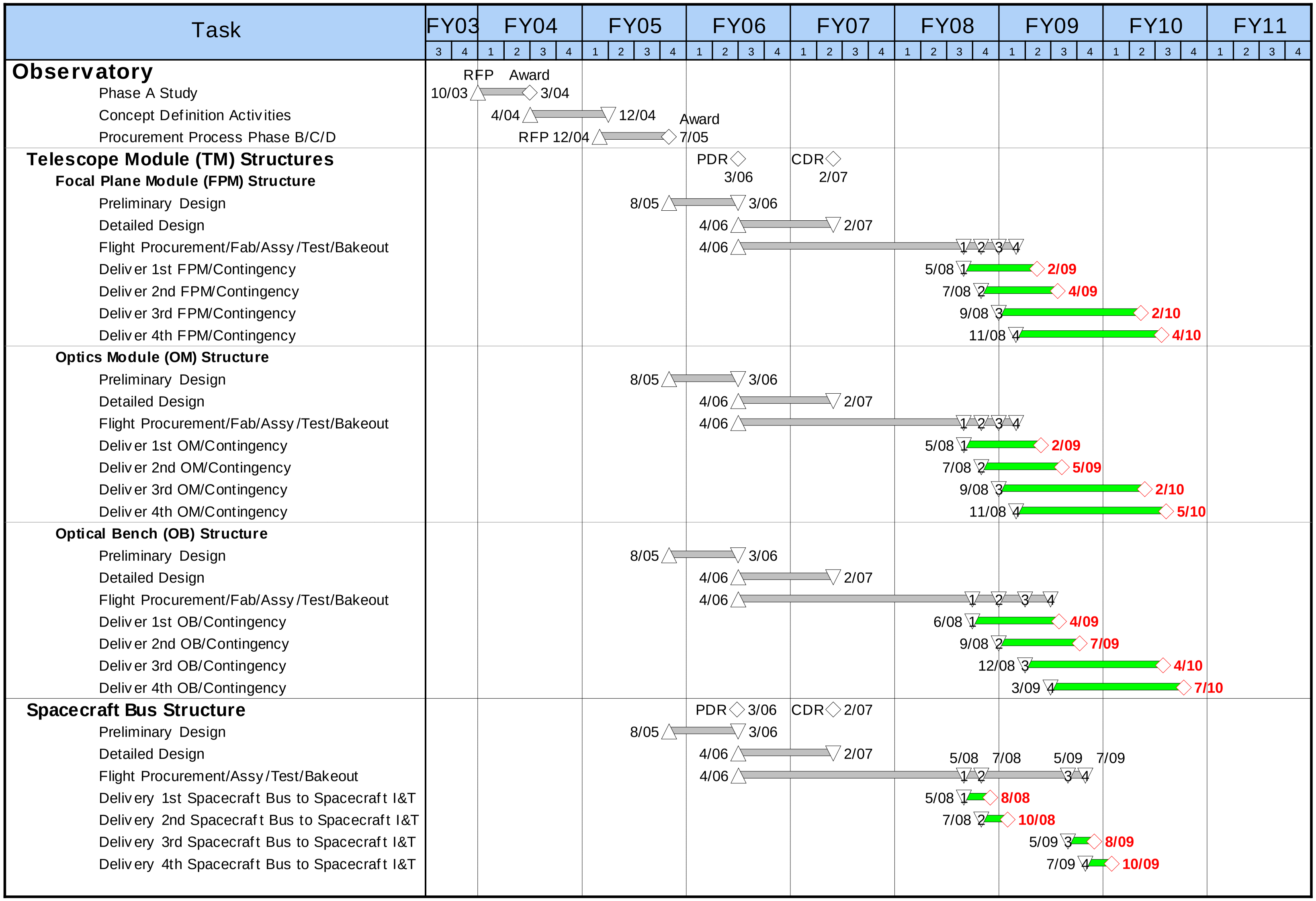

Spacecraft Bus Development Schedule

WBS 7.3

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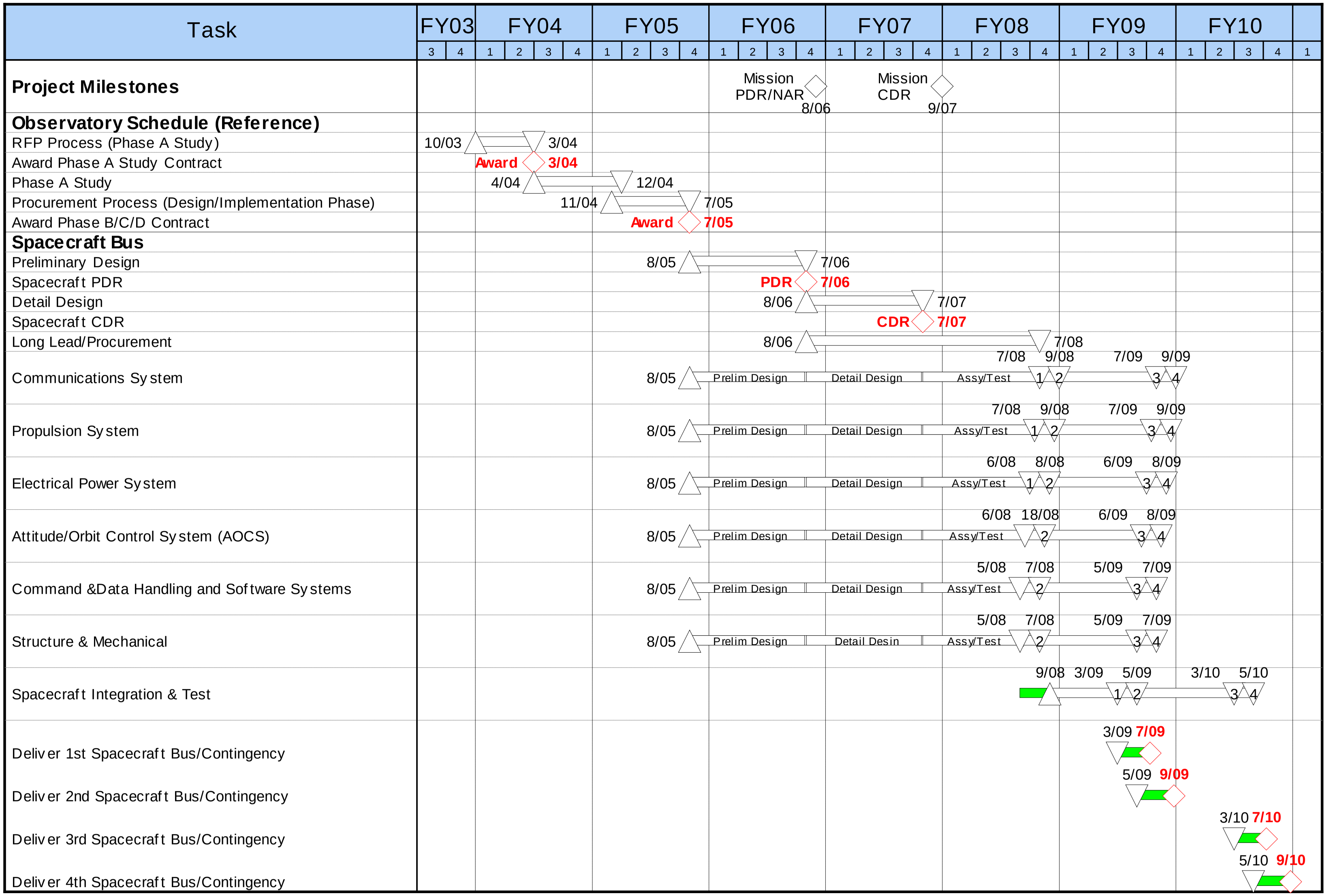
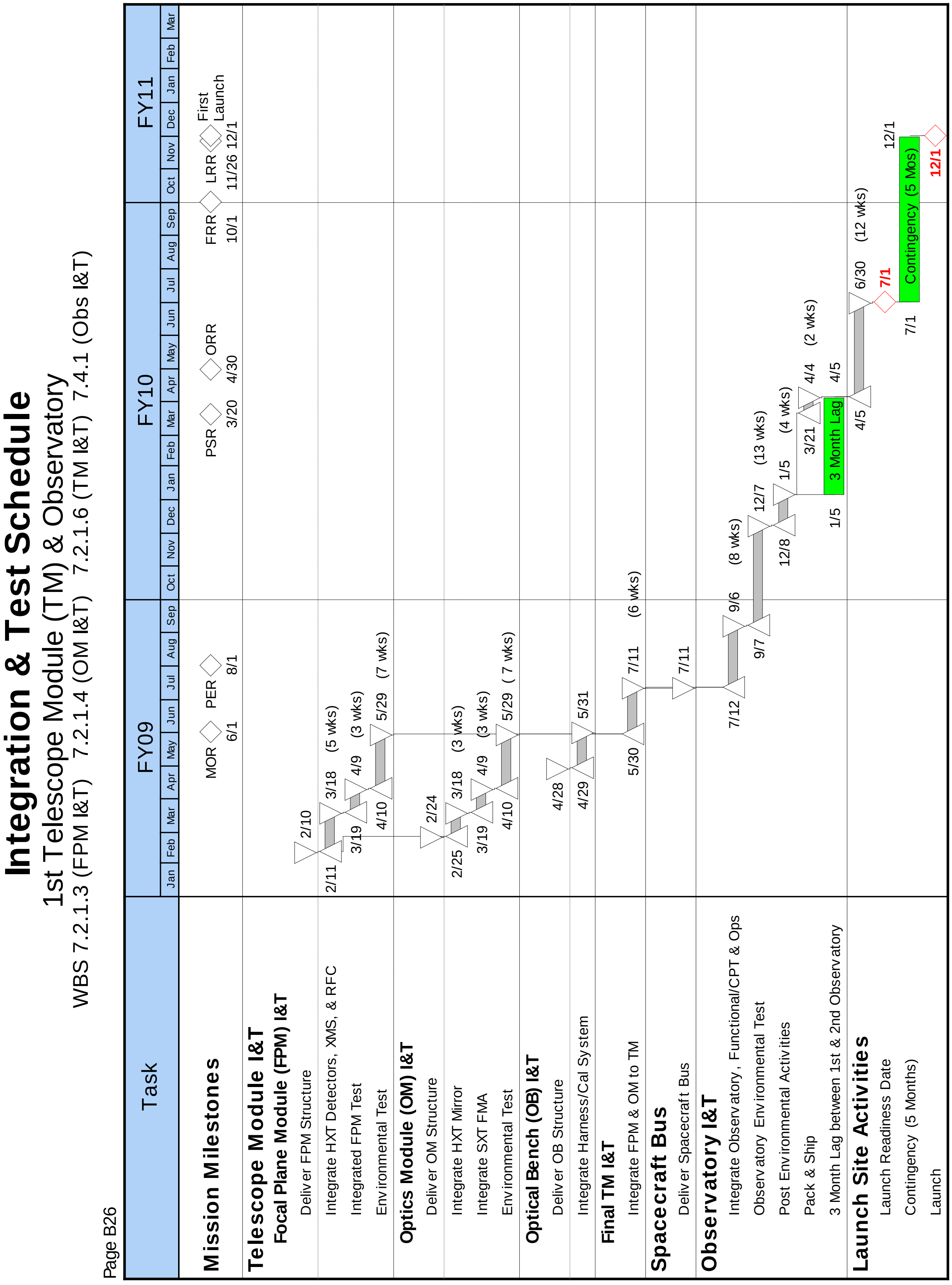


