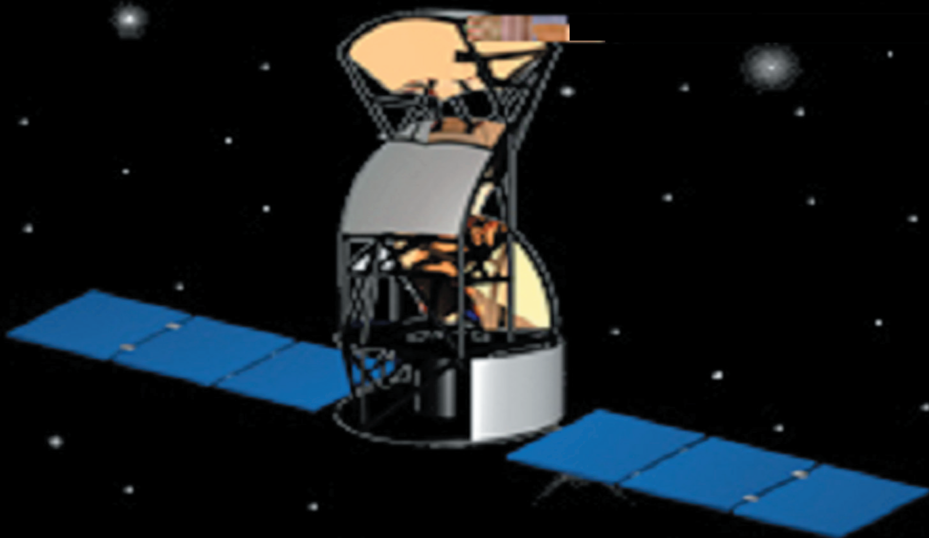

Mission Study Report for EXIST

Energetic X-ray Imaging Survey Telescope

December 2002

Goddard Space Flight Center
Greenbelt, Maryland

Acknowledgements

The Mission Study Team acknowledges significant contributions from the EXIST Science Working Group, and in particular, the Instrument Design Team at Harvard, Goddard Space Flight Center (GSFC), Lawrence Livermore National Laboratory (LLNL), California Institute of Technology (Caltech), Columbia and Marshall Space Flight Center (MSFC). The instrument design was clarified during an Instrument Synthesis and Analysis Laboratory (ISAL) team session at GSFC in late 2000. This ISAL session considered the instrument as an ISS Attached Payload and, was very helpful in developing details of the instrument design. This Mission Study Report is based, in large part, on a weeklong session of Integrated Mission Design Center (IMDC) at GSFC held in November of 2001 primarily to consider EXIST as a free-flying mission. The efforts of the IMDC Team, and, in particular, Gabe Karpati, were essential in the development of this Mission Study Report. The contributions of Fiona Harrison, Rick Cook, Chuck Hailey, Jerry Fishman, Alan Harmon, Scott Barthelmy, Ann Parsons, Carl Stahle and Sachidananda Babu were much appreciated for the ISAL and IMDC runs. Ruth Carter was a very capable and tireless Mission Study Team Lead, coordinating the entire report preparation. Steve DePalo was the Mission Systems Engineer throughout, and he has been instrumental in compiling this report. Additionally, discipline engineers from the GSFC Applied Engineering & Technology Development (AETD) Directorate (Code 500) have provided their support to this mission study above and beyond the mission study requirement. Their contribution was essential in the overall success of the mission study and this report. The contributing study design team engineers and organizations, along with other study members are listed below.

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1 Executive Summary

This report describes a technical mission study that was performed of the Energetic X-ray Imaging Survey Telescope (EXIST) mission at NASA's Goddard Space Flight Center (GSFC) during the period from September 2001 to July 2002. The study was done by a Goddard engineering team assembled by the EXIST Study Manager working with the EXIST science team.

EXIST is a mission to conduct an all-sky imaging hard x-ray survey in the 10 to 600 keV band. The survey sensitivity will be ~0.05 mCrab, which is comparable to that of the ROSAT survey of the soft x-ray sky. The mission will also provide observations of gamma-ray bursts to sensitivities 20 times better than that achieved by the BATSE instrument on the Compton Gamma-ray Observatory (CGRO). The primary science goal of EXIST is to perform the first all-sky imaging survey for black holes on all scales, from super-massive black holes in active galaxies to stellar mass black holes in our galaxy. Formation of black holes from the very first stars in the universe may be studied by the gamma-ray bursts they likely produce. A secondary goal is to observe gamma-ray bursts with the highest gamma-ray sensitivity and resolution ever achieved to probe the physics of these extreme objects as well as conditions in the early universe. An overview of EXIST science and the mission is maintained on the EXIST website at http://exist.gsfc.nasa.gov.

EXIST will incorporate a very large area (~8 m^2) imaging Cadmium-Zinc-Telluride (CdZnTe) detector and coded aperture telescope array, making it the most sensitive gamma-ray imager ever flown. It will have nearly half-sky instantaneous view and will scan the full sky each orbit providing rapid and deep all-sky monitoring for transient sources.

The report identifies the key areas of technology development that are required to move EXIST forward. The bottom line of this study is that EXIST is feasible as a free-flyer within a $400M mission cost (all elements included). The required technology is near ready to fly, with modest investment needed up front in detector and front-end electronics development.

Background

The EXIST mission is a strong candidate to be one of three “Einstein Probes” in the Roadmap of the Structure and Evolution of the Universe (SEU) theme of the NASA Office of Space Science. The Einstein Probes would begin flying in the 2010 timeframe. EXIST is well matched to the “Black Hole Finder Probe” in the Roadmap.

The EXIST mission concept was selected in 1994 as one of the new mission concepts. NASA’s Gamma-Ray Astronomy Program Working Group (GRAPWG) named it a priority mission in 1999. In the same year, the EXIST Science Working Group was formed and Goddard established a Study Office with a Project Scientist, Project Formulation Manger and engineering team. In 2000, The EXIST mission was recommended in the NRC Decadal Survey as a medium mission.

EXIST was, at one time, considered as a mission to be flown onboard the International Space Station (ISS) as an attached payload. In May 2000, the Instrument Synthesis and Analysis

Laboratory (ISAL) at Goddard completed a viable instrument design for Shuttle launch and ISS operation. In summer of 2001, NASA Headquarters' Office of Space Science (Code S) suggested that the mission be studied as a free-flyer. One of the objectives of the current study was to effect this change. Another objective was to develop a benchmark design of the mission. As part of this effort, engineering design studies were performed at and the Integrated Mission Design Center (IMDC). The results of these analyses are included in the report. The IMDC runs were followed by 6 months of intensive engineering study of the spacecraft and instrument subsystems that are described below.

The EXIST mission study began in August 2001, when the NASA Office of Space Science commissioned the EXIST mission study to the Goddard Space Flight Center's Project Formulation Office. The primary objective of the study was to determine if EXIST is feasible as a free-flying mission. Specific requirements included a high-energy telescope instrument and launch on an expandable rocket at the lowest inclination and altitude orbit possible. The mission would perform an all-sky survey for 3-5 years duration within the cost of an intermediate class space science mission.

The Project Formulation Office assigned the mission study to a study manger (Ruth Carter). The study manager, in collaboration with the Study Scientist (Neil Gehrels/GSFC) and Principal Investigator (Josh Grindlay/Harvard), formed a study team. The study team was composed of discipline engineers from GSFC Code 500 (Applied Engineering and Technology Directorate), the Lawrence Livermore National Laboratory (LLNL) EXIST team, led by Bill Craig, and the Harvard University and Harvard-Smithsonian Center for Astrophysics (CFA) EXIST team, led by Josh Grindlay. The study team was a highly successful collaborative effort between scientists, engineers, and managers from NASA, Lawrence Livermore National Labs and Harvard University.

Mission Study Summary and Recommendations

The study results clearly demonstrate that EXIST can be achieved with an acceptable level of technical, cost, and schedule risk. This mission study concentrated on the top-level mission issues due to the limited time and effort allowed. Additional EXIST concept development work is needed. Specifically:

- The EXIST instrument concept should be refined through a second design iteration with the GSFC Instrument Synthesis and Analysis Laboratory (ISAL).
- The instrument detector concept requires further development with prototype detector modules.
- Alternate designs and trades have been identified and should be evaluated for spacecraft subsystem and mission operations concepts. A future EXIST mission study should also include an evaluation and study by industry of a compatible commercially available spacecraft bus.
- A future EXIST mission study should also conduct additional cost trades and analyses as well as consider potential mission partners.

2 Science Summary

The following scientific summary is the input provided to the SEU Roadmap. EXIST is called the BHProbe in this section, since it could achieve the objectives of the "Black Holes Finder", one of the three "Einstein Probe" missions recommended for the roadmap.

The BHProbe will perform the first all-sky imaging survey for BHs on all scales: from super-massive BHs obscured in the nuclei of galaxies, to intermediate mass (approximately 100-1000 solar mass) black holes likely produced by the very first stars, to stellar mass holes in our galaxy. A wide-field (approximately 5sr) coded aperture telescope array operating in the hard X-ray band (approximately 10-600 keV), where accreting BHs are particularly luminous, is a promising approach since hard X-rays penetrate the veil. Such a survey [e.g. EXIST, as endorsed by the Astronomy and Astrophysics Committee (AASC)] would then be the first to achieve all-sky imaging every approximately 95-minute orbit, allowing BHs to be surveyed in both time and space.