Appendix B - Supporting Detailed Schedules



Integration & Test Schedule

2nd Telescope Module (TM) & Observatory

WBS 7.2.2.3 (FPM I&T)   7.2.2.4 (OM I&T)   7.2.2.6 (TM I&T) 7.4.2 (Obs I&T)

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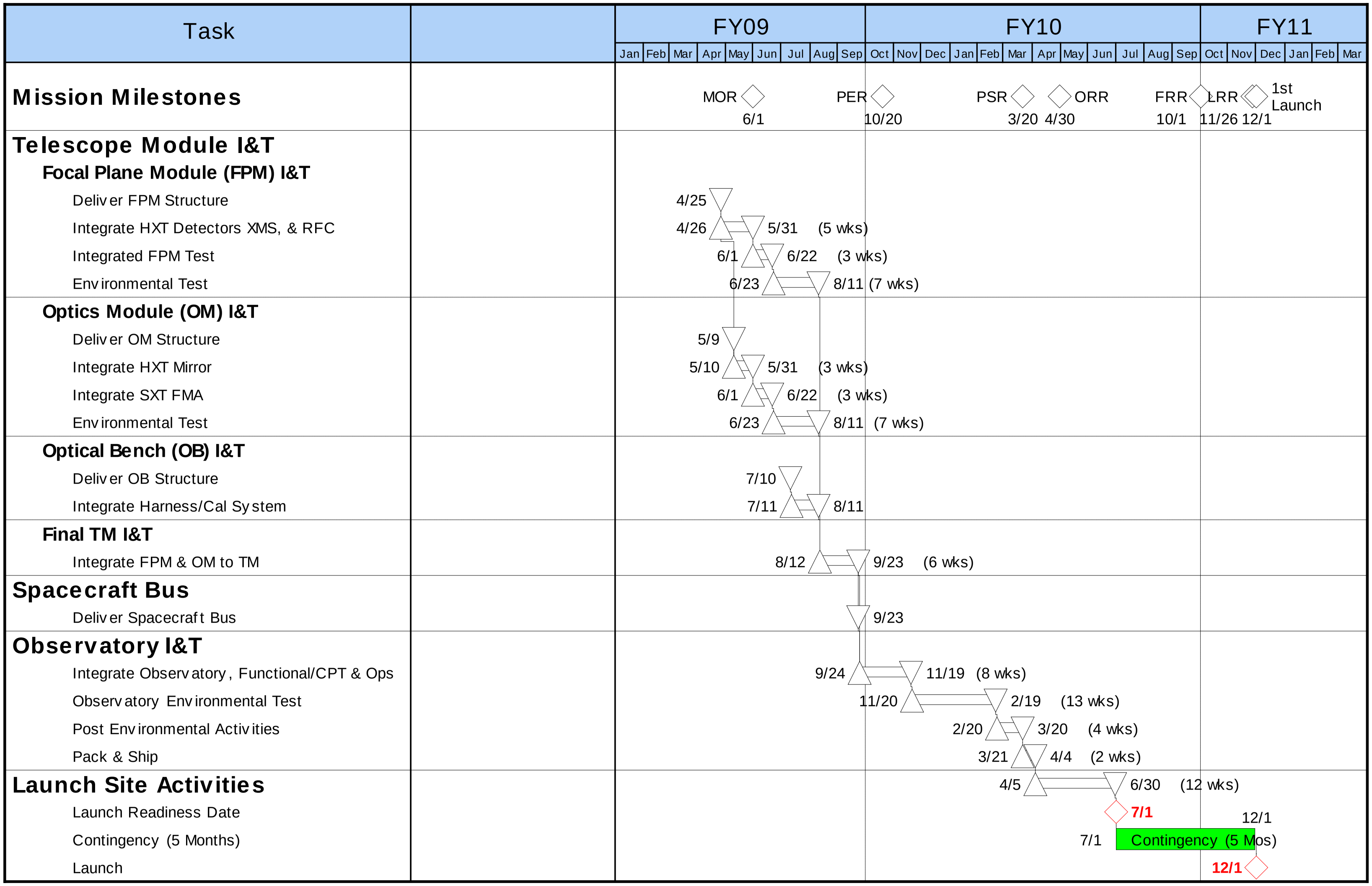

Launch Site Activites

1st Launch

WBS 8.1

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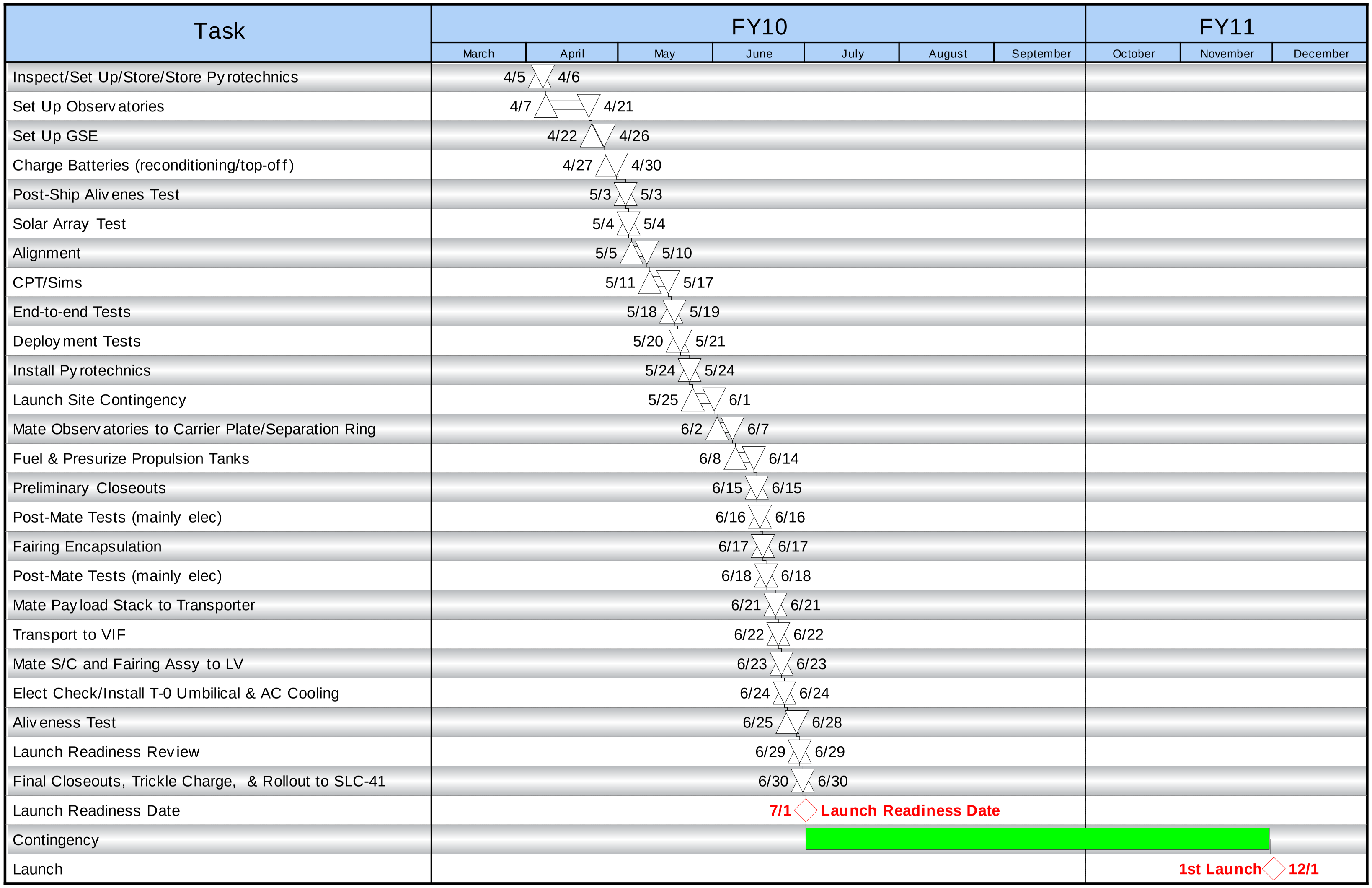

Appendix B - Supporting Detailed Schedules

Integration & Test Schedule

3rd Telescope Module (TM) & Observatory

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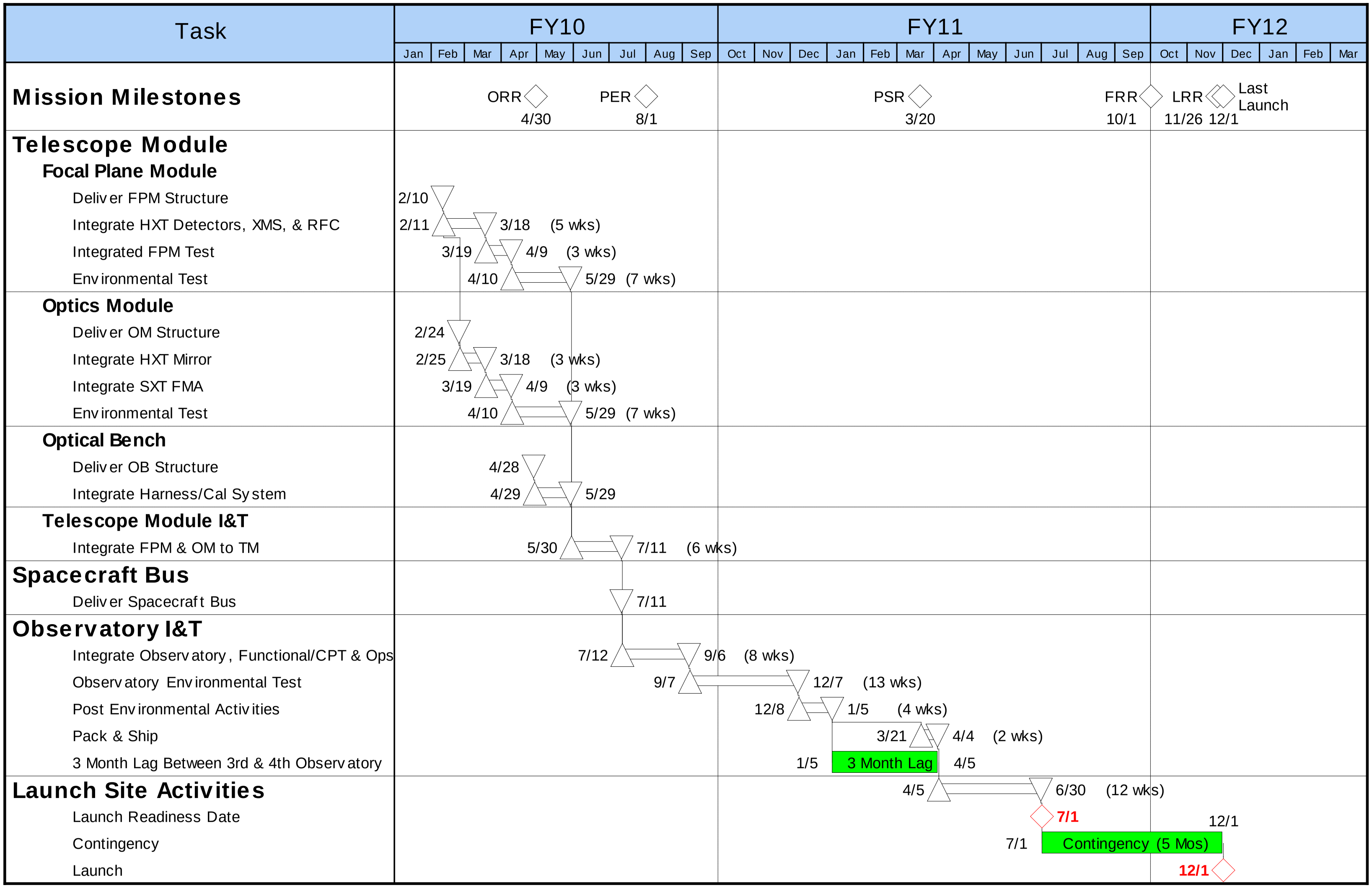
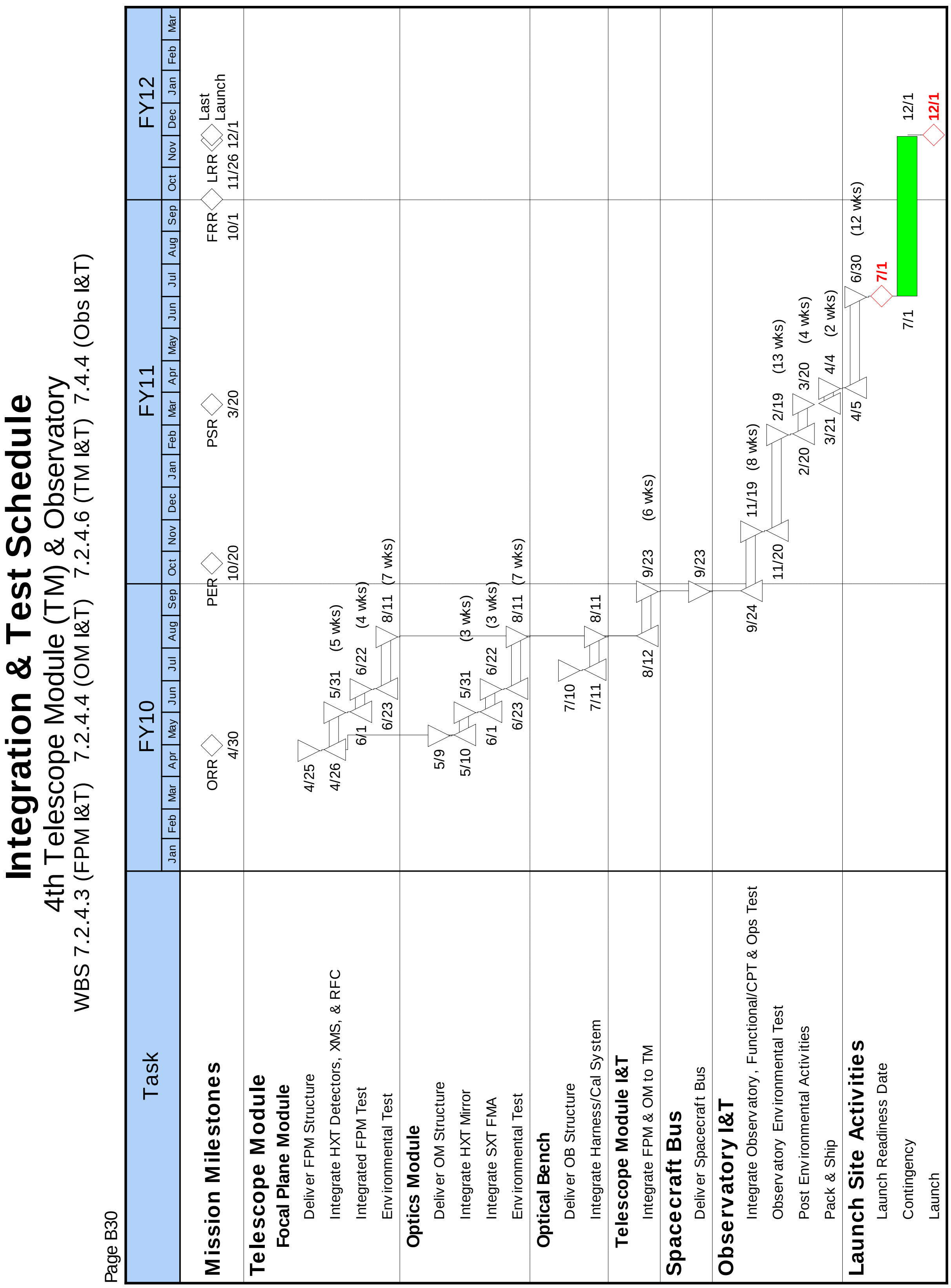