Recent evidence has suggested that a large fraction of massive BHs in the centers of galaxies are obscured by surrounding gas and dust in the nuclear vicinity. Indeed the three closest super-massive BHs are in the nuclei of obscured and optically dull galaxies. BHProbe would make the first census of such massive BHs in the local universe and distinguish them from "starburst" nuclei (in comparably dusty environments) by the hard X-ray spectra and variability unique to a central BHs. Such a census is critical to determine if massive BHs are present in all galaxies and were grown by accretion during the galaxy formation epoch, as suggested by the hard X-ray background radiation and general accretion (X-ray) vs. nuclear (starlight) luminosity density of the universe.

BHProbe would enable a wide range of fundamental studies of BHs and the extremes of astrophysics:

(1) BHProbe will measure the super-massive BH content of galaxies in the local universe for a wide range of both obscuration and accretion rate. BHProbe can identify the most luminous and thus massive obscured BHs at larger redshifts to constrain the growth rate of massive BHs. Next Generation Space Telescope (NGST) could measure the star formation rate in the same obscured Active Galactic Nuclei (AGN) for comparison. Follow-up detailed studies with Constellation-X and eventually the Black Hole Imager can measure fundamental BH properties (spin, mass) in the most optimal targets.

(2) BHProbe will perform the first continuous variability survey for BHs in the hard X-ray band, where their luminosity per decade of frequency locally peaks. The inherently unpredictable largest variations of these messy eaters, such as when entire stars are ingested, could be measured as hard X-ray flares (duration hours - days) from the preponderance of obscured AGN in the local universe. Comparisons with the Laser Interferometer Space Antenna (LISA) would allow the space-time vs. accretion disk (or flow) signatures to be disentangled for infall of compact vs. the more numerous non-degenerate stars. The large galactic population of stellar mass BHs in binaries, which appear as X-ray transients, would be mapped and distinguished from those with neutron stars by their hard X-ray spectral and temporal signatures.

(3) BHProbe will conduct a hard X-ray survey approximately 1000 times more sensitive than the only previous full-sky survey (HEAO-A4) and with approximately 20X more sensitivity than BATSE for GRBs. Increases in sensitivity, energy band coverage, temporal and spectral resolution are all factors of •5-10 over those projected for the Swift mission. Thus BHProbe would be the *Next Generation GRB mission*, allowing the most sensitive study of the highest redshift GRBs expected from the formation of intermediate mass BHs at the epoch of formation of the very first (massive) stars. Such objects are possible seeds for massive BH formation, may contribute to dark matter in galaxies, and could also be detected locally by BHProbe when they encounter dense cores of giant molecular cloud complexes and accrete as hard X-ray sources.

(4) BHProbe will at the same time survey other extremes of astrophysics: (1) through long duration timing studies of accreting X-ray binaries, it can improve our understanding of physical processes occurring in the extreme environments of high gravity, high magnetic field, and high radiation energy density; (2) through the detection of hard X-ray nuclear decay lines from ^{44}Ti and other species, it can provide crucial information on supernova and nova rates in the galaxy, and constrain models of cosmic nucleosynthesis; (3) through high sensitivity studies of soft gamma-ray repeaters, it can constrain the formation and evolution of neutron stars with the most extreme magnetic fields in the local universe; and (4) through measures of the hard X-ray spectra of distant AGN in conjunction with HE gamma-ray spectra from Gamma-ray Large Area Space Telescope (GLAST) and Very Energetic Radiation Imaging Telescope Array System (VERITAS), it will constrain the shape of the diffuse infrared (IR) radiation background (and thus star formation rate) as a function of cosmic time.

A possible implementation of BHProbe is being studied as the EXIST Mission Concept (http://exist.gsfc.nasa.gov/) at NASA/GSFC. Other concepts may exist, and of course the mission would be competed. The AASC recommended this mission science be conducted in this decade, which would allow it to support both Constellation-X and LISA as well as be still operative with GLAST. Discussions are underway with prospective European-national and ESA partners for possible participation.

BHProbe, as a hard X-ray survey mission, would consist of a very large area (approximately 4-8m^2) array of imaging solid-state detectors (CdZnTe or CZT), which view the sky through wide-field coded aperture masks. With three contiguous telescopes, each with 2.7m^2 of CZT (1.2mm pixel size) and active-passive collimation (60° X 75°) to define a combined 180° X 75° field of view (Fob), the full sky can be imaged each orbit with 3-5 arc min resolution defined by the unit-cell size of a passive (Tungsten) coded aperture mask array at approximately 1.5m above the detector planes. The telescope array is zenith pointed (approximately 1° pointing stability; each photon is aspect-corrected to approximately 5 arc sec) in the nominal survey, although inertial pointing for higher sensitivity studies of selected (wide) field studies or monitoring can be similarly conducted with minimal impact on the survey.

BHProbe would be sensitive in the 10-600 keV band, and thus connect the thermal (hot gas) to non-thermal HE universes. The survey flux sensitivity (50-100 keV, 5σ, 1y) would be F_{lim} approximately 5 X 10^{-13} erg cm^{-2}s^{-1}, or comparable to the ROSAT all-sky soft x-ray (0.5-2.5keV) sensitivity so that the full spectrum of accreting BHs can be studied and the obscured objects (invisible in soft X-rays) revealed. Bright sources 30σ are located by centroiding to approximately 10 arc sec so that optical/ IR/radio counterparts are readily available, whereas the faintest survey sources have one arc min precision, sufficient for identification with bright galaxies. Temporal resolution (e.g. for GRBs) is 2μs, whereas variability on faint persistent sources with flux F_{hx} can be measured down to timescales τ approximately $1.5h(20F_{lim} /F_{hx})$. Spectral resolution of approximately 1-4 keV (full width half maximum [FWHM]) over the full band would permit study of nuclear (e.g.^{44}Ti at 68, 78 keV) and positron annihilation (511keV) lines, as well as spectral break energies in BHs and GRBs over the full range they are likely.

BHProbe could be launched on a Delta-IV in low-Earth orbit. The major technology challenges are the large area (approximately $8m^2$) CZT detector arrays and their low-power readout systems, as well as data-handling and onboard processing systems. The upcoming Swift Midex mission (2003) will test a first generation large area ($0.5m^2$) CZT imager so that a technology development phase for BHProbe could be completed by 2006.

3 Mission Goals and Objectives

The EXIST mission science goals and objectives are to reveal the obscured objects in the universe; from super-massive BHs in galactic nuclei to stellar holes in molecular clouds and obscured supernova remnants. The most numerous objects in the EXIST survey are expected to be active galaxies; EXIST should locate at least 30,000 of these objects. Understanding the frequency of obscured AGN will elucidate the correlation of BHs mass to galaxy bulge mass and also constrain the effect of massive BHs on galaxy formation. By surveying the gamma-ray sky, EXIST will produce the first catalog of obscured AGN and thereby reveal the accretion history of the universe

Investigation of GRBs at the limit is the other primary EXIST science goal. The EXIST observatory will be designed to locate two to three GRBs a day. EXIST can detect GRBs at high redshift (approximately 10-20). The broad energy ban coverage of EXIST and the very large collection area for optimum statistics, will enable “photometric redshifts” to be derived from the observed relation between GRB time-lags and absolute luminosity.

4 Mission Requirements

To accomplish EXIST science goals and objectives, the EXIST observatory requires science instrumentation with a very large detection area and a wide-field coded aperture imager to meet high sensitivity and temporal coverage. Three identical high-energy (HE) telescopes will be on-board the EXIST observatory; each containing coded aperture and detector arrays. Three wide-field coded aperture telescopes will be mounted such that it will cover approximately 1/4 of the sky (fully coded) or approximately once per sky (partly coded) for instantaneous coverage and the full sky for coverage from Earth orbit.

The top-level mission requirements are:

- Produce a hard X-ray band image of the entire sky once per orbit, localize and study GRBs and other transients, and produce a deep survey of the sky over the mission life time
- Sky coverage shall be at least 95%
- The full sky shall be scanned for transients at least once per orbit
- Energy range shall be 10-600 keV
- Measurement sensitivity shall be approximately 0.1mCrab/6month and approximately 2mCrab/orbit.
- GRB positions will be determined on board to approximately 3 arc minutes and on the ground to approximately 10-50 arcseconds.
- EXIST shall operate at least 5 years on-orbit
- Mission orbit shall be 500-km circular orbit with <25° inclination
- GRB positions and other transients data shall be transmitted in near real-time
- Survey data shall be available within 1 day
- Observatory mass shall be less than 9,000 kg
- Power shall be < 1500W (orbit average)
- Observatory shall be designed to de-orbit (controlled) at the end of mission life
- Observatory shall be launched on a heavy-class expendable launch vehicle

5 Mission Overview

EXIST is a NASA Space Science Mission designed to survey the hard X-ray band using imaging telescopes. The EXIST observatory will have three identical wide-field coded-aperture telescopes, each viewing a contiguous portion of the sky. These telescopes will have CZT detector arrays and tungsten coded mask apertures. Due primarily to the size and thickness of the coded-aperture mask telescopes, and the detector shielding required, the EXIST observatory mass is approximately 8675 kg and it requires a heavy launch vehicle such as a Delta IV.

The EXIST Observatory consists of a S/C and the three instrument modules. The instrument mass is approximately 6250 kg, and the total envelope is approximately 8.0 meters high and 4.6 meters in diameter. The S/C is 1.8 meters high and 4.4 meters in diameter. The observatory employs an open-truss structure concept. The power system is designed to provide 1500 W orbit average power. It has a 100 Amp-hour NiH_2 battery and sun-tracking solar arrays (SA) with GaAs cells. The propulsion system uses bi-propellant fuel. Torquer bars, magnetometers, star trackers, and CSS, as well as gyros are utilized in the observatory attitude control system. The orbit averaged data rate is 1500 kbps. Data downlink is via X-band for science data and S-band for S/C commanding, health and safety. For GRBs and emergencies, near real-time TDRSS return demand access is used. The Observatory is fully redundant to meet a five-year on-orbit mission life. The mission will be launched from the Kennedy Space Center (KSC) to a circular orbit of 500 km with 22° inclination. Mission operations are baselined at staffing eight hours per day for five days per week.

Table 5-1. Key EXIST Mission Parameters

Energy range	10 - 600 keV
Field of View	180° × 75° (fully coded)
Angular Resolution	2-5 arc minutes (10 – 50 arc second source locations)
Energy, Temporal Resolution Sensitivity (5σ, approximately 10^7 s)	1-2 keV (<100 keV), 2-6keV (<600 keV); 2 μsec 0.05 mCrab (10-150 keV); 0.5 mCrab (150-600 keV)
Telescopes, Detectors	Coded aperture, 8 m^2 CZT
Pointing, Aspect Mass, Power, TM, Launch	Approximately 1° pointing, 5" instantaneous knowledge 8800kg, 1500W OAP, 1.5Mbs, Delta IV
Cost (including development, launch, MODA, & guest investigator program)	Approximately $390M (including contingency)

Figure 5-1. EXIST showing active collimator and CZT array for 1 of 3 telescopes

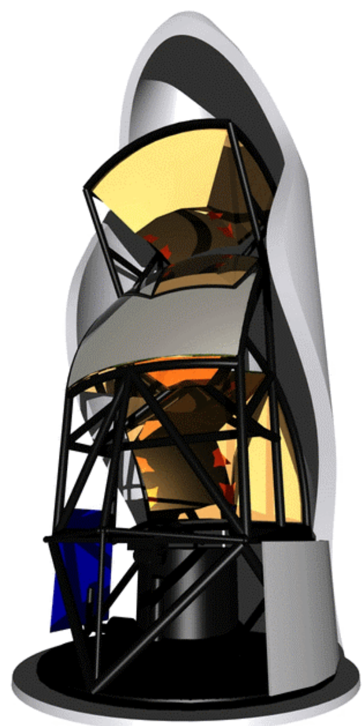


Figure 5-2. EXIST Observatory in Delta IV Shroud

6 Technology Development

The text in this section is based on the submission provided by the EXIST team to the Roadmap Committee. The questions asked by the Committee for Technology needs are listed and then answered in the form of the tables and notes provided here.

(1) What are the Level 1 and Level 2 science requirements for the proposed mission, and how do these motivate the candidate technologies, which will be investigated? Explain the connections between the science requirements and the engineering requirements on those technologies.

Table 6-1. Level 1 Science Requirements for EXIST

Objective	Parameter	Requirement (range) & [Justification]	Technology Development Needed (Notes)
Survey & GRBs	Sensitivity	0.05mCrab (10-100keV) [AGN & GRB sample size] 0.5-1mCrab (100-600keV) [AGN spectra; GRB spectral lags/luminos.;511keVsurvey]	CZT large area (>2-4m^2) imager: Tiling; 1.2mm pixel pitch contiguous (1) Low-noise ASIC & coupling board (2) CZT large area (>4-8m^2) imager: Tiling; 1.2mm pixel (1); multi-pixel readout (3) Thick (≥5mm)CZT crystals; depth-sensing (4) Thick (approximately 7mm), possibly curved, high-Z coded aperture masks (5)
Survey & GRBs	Instantaneous field of view	180°x75° (flat; fully-coded) [180°: fullsky/orbit x >60-75°: max. exp./orbit]	Coded aperture imaging simulations (6) & FOV (collimation and shields) studies needed. Auto-collimation. Studies for coded aperture (7)
Survey & GRBs	Sky coverage	Full sky each non-SAA orbit Simultaneous over full energy band [AGN & GRB counts; source spectra; variability]	None; but S/C pointing and ops issues (8)
Survey & GRBs	Angular resolution	Approximately 5' (10-100keV); Approximately 5-10' (>200keV) [AGN confusion; centroiding bright sources & GRBs: approximately 10"]	Imaging & coded mask design (6) Auto-collimation. Studies for coded aperture (7)
Survey & GRBs	Aspect	Approximately 5" [centroiding bright sources & GRBs to approximately 10"]	None; but telescope structure issues (9)
Survey & GRBs	Time resolution	2-5μsec [GRB lags, spectra; micro-bursts, SGRs; shields]	None, but anti-coincidence shield segment size; data bus design issues (10)

Notes: Numbered footnotes in Table 6-1 provide brief responses to the requested "connections between the science requirements and the engineering requirements on those technologies":

1) Large area (4-8m^2) CZT imager is the primary technology development needed. This is 8-16X the area of the Swift/BAT CZT array, implying engineering requirements:
   - Large-volume CZT production and uniformity (≥4-8 x 10^4 CZT crystals, 2cm x 2cm, each with 16 x 16 anode pixel arrays (1.25mm pixel pitch)). Pixel, not strip, readout needed for >200 keV (Compton regime)
   - Mounting CZT crystals onto detector crystal arrays (DCAs): probably 2x2 crystals (2cm ea.) bonded to single coupling board with interconnects to ASIC readout underneath
   - Tiling (close-packing) DCAs (7x6) into DMs with ≥90% packing efficiency (detector area/structure area)
   - Packaging DMs, shields and associated digital readout for high tiling efficiency
   - Calibration: test pulses (entire array) vs. distributed absolute calibration (tagged ^{241}Am)
   - Thermal control: CZT focal plane at approximately 0±5°C (heat-pipes, radiator)

2) ASIC development is critical and implies following engineering requirements:
   - Low-noise (<100-200ev), low power (<75μW/channel), 16x16 or 32x32 pixel readout
   - Development of techniques to optimally couple the CZT pixels to the (smaller: approximately 0.6mm) ASIC pixels
   - Development of optimum contact and bonding for both ASIC and CZT for large-scale, high-yield and space qualified CZT-ASIC coupling

3) Multi-pixel readout (sparse: peak + neighbor pixels, or pulse-height selected) needed for both inter-pixel charge-splitting and Compton analysis (at >100keV):
   - Extend present (Caltech) and planned (IDE) ASIC designs for sparse readout to optimize for EXIST application
   - Digital processing of multi-pixel data: centroiding vs. Compton (≥2 event) modes

4) Use of thick CZT (≥5mm) needed for >20% efficiency at approximately 500keV requires:
   - High uniformity CZT production (possible solution: IMARAD CZT)
   - Depth sensing readout for large FOV imaging (approximately 25° off-axis): projection onto CZT surface for HE events interacting deep in crystal
   - Depth sensing for optimum energy resolution (factor approximately 2 improvement for deep events)
   - Packaging of cathode readout and/or anode pulse-shape analysis

5) Design of thick (approximately 7mm) high-Z coded aperture masks (2.5mm pixel) requires:
   - Laser etching, laminated (50mil) construction; bonding & alignment issues
   - Self-supporting (isolated segments); tiled construction; random vs. URA patterns

- Possible curved vs. faceted (tiled) segments; structural supports; rigidity; thermal distortion

6) Wide-field, high resolution coded aperture imaging telescope design requires:
   - Imaging simulations for possible mask-detector configurations (e.g. hemispherical) to demonstrate that systematic noise effects in imaging are smaller than detector-background systematic noise effects.
   - Simulations of scanning survey vs. pointing (observatory mode) sensitivities
   - Single detector-mask design (current baseline) vs. separate LE (<100keV) and HE (>100keV) systems

7) Auto-collimation of coded aperture mask (2.5mm pixels in 7mm thick mask) requires:
   - Radial mask holes (hemispherical coded aperture imaging)
   - Imaging simulations to derive systematics across FOV; interplay with collimator
   - Imaging simulations to optimize curvature vs. faceted mask

8) Full sky each orbit and bright source (e.g. CygX-1) vs. telemetry (TLM) limits may require:
   - Low energy (<20 keV) 1D collimator (thin slat: approximately 10^o) or dynamic data sampling

9) Fine aspect (5") across full FOV requires:
   - Small intrinsic mask displacement (<50 micron) or relative mask displacement measurement
   - One star tracker per telescope (3 total), 2 needed (avoid Sun): tracker sensitivity for scan (approximately 200"/s) requires trackers pointed closer to orbital poles
   - X-ray aspect from bright sources (fractional sky coverage but interpolate for total check each orbit)

10) Anti-coincidence shields (rear) and active collimators require:
   - Segmented design for trigger rates below dead time limits
   - Differential rate and pulse height processing to distinguish particle bursts from GRBs; GRB spectra (approximately 0.6 - 5 MeV); coarse GRB positions (BATSE type), combined with DM trigger rates, to speed up initial coded aperture imaging analysis on board (<10sec) for prompt GRB positions to ground via TDRSS low data channel

Table 6-2. Level 2 EXIST Science Requirements

Objective	Parameter	Requirement. (Range)& [Justification]	Technology Development Needed (Notes)
BH transients and Novae	Response	Inertial pointing by next orbit [study rare events]	20-100keV continuum band (BHs) and 511keV band (novae) onboard imaging analysis (1)
GRB spectra at >0.6MeV	Sensitivity and resolution	0.5 - 5 MeV [extend GRB spectral lags to higher Energy]	None, but simulations for PHA on external collimator shields only or also rear shield
GRB & bright cont. source polarization	Sensitivity	<10% for >100mCrab [non-thermal physics]	Multi-pixel readout: Measure detected PSF asymmetry on detector plane for imaged counts(2)

Notes: Numbered footnotes in Table 6-2 provide brief responses to the requested ``connections between the science requirements and the engineering requirements on those technologies":

1) Fast bus and onboard processing for partial imaging analysis (several bands) each orbit requires:
- Large format memory (each DM or Telescope) for local processing; hardware back-projection lookup tables and fast central processor to combine 3 telescopes and aspect

2) Multi-pixel readout for polarization measurement requires:
- Compton scattered event (typically >100 keV) in CZT and projected (on focal plane) azimuthal asymmetry of primary and secondary events. Simulations and ASIC design studies needed

Original questions 2 - 7 from the SEU Roadmap Committee follow, with bulleted responses and brief explanatory notes:

(2) What are the significant technological challenges for these technologies --- i.e., which technical capabilities have not already been demonstrated?