Appendix B - Supporting Detailed Schedules



Integration & Test Schedule

4th Telescope Module (TM) & Observatory

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Launch Site Activites

2nd Launch

WBS 8.2

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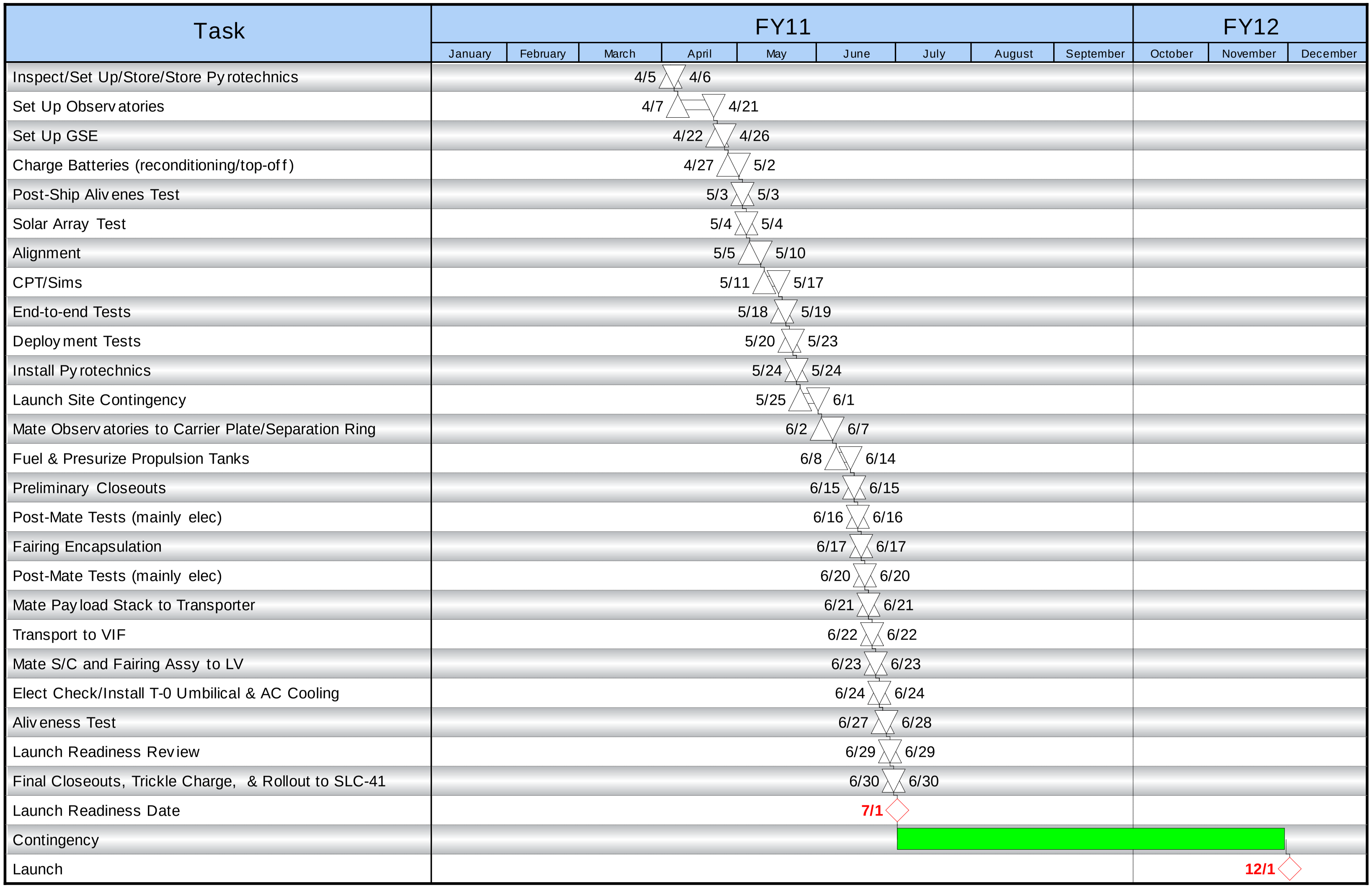

Appendix B - Supporting Detailed Schedules

Mission Operations & Data Analysis

WBS 10

Detail 1 of 7

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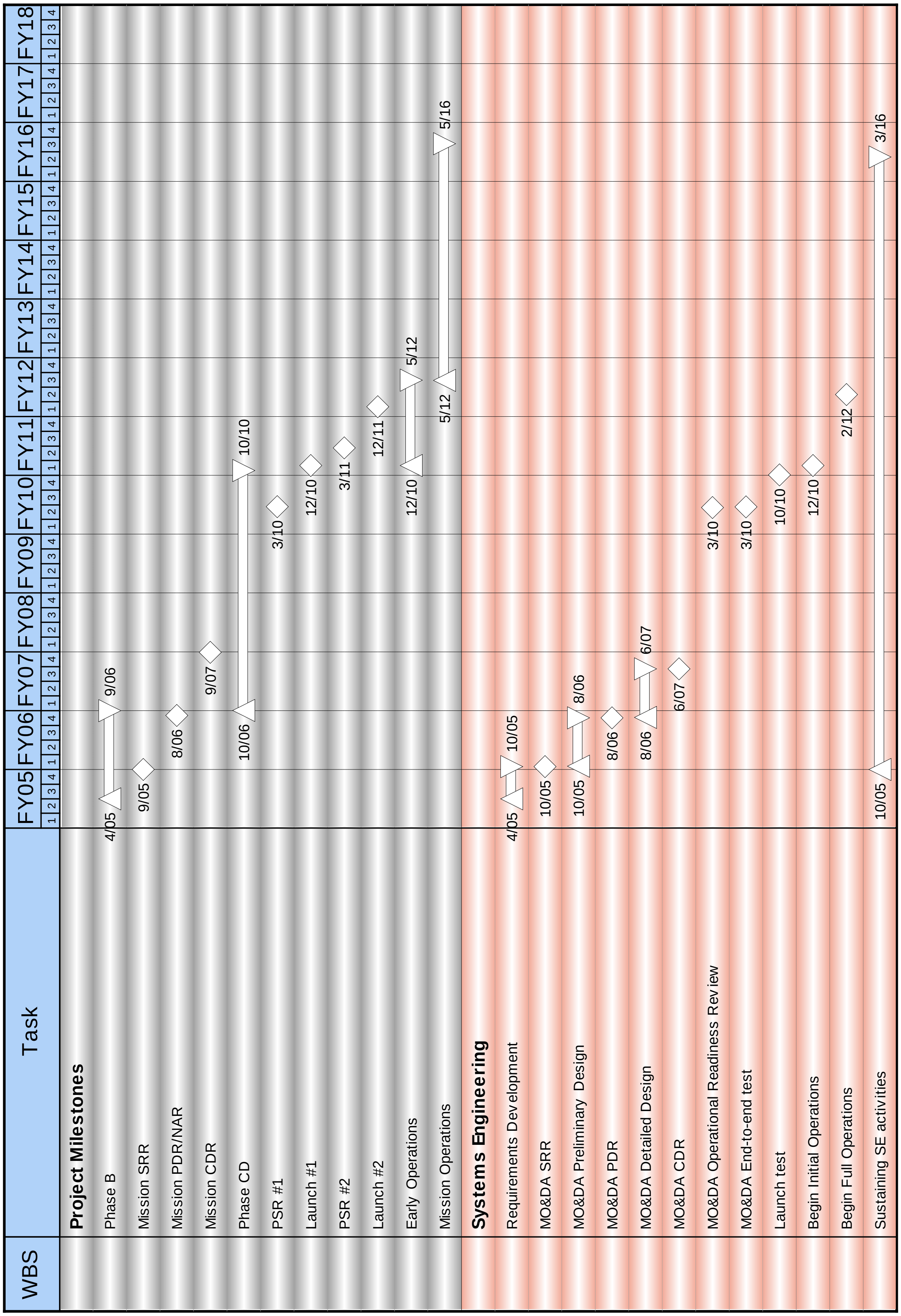

Mission Operations & Data Analysis

WBS 10

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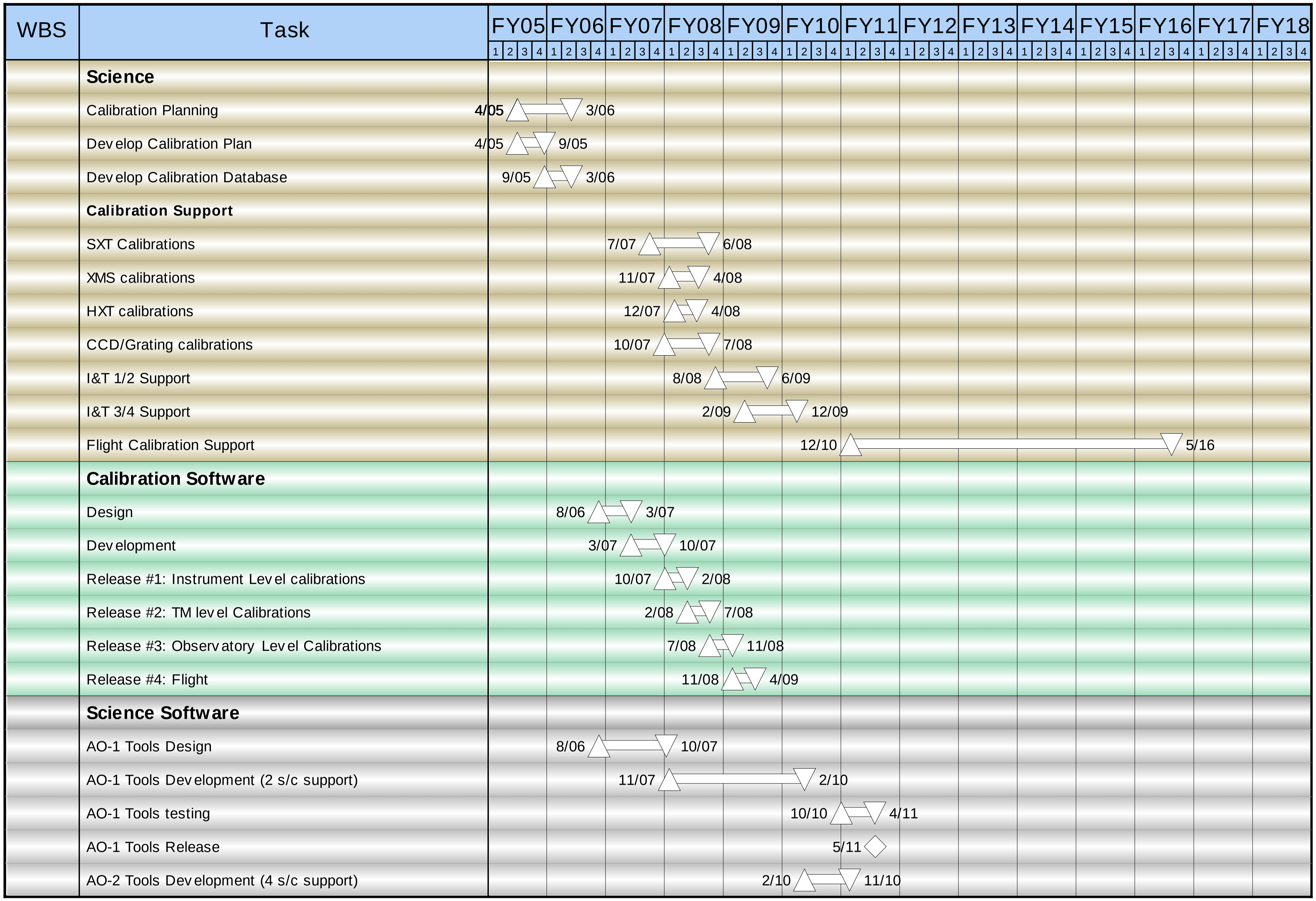
Detail 2 of 7