There are four primary technological challenges, in ranked order:
- Large area (4-8m^2), low-cost (approximately \$200/cm^2), high-uniformity CZT
- Tiled ASICs (large scale) with 50-75 μW per pixel (<600W, total)
- Digital bus architecture to read all the ASICs and combine the data; high data volume and need for on-board processing for rapid GRB (10sec) and transients (1 orbit) positions
- Coded aperture imaging with curved (or faceted) masks; scanning geometry

And several secondary challenges:
- Imaging effects of supports, structural elements
- Mask support (want to support an arbitrary pattern, which means near unsupported pixels: laminate, overburden or inter-pixel support grid?)
- Structure: this will be one of the largest composite structures to fly; it has been designed in concept but would benefit from technology development
- Large area/volume shields: tiling, segmentation, rates and trigger issues; optical path length: APD or PMT readout; spectroscopy on shields (for GRB spectra at >1MeV): ability to unfold spectra from rear vs. side shields
- Read-out, power, LE threshold

The primary challenges are the very large area of pixilated solid-state detector, with implied power and data requirements, and the wide field but high angular resolution coded aperture telescope design. Given the modular approach and current status of CZT and ASIC development, and a program of simulations and laboratory-balloon imaging tests, these are achievable with a technology development program. The requirement for

CZT availability, uniformity and cost may be achieved by the IMARAD Corp. (though other sources should still be pursued). The ASIC requirement also has several prototype solutions (outlined below) but is in need of significant development for optimization to the tiled CZT crystal (contiguous crystal mounting) and crystal-ASIC coupling needs for EXIST. The imaging considerations can partly be investigated through detailed simulations (already underway) but balloon flight tests are needed. It is likely that the very large pixel count, and scanning geometry (with systematic effects averaged over a very large number of pixels) will minimize the effects of the non-planar coded mask vs. detector geometry currently envisioned (*e.g.* hemispherical or faceted coded aperture). This would allow fine imaging over the very large FOV without significant auto-collimation.

(3) For each technological challenge, what are the metrics by which success --- i.e., technical readiness --- is to be measured?

- Measure significant number (>100) 2cm x 2cm x 0.5cm CZT crystals with reference coupling board and ASIC to measure contact uniformity; crystal homogeneity; temperature sensitivity. Metric: $\leq$10% variation
- Fabricate significant number (>100) Detector Crystal Arrays (DCAs) (2 x 2 CZT crystals and bonded ASIC) and measure sample variance in detector-pixel gain and detector quantum efficiency with uniform illumination at fixed energies (e.g. ^{57}Co: 14, 122, 136 keV; ^{133}Ba: 30, 80, 276, 302, 356 keV). Metric: *$\leq$10% variation*
- Large scale 50-75μW/ch ASICs: actual power measurement from one DM (750cm^2) and one sub-telescope (ST) array (4 DMs), with 1.92 x 10^5 channels, with digital processing. Metric: *verify scaling*.
- Digital bus architecture: breadboard prototype, measure a) noise, b) power consumption c) cross-talk d) data throughput and e) high event rate processing time to source positions
- Imaging: demonstrate through Monte-Carlo that sensitivity goal and angular resolution requirements are met when reconstructing through a) idealized curved masks and b) a 'real' system (faceted vs. curved mask, c) effects of structural supports: quantify imaging and spectral sensitivity for cases a) - c). Metric: agreement within approximately 20% of lab imaging with single ST array and partial mask
- Mask support: measurement of overburden impact on LE cutoff for candidate mask fabrication technology. Metric: $\leq$50% loss at 10keV
- Structure: mass analysis for optimized design, strength and vibration testing for telescope and mask structures. Metric: vibration testing on ST & mask prototype for launch loads
- Shields: LE threshold in prototype shield crystals. Metric: 60 keV (^{241}Am source scans) threshold achieved over >90% of shield area

A prototype mission concept design (developed from IMDC study, follow-up study, and ongoing SR&T development) has identified both technology challenges and metrics for their solution.

(4) *What kinds of demonstrations are required to validate technical readiness? Will ground testing be sufficient, or are there technical capabilities, which can only be demonstrated in space?*

- Lab demonstration of prototype DM (power; thermal; rate limits)
- Lab demonstration of wide-field, high resolution, imaging (curved vs. faceted masks)
- Balloon flight demonstration of DM performance and stability (gains; calibration), shielding and backgrounds, and scan-survey imaging (initial tests through SR&T program)

The technology demonstrations are outlined also in response to question three. Most of the needed program is laboratory based, but a balloon flight demonstration and test program is also advisable for full testing. The prototype elements of balloon tests can be conducted under the SR&T program, though a full-scale EXIST ST and detector system, with data and power requirements for the full mission, will require support from the mission technology program.

(5) *What is status of each metric --- i.e., compare the current capability with the required capability?*

- Detector array size: INTEGRAL/ISGRI has 0.26 m^2 of CdTe detectors and Swift has 0.52 m^2 of CZT detectors (both 2mm thick) vs. 2.7 m^2 (5-10mm thick) for each of 3 telescopes for EXIST
- Demonstration of ASIC power and energy resolution (Caltech HEFT detector): approximately 50μW/ch in 24 x 48 pixel ASIC, with 0.5 keg (FWHM) resolution in CZT
- Demonstration of cathode depth sensing (Harvard CZT3 detector): approximately 0.5mm depth sensing in lab setup but not yet on extended imaging array
- Data processing (onboard GRB positions): system and algorithms being developed for Swift

  Many of the basic elements required have been partly developed in the lab or with other missions. However the extension of these to a full system on the scale needed for EXIST requires a mission technology program.

(6) *Is the required capability a reasonable extension of the current capability or does it require a significant advancement or new approach?*

- 4-8 m^2 of total CZT detector area and associated ASICs are in modular increments that scale from Swift but may require new approaches for large volume production, CZT-coupling board-ASIC bonding, and testing
- Packaging of CZT arrays and shields into DCAs and DMs for modular redundancy should be considered vs. other highly modular systems
- On-board calibration of such a large area system may present new challenges (distributed low-level tagged ^{241}Am sources (+ test pulse systems)

- Requirements for low-power over 5 x 10^6 channels should scale from achieved performance in 10^3 channel devices
- Requirements for high-MIPS processing (on-board positions) may require new parallel approaches; data bus and hardware correlation processing may need new development

  No radical new approaches are foreseen as required; the large area detector and readout appears possible to design from current prototypes, though again demonstration and optimization are needed.

(7) *Is the specific technological challenge being addressed for other applications? Identify technical synergies with other NASA programs if they exist.*

- CZT total area and production/mounting: DOE program for radiation monitoring devices will provide useful input for large-scale CZT-ASIC integration (possibly approximately 30m^2 of CZT but distributed and mounted on approximately 10^4 devices)
- CZT crystal acquisition and testing-mounting: Swift has approximately 33 x 10^3 CZT crystals (each 4mm x 4mm x 2mm) individually tested and mounted on 256 coupling boards (128 crystals per single ASIC readout) vs. 20 x 10^3 CZT crystals (each 2cm x 2cm x 0.5cm) mounted on 5000 coupling boards (4 crystals per single ASIC readout) for EXIST
- CZT array size: INTEGRAL/ISGRI has 2600 cm^2 of CdTe detectors; Swift has 5200 cm^2 of CZT detectors
- CZT detector energy resolution: medical imaging goals are <2% energy resolution
- CZT detectors high-energy response: medical goals are imaging 99-Tc 141 keV line for bone scans; nuclear surveillance imaging will extend to >400 keV.
- Number of electronics channels: GLAST/LAT has approximately 10^6 electronics channels for Si strip detector (tracker)
- Number of pixels: SNAP has 144 CCDs of 1600x1600 pixels = 3.7x10^8 pixels

Other space missions (primarily Swift) will have developed some of the required technologies. The required CZT crystal count for EXIST is actually smaller than for Swift. However, the fine pixel size (1.2mm for EXIST vs. full 4mm crystal size for Swift) imposes a much more significant readout and data acquisition challenge, as well as total packaging and integration challenge with approximately 20X the number of CZT-ASIC detectors (DCAs) needed. The shielding requirements are more challenging than Swift but no more so than INTEGRAL. The total data channel count is comparable to GLAST but with the key difference that, for EXIST, these are spectroscopic, not discriminator, channels. The onboard data throughput and data processing needs for GRB (and transient) source positions are more challenging than for Swift but are not beyond projected data processing and power capabilities in the mission timeframe.