Mission Operations & Data Analysis

WBS 10

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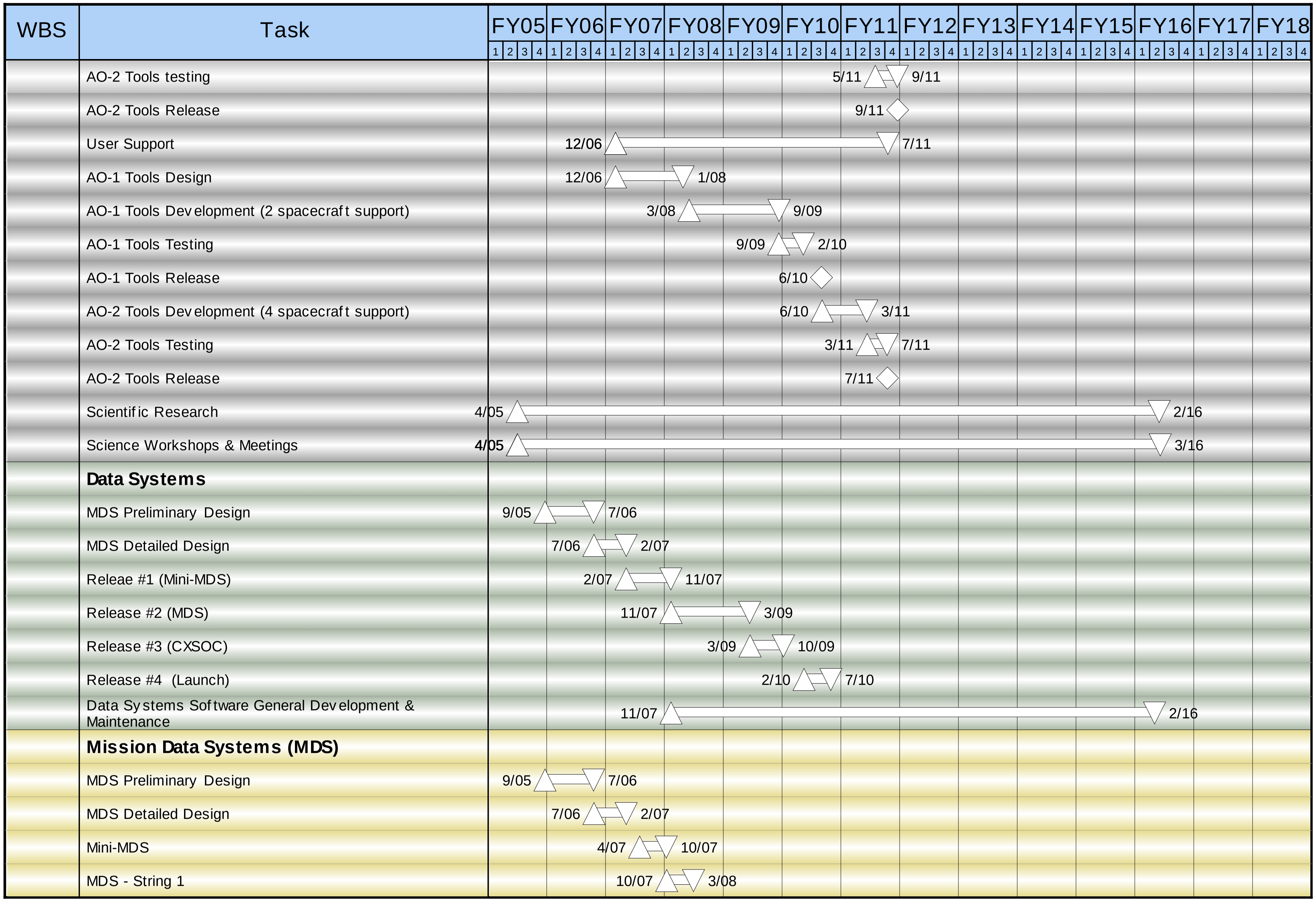
Detail 3 of 7



Mission Operations & Data Analysis

WBS 10

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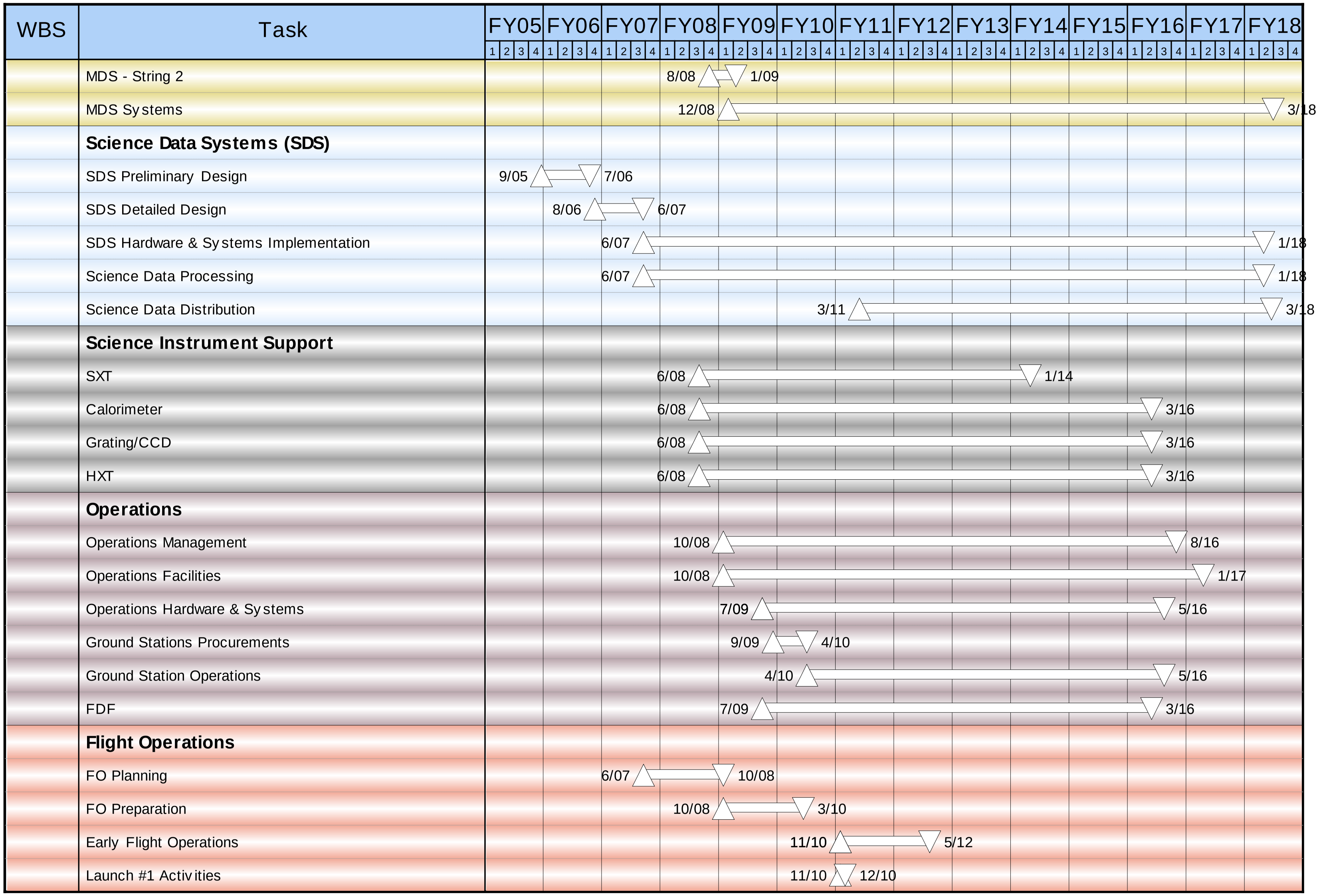
Detail 4 of 7