7 Mission System Design Concept

7.1 System Overview

The EXIST mission architecture is based on a zenith pointing, free-flying observatory in low Earth orbit (LEO). The essential segments of the systems consist of a customized S/C bus, instrument modules, and ground system. An Evolved Expendable Launch Vehicle (EELV) of a Delta IV type will be needed to carry the observatory into a stable LEO approximately 500km in altitude at an inclination of 22° or lower depending on launch vehicle performance and payload mass. Each segment and its subsystems are thoroughly described in the document and along with discussions on alternate concepts, trades, and risks that have been considered.

The S/C bus will provide the normal engineering health and safety functions associated with Earth orbiting S/C. The S/C structure will be constructed primarily of milled aluminum and honeycomb panels with carbon composites for weight savings as needed. Thermal systems provide active heating and semi-passive cooling via a loop heat pipe and passive thermal control with MLI. The power system will use state of the art triple junction gallium-arsenide (GaAs) SAs and nickel-hydrogen batteries to support a 1500 W orbital average load. The EXIST Attitude Determination and Control System (ACS) employs a zero-momentum ACS with star trackers and an inertial reference unit (IRU, or "gyro") as its primary science-mode sensors. Reaction wheels will control the attitude, with continuous unloading of secular torques using magnetic torque rods. A bi-propellant propulsion system using MMH fuel and nitrogen tetroxide (NTO) oxidizer will be required for on-orbit maintenance and de-orbit maneuvers. The Command Data Handling (C&DH) subsystem processes the commands received from the ground, and the data from the S/C subsystems and the instruments. The C&DH can store 1 day worth of instrument and S/C data and supports a nominal 7 to 8 ground contacts per day. EXIST will utilize existing multi-user ground stations to recover the survey science data and to uplink routine commands. The RF communications system is baselined to downlink science data at 20 Mbps using X-band transmitter. An S-band link will be used for ground commanding and S/C engineering health and safety data. The gamma ray burst alerts will use the TDRSS Demand Access Service and will be used by the S/C to alert the operations team of any onboard anomalies.

The EXIST instrument consists of three High Energy Telescopes (HETs). Each of the three telescopes are mounted into a single supporting structure (compatible with a Delta IV launch vehicle) such that together they provide a 180° by 75° instantaneous FoV. Each EXIST telescope has a coded aperture mask that creates a shadow pattern on the detector plane, allowing the telescope to image the hard x-ray sky. The mask is effective from 10 keV up to 600 keV and utilizes 7.0-mm thick tungsten, with its high atomic number, density and thus stopping power and shadow contrast, to meet all science requirements. Use of this material dictates the need for adequate propulsion systems for a controlled end of mission de-orbit. The observatory is oriented (see Fig 7-1) so that the orbital ram direction sweeps this 180° by 75° fan beam across the entire sky once per orbit.

The EXIST ground segment will use existing multi-user ground stations to recover the survey science data and to uplink routine commands. The communications system is baselined to downlink data at 20 Mbps using X-band. EXIST generates about 60 gigabits of data per day (compressed), which require 7 or 8 contacts to transfer to the ground.

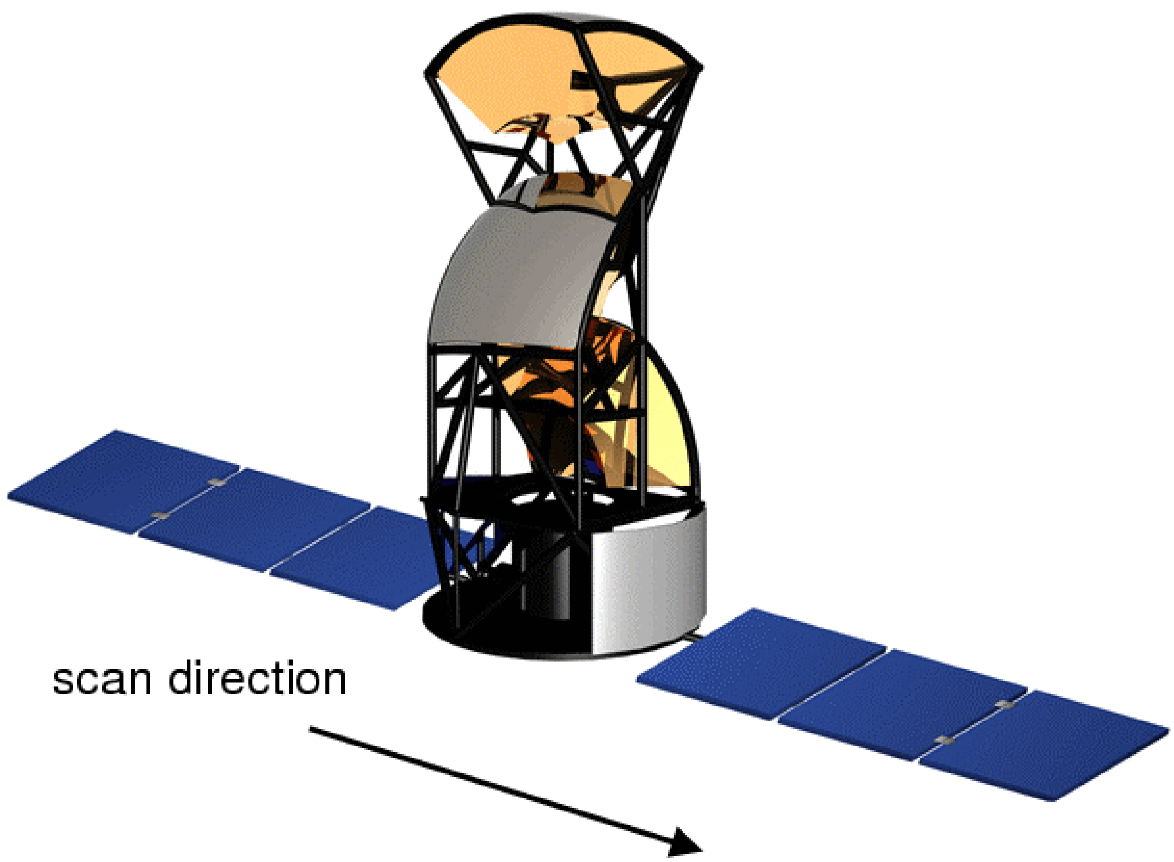


Figure 7-1. EXIST Observatory (shown without full structures, radiators, and thermal blankets)