Appendix B - Supporting Detailed Schedules

Mission Operations & Data Analysis

WBS 10

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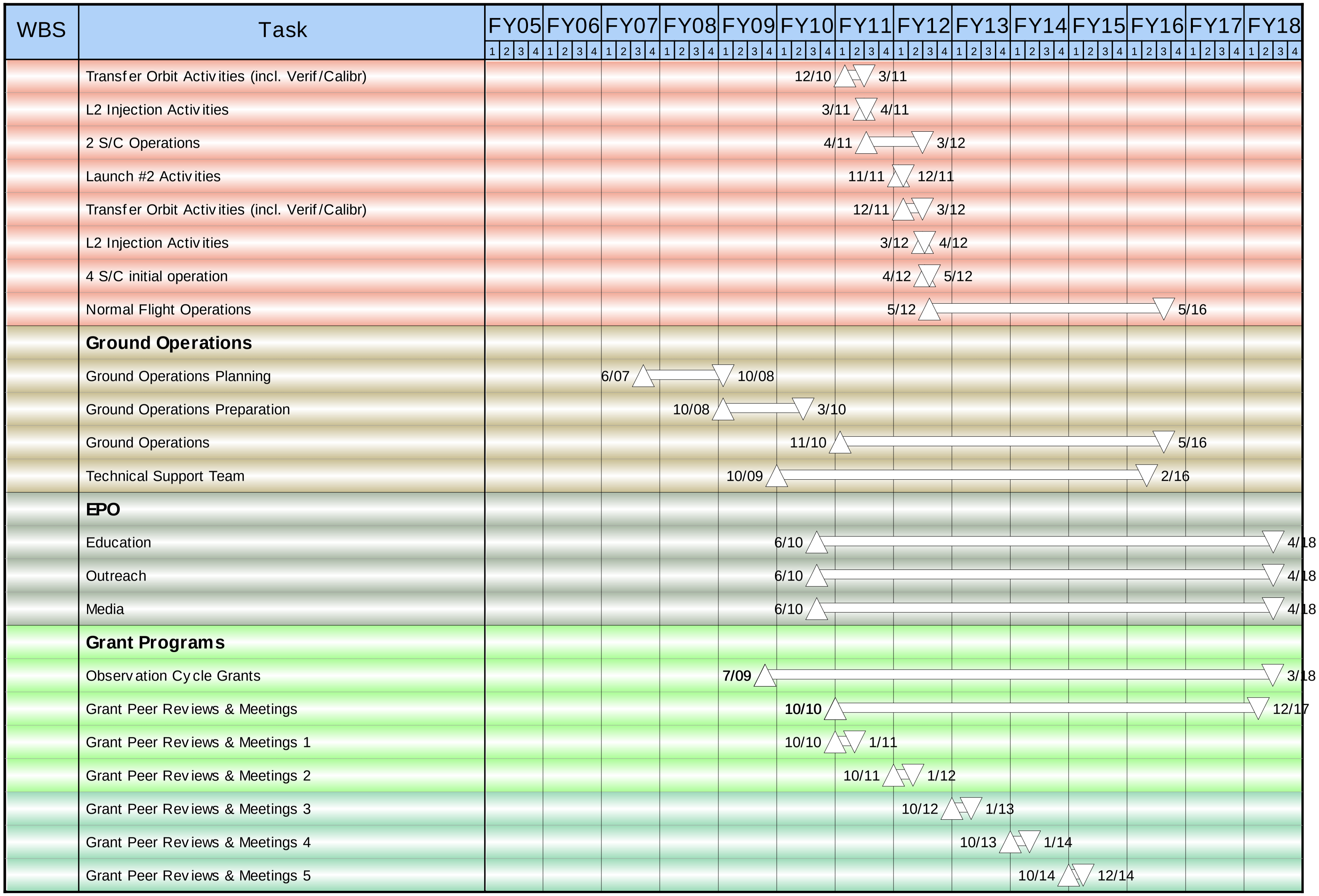
Detail 5 of 7



Mission Operations & Data Analysis

WBS 10

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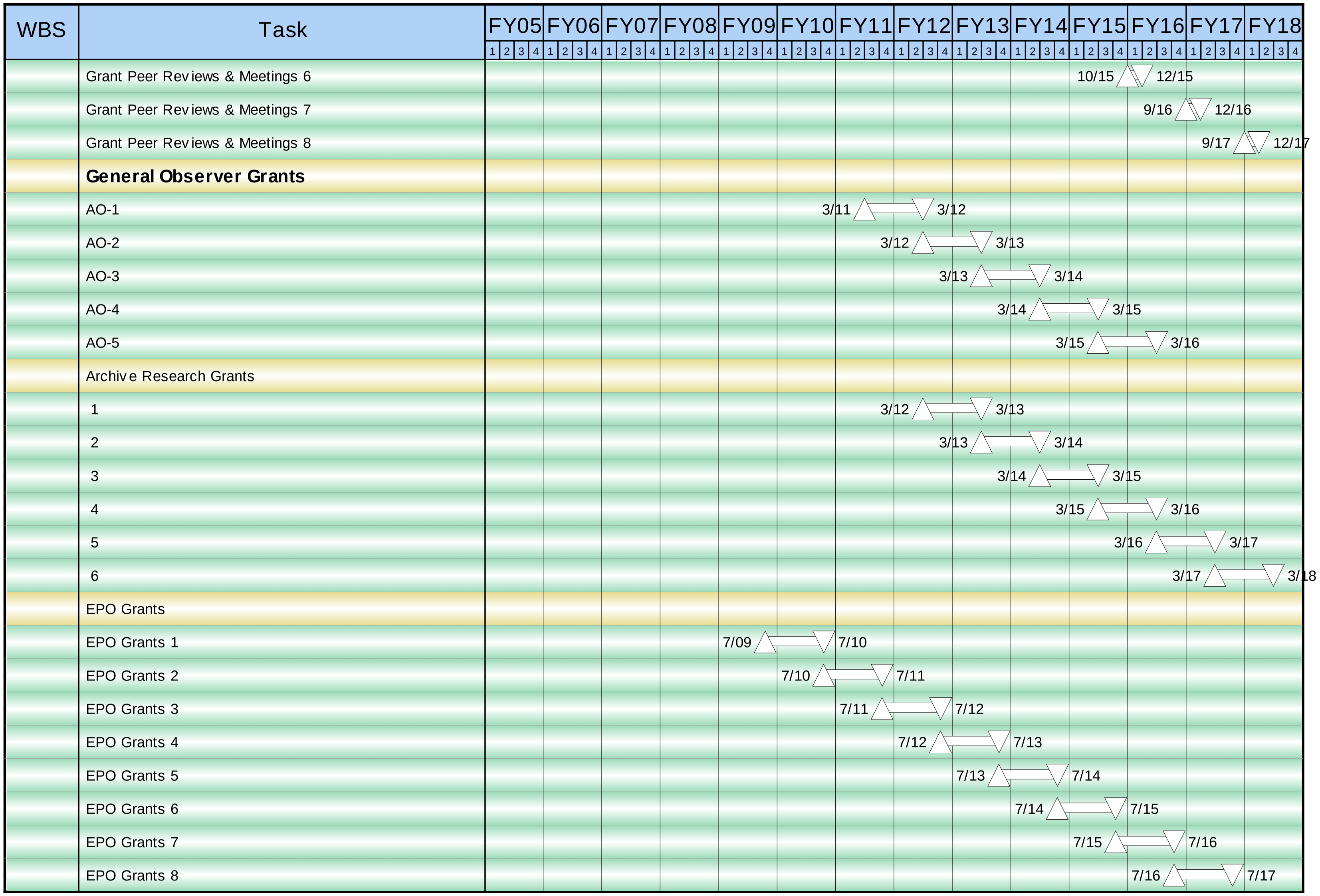
Detail 6 of 7



Mission Operations & Data Analysis

WBS 10

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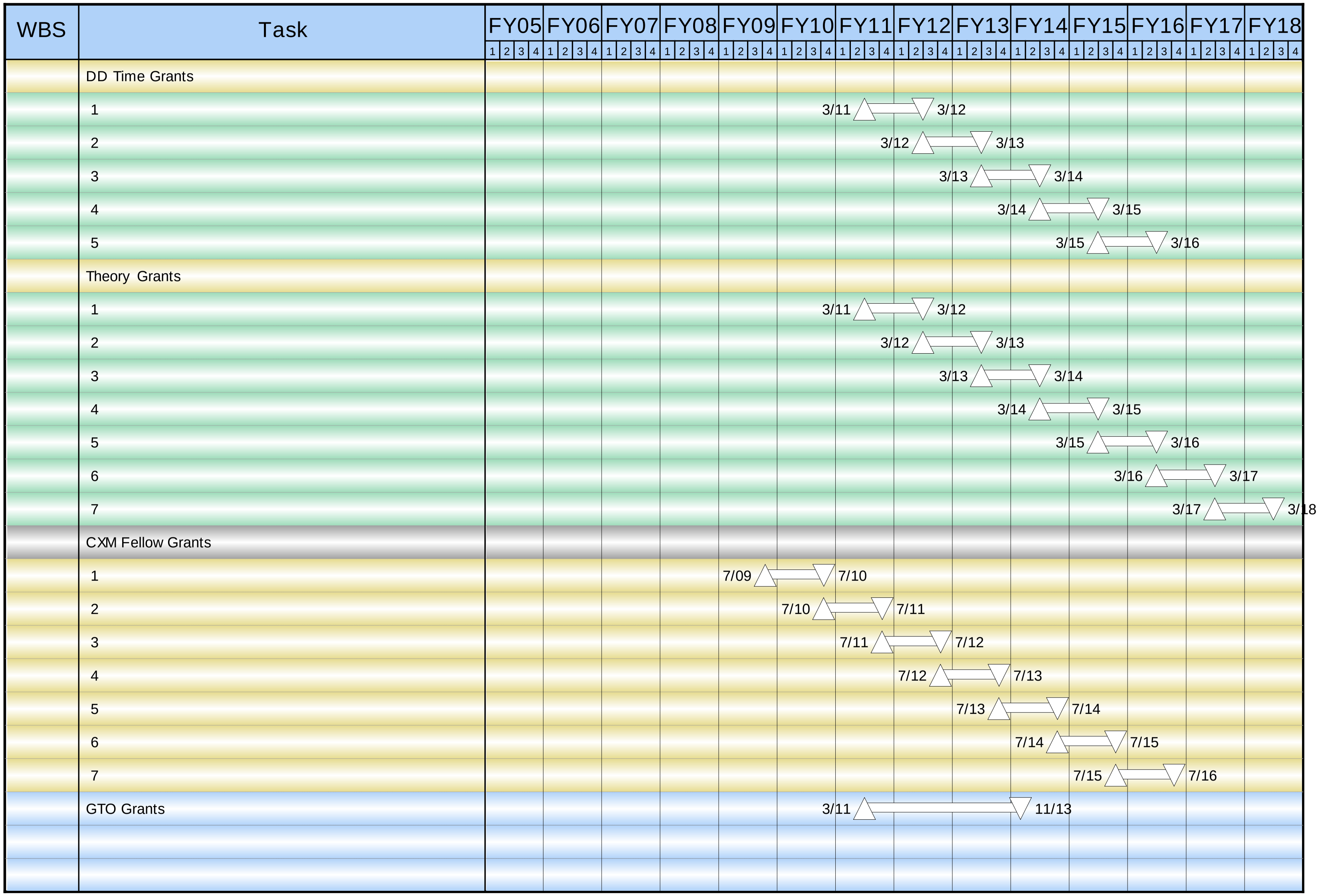
Detail 7 of 7



Appendix C - Draft International Participation

OMITTED

Appendix D - Outline of Technical Responsibilities for International Partners

At this time there are no formal agreements in place for international partnerships and associated responsibilities. We have a stated openness to multi-agency participation within the U.S. and to foreign contributions to the mission. Within the U.S. we have team members already supported by funding from NASA, Smithsonian, DOE, NIST, and NSF.