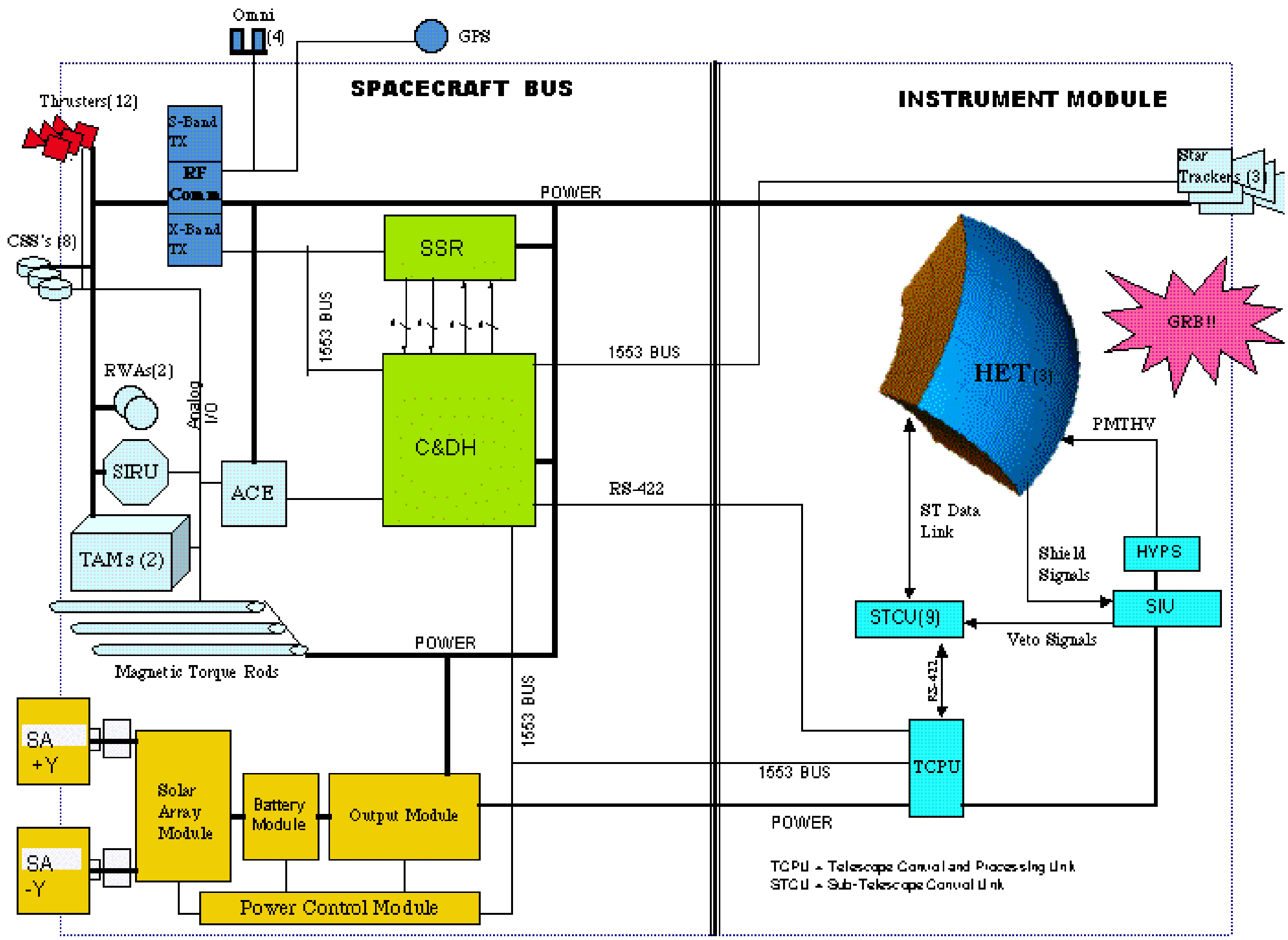


Figure 7-2. EXIST System Block Diagram

7.2 Systems Engineering

7.2.1 Overview

System engineering has been involved from the very early stages of the EXIST mission concept study beginning with operational concepts as both an ISS attached payload and most recently the free-flyer spacecraft mission which is the subject of this study report. The initial operations concept of the EXIST "free-flyer" mission archeticture and observatory design was a direct result of systems engineering process that begin with top level mission objectives and requirements as stated by the EXIST lead scienctists. These requirements were analyzed and developed for validity in terms of functionality and performance by GSFC's IMDC in the first mission design iteration.

The IMDC was commissioned to complete the first all-up mission operations and S/C concept for implementing EXIST as a "free-flyer" in November of 2001. The efforts of this study served as the technical basis for the S/C bus section of this report. The IMDC team focused on the S/C bus and subsystems design, instrument interfaces, launch vehicle selection, orbit placement and maintenance, S/C operations and data collection, safety and reliability through end-of-life and eventual disposal. A subsequent team of mission systems and key discipline - engineers and specialists further refined the design and alternate solutions.

The HET instrument development was done in collaboration with Lawerence Livermore National Labs, GSFC and Harvard University. An earlier instrument concept development was completed by GSFC's Instrument Systhensis and Analysis Lab (ISAL) in October, 2000 for an ISS Attached Payload.

Additionally, new technologies necessary for mission success were explored and potential risks identified and included in risk identification section.

7.2.2 Systems Engineering Process Implementation

The systems engineering process implemented for EXIST consisted of a number of activities, functions, methods, and products with a major goal of coordinating the engineering development of a mission architecture and observatory design that meets the requirements consistent with the operations concept to operate in the expected mission environment, and could be developed on schedule and within cost. The following activities were performed within the realm of Systems Engineering:

Requirements Identification and Analysis: Identified and defined the assumptions, functions, parameters and levels of performance for the system.
Operational Concept: Developed a concept as to how the system will be operated in the expected environment and meet the stated mission objectives.
Design Synthesis: Developed a mission architecture and observatory design to meet the requirements and support the operations concept.
Validation of Requirements and Assumptions: Evaluated the assumptions and requirements against the objectives.
Validation of Operational Concept: Evaluated the operational concept against the mission objectives and requirements.
Validation of Design: Evaluated the observatory design against the mission objectives and requirements.
Risk Identification and Resolution: Identify risk items and perform analyses, tests, prototyping, etc. to reduce the risk.
Verification Planning: Identify the method, program activity, facilities and equipment needed to verify the system against the requirements.
Validation of Verification Plan: Evaluate whether the verification plan is complete and achievable.

7.2.3 Additional Systems Engineering Efforts

7.2.3.1 System Interfaces and ICDs

Defining interfaces between major subsystems is an important outgrowth of requirements analysis and allocation, and will allow multiple detailed designs to proceed in parallel. Once requirements and functions are partitioned, the interfaces were then defined. Preliminary block diagrams for the EXIST system and key subsystems were developed to aid this process. EXIST interface requirements should be well defined, before PDR, to allow detailed design to proceed with minimal risk of changes. Interface Control Documents (ICDs) are needed to describe where and how various system elements need to connect or communicate with each other and also where isolation is required to prevent interference

7.2.3.2 Technical Resource Budget Allocation and Tracking

EXIST must define acceptable resource margins and then set up a margin management philosophy based on design maturity and time.

The margin philosophy includes a process for reducing required margin throughout the project's life. For example at PDR, a 20% margin may be appropriate. At CDR, a 10% margin could be appropriate. Another factor in margin tracking is the precision of the estimate. Estimated, calculated and measured numbers can carry different uncertainties and may require different margins.

Resource budgets typically include, Mass, Power, Battery, Fuel, Memory, CPU Usage, Data rate and volume, TLM, Commands, Data Storage, RF Link, Contamination, Alignment, Total Dose Radiation, SEU, Surface and Internal Charging, Meteoroid, Atmospheric (atomic oxygen), ACS Pointing and Disturbance (Atmospheric Drag, Gravity Gradient, Solar Pressure), and RF exposure on the ground and on orbit.

Initial budgets for mass and power have been developed in support of the EXIST free-flyer concept presented in this study report. A total of 8800 kg is allocated for observatory mass based on the selected launch vehicle, a Delta IV, with a 22°inclination and 500 km altitude orbit. Based on the instrument and S/C bus needs, the power system design is capable of providing an on-orbit average of 1500 watts and peak power of over 3000 watts. The estimated mass and power margins are positive and include a 20% factor for mass contingency while power numbers include a 30% contingency factor. See Table 7-1, Estimated Mass and Power Summary.

Table 7-1. EXIST Mass and Power Summary

EXIST MASS & POWER SUMMARY		
Element	**Mass* (kg)**	**Power* (W)** (orbit avg)
S/C Bus Structure	692	0
Communications System	24	56
ACS	275	317
Propulsion System (dry) (thrusters, tanks w/heaters, lines)	76	39
Propellant (w/pressurant)	881	0
Power System (batteries/arrays)	241	68
C&DH	29	64
Active Thermal Systems	36	46
Misc. Harnesses	26	0
Spacecraft Bus total (wet)	**2280**	**590**
Mask Subsystem	1446	0
Shield Subsystem	2115	86
Detector & Electronics	663	722
Telescope Structures	921	0
Instrument support structure	1000	0
Instrument thermal control	101	40
Instrument Module	**6246**	**848**
Observatory Total	**8526**	**1438**
Allocated	8800	1500
Margin+	3.21%	4.31%

*(Values include contingency factor: 20% for mass/30% for power)

Note: Excess Delta IV launch capacity is used to reduce inclination from a nominal 28.5° value. Substantial additional mass margin is available by launching Into a higher inclination while still meeting all science requirements.

7.2.3.3 Systems Engineering Management Plan

The entire systems engineering process is applied to each design phase of the project life cycle with increasing detail and refinement. Tailoring of how, when, where, and by whom these functions are performed is best described in the Systems Engineering Management Plan (SEMP) to be deveolped for EXIST and reviewed for updating at each major phase milestone completion. As described in GSFC's Draft Procedure Guidelines (PG) document for Systems Enginereeing, Table 7-2, Systems Engineering Key Functions Matrix, provided a view of the evolution, in maturity and fidelity, of the systems engineering functions over the systems engineering life-cycle.

Table 7-2. Systems Engineering Key Functions Matrix

Key Function	**Advanced Studies** Pre-Phase A ("Find a suitable project")	**Preliminary Analysis** Phase A ("Make sure the project is worthwhile")	**Definition** Phase B ("Define the project and establish a preliminary design")	**Design** Phase C ("Complete the system design")	Development Phase C/D ("Build, integrate, and verify and launch the system, and prepare for operations")	Operations Phase E / F ("Operate the system and dispose of it properly").
Understanding Objectives	Concept	Baseline	Commitment Note 1	Track Changes	Track Changes	Track Changes
Operations Concept	Concept	Baseline	Refine	Complete	Operations Plan	Track Changes
Mission Architecture & Design (Block Diagrams)	Concept	Baseline	Complete	Track Changes	Track Changes	Track Changes
Requirements Management	Concept	Top Level Baseline	Complete	Track Changes	Track Changes	Track Changes
Verification	Initial	Concept	Assign Method	Develop Plans	Complete	
Interfaces and ICDs	Concept Note 2	Initial	Baseline	Complete	Track Changes	
Space Environments & Specialty Engineering	Initial	Baseline	Complete	Track Changes	Track Changes	Track Changes
Resource Budget Tracking	Concept	Initial	Baseline	Track Changes	Track Changes	Track Changes
Risk Management	Estimate	FTA, RBD	FMEA, 2nd FTA, RBD	FTA, FMEA, RBD, PRA	Update Changes	Update Changes
Reviews	MCR	MRR, MDR	SDR, PDR	CDR	PER, MOR, TRR, SAR, FRR, ORR	DR
Configuration Management and Documentation	Informal CM	Control Level 1 Requirements	Start Formal CM	Track Changes	Track Changes	Track Changes
Systems Engineering Management Plan	Concept	Baseline	Complete	Track Changes	Track Changes	

7.3 System Verification and Validation Approach

7.3.1 Verification Program:

A verification program will ensure the EXIST system complies with requirements as defined in project documentation. Those requirements will be contained in such documentation as mission and system level requirements documents, subsystem specifications, ICDs, and drawings. Verification is accomplished at each level of the systems architectural hierarchy (e.g. component, subsystem, system) as deemed necessary to provide the needed confidence in ensuring that the system has been properly designed and built. The verification program plan will define the compliance program that identifies how the results of the verification activities will be submitted, reviewed, and tracked to demonstrate that the requirements are satisfied.