On the international side, our approach to date involves substantial international participation in the Facility Science Team (FST) and in several of the technology development efforts. The FST oversees the scientific aspects of the mission during its formulation stages. It is comprised of approximately 50 scientists from 30 different institutions and 5 different countries (U.S., UK, Denmark, Italy, and Japan). FST scientists from outside the U.S. have been heavily involved in technology work on the Spectroscopy X-ray Telescope and the Hard X-ray Telescope mirrors. Non-U.S. companies are providing glass for technology efforts on both sets of optics, mandrels for the SXT, and masters for replicating off-plane reflection gratings. At this time we advocate open exchange of ideas and discussions of approaches and progress (as well as challenges) without formally obligating NASA or the Constellation-X mission to any formal teaming arrangements or financial commitments. It is our intent that decisions be driven by performance demonstrated during the technology studies and by open competition through the AO for science instruments.

As we proceed, there will be natural opportunities for international collaboration. Our approach to the SXT mirror draws heavily on the ESA experience with replicated optics for the *XMM-Newton* mission. There are also similarities in our SXT requirements and the optics for the ESA XEUS mission (although the XEUS requirements are more demanding). There have been ongoing discussions about possible closer collaboration on the mirrors, but at this time substantial differences in programmatic approaches and limited ESA funding have limited collaboration to exchange of ideas. We have agreed to revisit possible ESA (or individual European country) involvement in the SXT mirrors over the next 1-2 years. Possibilities range from provision of the mandrels ($49M RY), to mandrels plus finished reflectors ($91M), to mandrels plus reflectors plus mirror assembly and test ($147M).We are also keeping tabs on totally different technical approaches in Europe (and in the U.S.) which deliver additional SXT performance at comparable cost to our current baseline approach. Success in such developments on the European side would no doubt spur further discussions about additional ESA or European involvement (perhaps from Germany and Italy), since it would make contributions more meaningful to those involved. At the least, we will have the option of using U.S. Constellation funds to procure optics (or other hardware) with enhanced capabilities from non-U.S. vendors if that proves in the best interest of the project.

For the Hard X-ray Telescope there are equally interesting possibilities. Our Italian collaborators at OAB have already stated an interest in providing the HXT optics using Italian Space Agency funding. Their approach is using silicon carbide carriers with replicated shells and multi-layer coatings to produce the optics. While there is not a formal commitment in this area, that is at least in part due to our stated intention to continue technology developments to the point where performance is demonstrated at the required level, enabling us to make decisions which are driven by performance as well as cost considerations. HXT optics if provided by Italy would represent a contribution of $35M to the Constellation-X program. There is also a possibility of Japanese involvement in the HXT. Japanese team members have developed segmented aluminum with multi-layer coatings for HXT-like optics and might be interested in providing these for Constellation-X at a similar cost value to the Italian HXT optics, assuming these metal optics can meet the HXT requirements. One approach would be to negotiate participation of an international partner and formalize the agreements in a LOA or MOU as described in Appendix C.

In addition, non-U.S. groups almost surely will compete for one or more of the Constellation instruments - X-ray Microcalorimeter Spectrometer, Reflection Grating Spectrometer, or HXT optics and detectors. If such a team is successful under the AO, the value of their contribution (in non-U.S. funds) to Constellation-X could range from approximately $55M to $130M.

Appendix E - Abbreviations and Acronyms

Å	Angstrom
ACE	Advanced Composition Explorer
ACE	Attitude Control Electronics
ACIS	AXAF CCD Imaging Spectrometer
ACTDP	Advanced Cryocooler Technology Development Program
A/D	Analog/Digital
ADR	Adiabatic Demagnetization Refrigerator
AETD	Applied Engineering Technology Directorate
AGN	Active Galactic Nucleus
AH	Ampere-hour
AIRS	Atmospheric Infrared Sounder
Al	Aluminum
AO	Announcement of Opportunity
AOCS	Attitude and Orbit Control System
arcmin	arc minutes
arcsec	arc seconds
ASCA	Advanced Satellite for Cosmology & Astrophysics
ASIC	Application-Specific Integrated Circuit
ATD	Advanced Technology Development
Au	Gold
AXAF	Advanced X-ray Astrophysics Facility
BAE	British Aerospace
BASD	Ball Aerospace Systems Division
BBXRT	Broad Band X-ray Telescope
BGO	Bismuth Germanate
BHC	Black Hole Candidates
BI	Back-Illuminated
Bi	Bismuth
B-MINE	Balloon-borne Microcalorimeter Nuclear Line Explorer
BOL	Beginning of Life
bps	bits per second
BPSK	Biphase Shift Keying
C	Carbon
C	Celsius
C&DH	Command and Data Handling
CADR	Continuous Adiabatic Demagnetization Refrigerator
CADR	Continuous Adiabatic Demagnetization Refrigerator
CalDB	Calibration Database
CCAFS	Cape Canaveral Air Force Station
CCB	Common Core Booster™
CCB	Configuration Control Board
CCD	Charge-Coupled Device
CCSDS	Consultative Committee for Space Data System
Cd	Cadmium
CDA	Centroid Detector Assembly
CDMS	Cryogenic Dark Matter Search
CDR	Critical Design Review
CdZnTe	Cadmium Zinc Telluride
CEA	Center Export Administrator
CEASE	Compact Environmental Anomaly Sensor
CETDP	Cross Enterprise Technology Development Program
CFR	Code of Federal Regulations
CGRO	Compton Gamma Ray Observatory
ChIPS	Chandra Imaging and Plotting System
CIAO	Chandra Interactive Analysis of Observations
CLASS	Communications Link Analysis and Simulation System
cm	centimeter
COBE	Cosmic Background Explorer
COI	Composite Optics, Inc.
COTS	Commercial Off-the-Shelf
cps	counts per second
CPT	Comprehensive Performance Testing
CPU	Central Processing Unit
CRC	Cyclic Redundancy Code
CRIS	Cosmic Ray Isotope Spectrometer
Cs	Cesium
CSOC	Chandra Science Operations Center
CSR	Center for Space Research
CSS	Coarse Sun Sensor
CTE	Coefficient of Thermal Expansion
CTI	Charge Transfer Efficiency
cts	counts
Cu	Copper

CXC	Chandra X-ray Center
CXSOC	Constellation-X Science and Operations Center
CY	Calendar Year
C_z	Critical Temperature
DARPA	Defense Advanced Research Projects Agency
dB	Decibel
DDF	Director’s Discretionary Fund
Dec	Declination
DET	Direct Energy Transfer
DOF	Degree-of-Freedom
DOORS	Dynamic Object Oriented Requirements System
DRM	Design Reference Mission
DSN	Deep-Space Network
DSRI	Danish Space Research Institute
DT&E	Development Test and Evaluation
E	Energy
EAR	Export Administration Regulations
EDCCD	Event Driven CCD
EELV	Evolved Expendable Launch Vehicle
EEPROM	Electronically Erasable Programmable Read-Only Memory
EGSE	Electrical Ground Support Equipment
ELV	Expendable Launch Vehicle
EMI/EMC	Electromagnetic Interference/Compatibility
EO-1	Earth Observing-1
EOL	End of Life
EOS	Earth Observing System
E/PO	Education and Public Outreach
EPS	Electrical and Power Subsystem
ESA	European Space Agency
ET	Environmental Testing
EU	Engineering Unit
eV	electron Volts
EVD	Engine Valve Driver
EVM	Earned Value Management
EXITE	Energetic X-ray Imaging Telescope Experiment
FAD	Formulation Authorization Document
FDAB	Flight Dynamics Analysis Branch
FDF	Flight Dynamics Facility
Fe	Iron
FEI	Frequency Electronics, Inc.
FI	Front Illuminated
FITS	Flexible Image Transport System
FMA	Flight Mirror Assembly
FOT	Flight Operations Team
FOV	Field of View
FPC	Focal Plane Camera
FPGA	Field Programmable Gate Arrays
FPM	Focal Plane Module
FPPD	Flight Programs and Projects Directorate
FRA	Focal plane Readout Array
FRR	Flight Readiness Review
FST	Facility Science Team
FSW	Flight Software
FTE	Full Time Equivalent
FTS	Fiducial Transfer System
FU	Flight Unit
FUSE	Far Ultraviolet Spectroscopic Explorer
FWHM	Full Width Half Maximum
FY	Fiscal Year
G	Gravity
Gbytes	Gigabytes
Ge	Germanium
GFE	Government Furnished Equipment
GLAS	Geoscience Laser Altimeter System
GLAST	Gamma Ray Large Area Space Telescope
gm	gram
GO	General Observer
GOES	Geostationary Operational Environmental Satellites
GPG	Goddard Procedure Guidelines
GR	General Relativity
GRACE	Gravity Recovery and Climate Explorer
GREP	Graphite-Reinforced Epoxy
GRO	Compton Gamma Ray Observatory
GS	Ground System
GSE	Ground Support Equipment
GSFC	Goddard Space Flight Center
GUI	Graphical User Interface