7.3.2 Verification Activity

The verification activity will define the verification method(s) (*e.g.* test, analysis, inspection, etc.) that will be performed to satisfy each requirement and the level at which the method(s) will be performed. Verification planning information will describe the detail activities associated with performing the identified verification method(s). Success criteria will be established that will indicate successful completion of each verification activity.

7.3.3 Validation Program

The System Validation Program ensures that EXIST is ready for its intended mission and meets the desired mission parameters as an integrated system. Although performed primarily at the fully integrated system level, validation will continuously occur concurrently along with verifications and as the system undergoes various stages of integration. For example, validation occurs at the S/C bus segment, instrument segment and finally at observatory level. A complete "end-to-end test" and "test as you fly/fly as you test" philosophy will be used in the validation activity to ensure that the EXIST system configuration that is being tested is one that ultimately flies and performs the mission.

The program consists of a series of functional demonstrations, analytical investigations, physical property measurements, and tests that simulate the environments encountered during handling and transportation, pre-launch, launch, in-orbit, retrieval, reentry, and landing. All prototype or protoflight hardware will undergo qualification to demonstrate compliance with the validation requirements.

The GSFC General Environmental Verification Specification for STS & ELV Payloads, Subsystems, and Components (GEVS-SE), is a baseline guide for developing the validation program. Alternative methods are acceptable provided that the net result demonstrates compliance with the intent of the requirements.

7.3.4 Validation Activity

Like the verification activity, the validation activity will define the validation method(s) and success criteria that will indicate successful completion of each validation activity. Similarly, the validation program plan will define how the results of the validation activities will be submitted, reviewed, and tracked to demonstrate that the originally established needs are met.

The validation activities begin with functional testing of assemblies. It continues through functional and environmental testing supported by appropriate analysis, at the unit/component, subsystem/instrument, and S/C /payload levels of assembly. The program concludes with end-to-end testing of the entire operational system including the payload, the Payload Operations Control Center (POCC), and the appropriate network elements.

7.4 EXIST Instrument

The EXIST instrument has been designed to meet the science requirements detailed in this report. Instrument sensitivity is the most important parameter driving the design. Fundamental performance criteria that directly affect sensitivity are:

- Field of view
- Detector area
- Shield configuration
-

The large instantaneous FoV needed by EXIST and available launch vehicle accommodation requires three HETs. Each of the three telescopes are mounted into a single supporting structure (compatible with a Delta IV launch vehicle) such that they provide a 180° by 75° instantaneous FoV (fully-coded imaging). The observatory is oriented with the 180° direction of the fan beam perpendicular to the orbital ram direction so that the orbital motion sweeps this 180° by 75° fan beam across the entire sky once per orbit (see Figures 7-1 & 7-3).

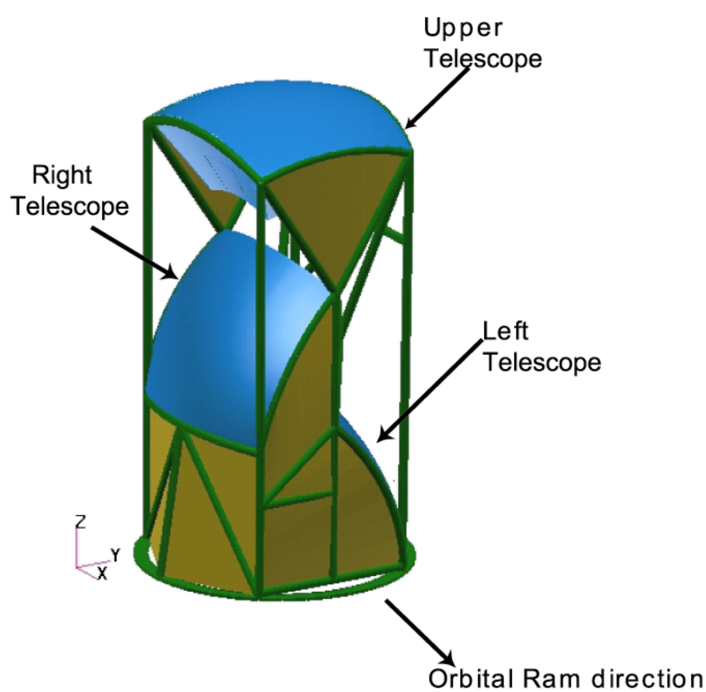
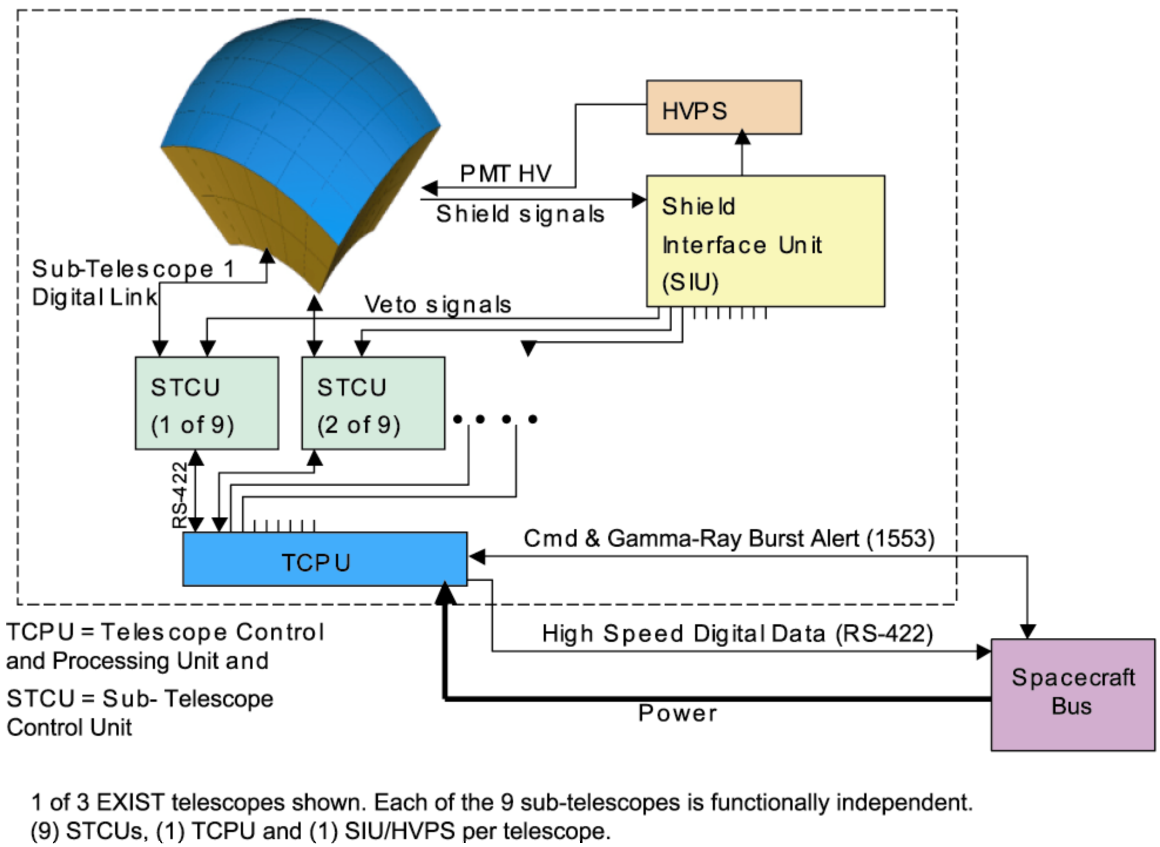


Figure 7-3. EXIST instrument High-Energy Telescope (HET) Modules.

Telescopes

Each telescope consists of a coded aperture mask and a position sensitive detector focal plane located 150cm behind the coded aperture. The detector plane is shielded by a combination of active and passive panels to reduce background from particles and photons that do not enter through the coded aperture mask. Each of the three telescopes are independent modules with their own processor and communication line to the S/C. Each telescope is constructed as a 3x3 array of sub-telescopes (STs) with individual FOV's 50°x58° and offset to give each telescope a 60°x75° FOV (fully-coded imaging; partially-coded imaging extends the FOV to approximately 5sr for the 3 telescopes combined). The functional block diagram for one of the telescopes is shown as Figure 7-4.



(Note: Nine STs (3x3 array) are co-aligned to form a telescope. Three telescopes form the entire instrument.)

Figure 7-4. EXIST telescope functional block diagram.