H	hyperbolic
HAWC	High Resolution Airborne Wideband Camera
H/K	house keeping
He	Helium
HEAO	High Energy Astrophysical Observatory
HEASARC	High Energy Astrophysics Science Archive Research Center
HEFT	High Energy Focusing Telescope
HEO	High Earth Orbit
HERO	High Energy Replicated Optics
HETE	High Energy Transient Experiment
HETG	High Energy Transmission Grating
HPB	High-Pressure Bridgeman
HPD	Half Power Diameter
HQ	Headquarters
HST	Hubble Space Telescope
HV	High Voltage
HXT	Hard X-ray Telescope
Hz	Hertz
I	Iodine
ICESat	Ice, Cloud, and Land Elevation Satellite
I/O	Input/Output
I&T	Integration and Test
ICD	Interface Control Document
ID	Inner Diameter
I/F	Interface
IGM	Intergalactic Medium
IIRT	Integrated Independent Review Team
IM	Instrument Manager
IMAGE	Imageer for Magnetopause-to-Aurora Global Exploration
InFOCμS	International Focusing Optics Collaboration for μCrab Sensitivity
IPT	Integrated Product Team
IR&D	Independent Research and Development
IR	Infrared
IRU	Inertial Reference Unit
ITAR	International Traffic in Arms Regulations
IV&V	Independent Verification and Validation
JEXT	Joint European X-ray Telescope
JFET	Junction Field Effect Transistor
JHU/APL	Johns Hopkins University/Applied Physics Laboratory
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
K	Kelvin
kbps	kilobits per second
kByte	Kilobyte
keV	Kilo electron Volts
kg	Kilogram
kHz	KiloHertz
KOH	Potassium Hydroxide
ksec	kilosecond
KSC	Kennedy Space Center
LCC	Life Cycle Cost
LEO	Low Earth Orbit
LL	Lincoln Labs
LLNL	Lawrence Livermore National Labs
LM	Lockheed-Martin
LOA	Letter of Agreement
LRF	Line Response Function
LRR	Launch Readiness Review
LV	Launch Vehicle
LV	Low Voltage
LVPC	Low Voltage Power Converter
LVPS	Low Voltage Power Supply
LZP	Level Zero Processing
m	meter
MHz	Megahertz
mm	millimeter
ms	millisecond
MAP	Microwave Anisotropy Probe
MAR	Mission Assurance Requirements
MAXIM	Micro Arcsecond X-ray Imaging Mission
MBE	Molecular Beam Epitaxy
MDR	Mission Definition Review
MDS	Mission Data System
MISC	Minimal Instruction Set Computers
MIT	Massachusetts Institute of Technology
mK	milliKelvin
MLI	Multilayer Insulation
Mo	Molybednium
MO&DA	Mission Operations and Data Analysis

MOC	Mission Operations Center
MOR	Missions Operation Review
MOU	Memorandum of Understanding
MRF	Magneto-Rheological Finishing
m/s	meters per second
ms	millisecond
MSE	Mission Systems Engineer
MSFC	Marshall Space Flight Center
mT	milliTesla
MUX	Multiplexer
mW	milliWatt
N	Neutron
NAR	Non-Advocate Review
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
Nb	Niobium
NEAR	Near Earth Asteroid Rendezvous
NICMOS	Near Infrared Camera and Multi-Object Spectrometer
NIST	National Institute of Standards and Technology
nm	nanometers
NMP	New Millennium Program
NPD	NASA Policy Directive
NPG	NASA Procedure and Guideline
NRA	NASA Research Announcement
NRE	Non-recurring Engineering
NSS	NASA Safety Standard
NTD	Neutron Transmutation Doped
OAB	Osservatoria Astronomico Di Brera
OAP	Optical Alignment Pathfinder
OB	Optical Bench
OBC	On-Board Computer
OD	Orbit Determination
OD	Outside Diameter
ODRM	Observation Design Reference Mission
OM	Observatory Manager
OM	Optics Module
ORR	Operations Readiness Review
OS	Operating System
OSO-8	Orbiting Solar Observatory 8
OSS	Office of Space Science
OSSE	Oriented Scintillation Spectrometer Experiment
OSSMA	Office of Systems Safety and Mission Assurance
P	parabolic
PA	Power Amplifier
PDR	Preliminary Design Review
PER	Pre-Environmental Review
PG	Procedure Guideline
PHA	Pulse Height
PI	Principal Investigator
PLF	Payload Fairing
PM	Project Manager
PMD	Propellant Management Device
PMT	Photo Multiplier Tube
POP	Program Operating Plan
PPL	Preferred Parts List
PRICE	Parametric Review of Information for Costing and Evaluation
PS	Pseudo-Random
PSE	Power Supply Electronics
PSF	Point Spread Function
psi	pounds per square inch
PSI	Pressure Systems, Inc.
PSR	Pre-Shipment Review
PST	Point Source Transmittance
QA	Quality Assurance
QE	Quantum Efficiency
QPO	Quasi-Periodic Oscillations
QSO	Quasi-Steller Objects
R	Spectral Resolving Power
RA	Right Ascension
RAM	Random Access Memory
RF	Radio Frequency
RFC	RGS Focal Plane Camera
RFI	Request for Information
RFP	Request for Proposals
RGA	RGS Grating Array
RGS	Reflection Grating Spectrometer
RHESSI	Reuven Ramaty High Energy Solar Spectroscopic Imager
RIE	Reactive Ion Etch
RMD	Reference Mission Description
RMS	Root Mean Square
ROCSAT	Republic of China Satellite
ROM	Rough Order of Magnitude
ROSAT	Roentgen-SATellite

ROSS	Research Opportunities in Space Science
RSDO	Rapid Spacecraft Development Office
RSS	Root Sum Square
RT	real time
RW	Reaction Wheel
RY	Real Year
RXTE	Rossi X-ray Timing Explorer
S.	Sulfur
SAI	Swales Aerospace, Incorporated
s/c	spacecraft
SAFIRE	Submillimeter and Far Infrared Experiment for SOFIA
SAM	System Assurance Manager
SAO	Smithsonian Astrophysical Observatory
SAX	Satellite per Astronomia X-ray
SBIL	Scanning Beam Interference Lithography
SCUBA	Submillimeter Common User Bolometer Array
SDP	Safety Data Package
SDS	Science Data System
SE	Systems Engineer
sec	second
SEM	Scanning Electron Microscope
SEU	Structure and Evolution of the Universe
Si	Silicon
SI	Science Instrument
SIS	Solid-State Imaging Spectrometer
SMA	Safety and Mission Assurance
Sn	Tin
SNL	Space Nanotechnology Laboratory
SNR	Signal-to-Noise Ratio
SOHO	Solar and Heliospheric Observatory
SOPHIA	Stratospheric Observatory For Infrared Astronomy
SQUID	Superconducting Quantum Interference Device
SR&T	Supporting Research and Technology
SRC	Spectroscopy Readout Camera
SRR	Systems Requirements Review
ST	Star Tracker
STEP	Satellite Test of the Equivalence Principle
STEREO	Solar Terrestrial Relations Observatory
STIS	Space Telescope Imaging Spectrograph
SWAS	Submillimeter Wave Astronomy Satellite
SWG	Science Working Group
SXT	Spectroscopy X-ray Telescope
Ta	Tantalum
TB	Thermal Balance
TBD	To Be Determined
TBR	To Be Resolved
TDRSS	Tracking and Data Relay Satellite System
Tbyte	Terrabyte
TCP/IP	Transmission Control Protocol/ Internet Protocol
Te	Tellurium
TES	Transition Edge Sensor
TES	Tropospheric Emission Spectrometer
Ti	Titanium
TLM	telemetry
TLRD	Top-Level Requirements Document
TM	Telescope Module
TOO	Target of Opportunity
TPF	Terrestrial Planet Finder
TRACE	Transition Region Coronal Explorer
TRIP	Technology Readiness and Implementation Plan
TRL	Technology Readiness Level
TRMM	Tropical Rainfall Measuring Mission
TST	Technical Support Team
TT&C	Tracking, Telemetry and Command
TV	Thermal Vacuum
USO	Ultra Stable Oscillator
UTC	Universal Time Code
UV	Ultraviolet
UW	University of Wisconsin
V	Velocity
V&V	Verification and Validation
VPSBIL	Variable Period SBIL

W	Watt
WBS	Work Breakdown Structure
WIRE	Wide-field Infrared Explorer
VLSI	Very Large Scale Integration
XEUS	X-ray Evolving Universe Spectroscopy Mission
XIS	X-ray Imaging Spectrometer
XMM	X-ray Multi-Mirror Mission
XMS	X-ray Microcalorimeter Spectrometer
XO	Crystal Oscillator
XQC	X-ray Quantum Calorimeter
XRCF	X-ray Calibration Facility
XRB	X-ray Binaries
XRS	X-ray Spectrometer
XTE	Rossi X-ray Timing Explorer
z	red shift
Zn	Zinc
ZOC	Zero Order Camera
µm	micrometer

Appendix F - References

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