7.4.1 Subsystems

The subsystems that make up each EXIST telescope include the coded aperture mask that creates a shadow pattern on the detector plane, allowing the telescope to image the hard x-ray sky. This pattern is imaged by the large detector array, consisting of CdZnTe (CZT) detectors, pixilated to deliver 1.3 mm spatial resolution at the detector plane. The shielding subsystem, which prevents the particle and photon background from being counted as hard x-ray photons from the sky, surrounds the detector array. An ASIC readout is epoxy-bonded to the CZT detectors and is read out by a modular digital back-end unit that is in turn controlled by a single processing unit per telescope. This processing unit provides the electronic/communication interfaces with the S/C and also controls the individual telescope components. The entire telescope is held together by a composite structure that provides strength and stability. Each of these subsystems will be discussed in turn. Mass and power summary tables by subsystem follow.

Table 7-3. Mass budget for Instrument subsystem, and observatory

Instrument Component	Mass (kg) Estimate	Contingency %	Mass (kg)
Mask mass per telescope	438	10	482
Shield mass per telescope	598	18	705
Detector/readout/harnessing mass per telescope	190	16	221
Structure per telescope	256	20	307
Subtotal for 3 telescopes	**4446**	**-**	**5145**
Instrument support structure	833	20	1000
Instrument thermal control	81	20	101
Total instrument mass (including contingency)			**6246**
S/C Wet mass (incl. 20% contingency)			2280
Total Observatory Mass (wet)			**8526**

Table 7-4. Power budget for Instrument subsystem, and observatory

Component/Subsystem	Power (W)
CZT readout	256
Shield subsystem	66
Digital processing	299
Thermal Control System	31
Instrument power	652
Contingency (30%)	195.6
Instrument power total	**847.6**
Spacecraft power	455
S/C contingency (30%)	136.5
S//C power total	**591.5**
EXIST Observatory Power	**1439**

7.4.1.1 Masks

The mask is required to be effective from 10 keV up to 600 keV. For this high-energy performance a thick material with a high atomic number is required. The baseline material is 7.0 mm thick tungsten. This choice meets all science requirements. The mask pitch, or pixel size, is set by science requirements based on source positioning capability, the mask thickness, and the requirement that the mask not interfere with the FoV of any pixel (this FoV should be defined by the shielding). The baseline mask pixel pitch is 0.25 cm, which results in an angular pitch of 5.7 arc minutes and the ability to localize sources to 34 arc seconds for a 10-sigma detection. The mask geometry is set by the requirement that a ray defining the half angle FoV from a pixel on the edge of the detector intersect the edge of the mask.

The mask can be curved, or faceted, to maintain an approximately constant mask to detector distance although the planarity of the DM between STs causes some small (few cm) variations in this distance for a curved mask. An option where the mask is flat for each ST may be feasible and will be studied during instrument trade studies. Total mask area for the three telescopes is constrained by both the launch shroud diameter and center of mass (CM) constraints within the shroud.

The details of the mask pattern will also be determined during a subsequent mission study phase. The fraction of the mask that is open is baselined as 50% for mass budget purposes. Science or imaging considerations or mechanical support requirements (e.g., an interleaved 2.5cm pitch thin [0.2mm] grid to support isolated pixels) may change this open fraction after further study but changes will not increase the current mask mass allotment.

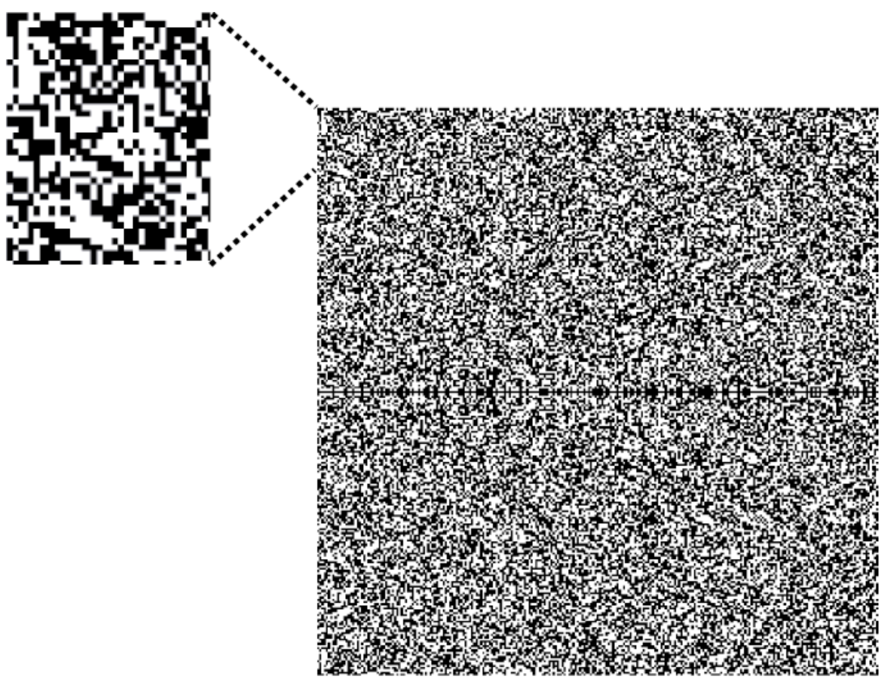


Figure 7-5. EXIST coding approach (pseudo-random).

Table 7-5 EXIST coded aperture mask parameters (each of three telescopes).

Mask Area (sq meters per telescope)	7
Mask Thickness (cm)	0.7
Mask density (g/cc)	19.25
Mask open fraction	0.5
Mask mass per telescope (kg)	438
Mask pitch (cm)	0.25
Mask to detector distance (cm)	150
Mask angular pixel size (arcminutes)	5.7

7.4.1.2 Detectors

The detector material will be Cadmium-Zinc-Telluride (CZT). This solid-state crystalline material offers energy resolution of approximately 1-3keV, spatial pixilation and an operating temperature range that will not require active cooling of the detector focal planes on orbit. The detector development plan described in Section 6 of this report covers the detector trade space that is still open; a nominal baseline configuration is described here. The detector thickness must have appreciable sensitivity for the high-energy end of the band pass, 600 keV photons, and must maintain good energy resolution throughout the band. Baseline thickness of the CZT is 0.5cm although thicknesses of up to 1.0 cm are being considered (for still better high-energy response). Imaging requirements lead to a detector pixel size that should be no more than one half that of the mask pitch. The baseline pitch is 0.125 cm. The individual detector assemblies will arrive from the manufacturer in small assemblies known as detector crystal assemblies (DCAs) as shown in Figure 7-5. The assemblies are 2 x 2 close-tiled arrays of 2.08 x 2.08cm crystals mounted in 4.16 x 4.16 cm geometry. Detector 'modules' will be built up as 25 x 29-cm units to accommodate focal plane packing geometry and electronics modularity. An array of 6 x 7 DCAs, as shown in Figure 7-6, makes up a DM. Each detector crystal assembly (DCA) is bonded to a readout chip that individually amplifies and conditions each of the 1024 pixels in the crystal. The detector and readout sub-assembly, described in section 7.3.1.5, are individually tested and then inserted into a tray assembly to construct a DM.

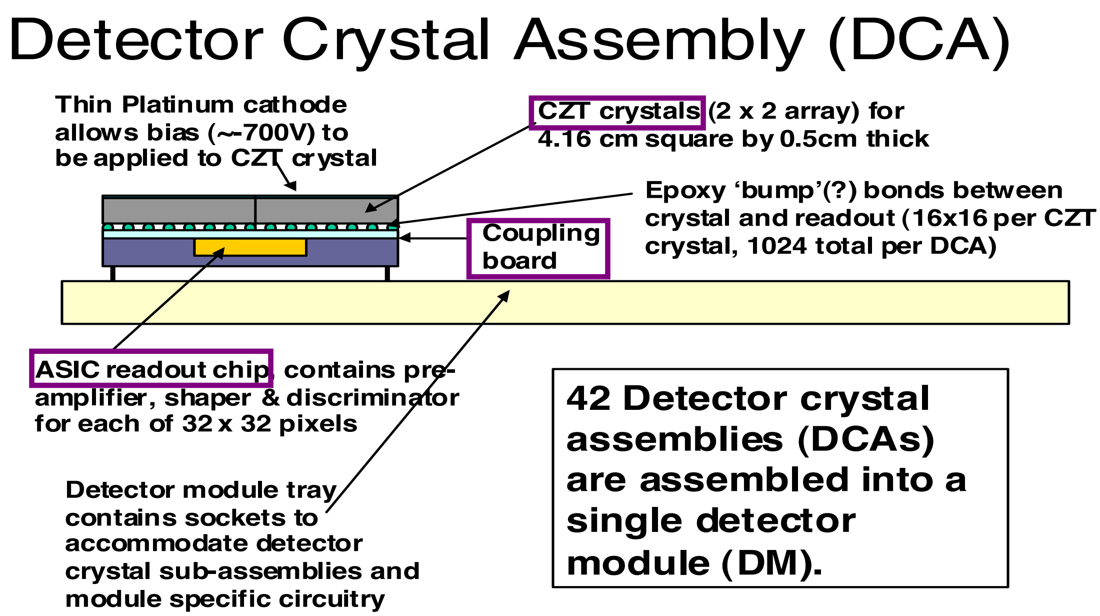


Figure 7-6. Detector crystal assembly and detector module tray.

(NOTE: Elements requiring further technology development are identified in the colored boxes)

Not shown above is the likely separate system that would be employed for cathode readout of each crystal. The combined cathode-anode readout for each event allows depth measurement for each event that in turn allows energy resolution to be enhanced, and off-axis imaging (projection effects) to be optimized. A system has been designed which would not interfere with the LE response of the detector module.

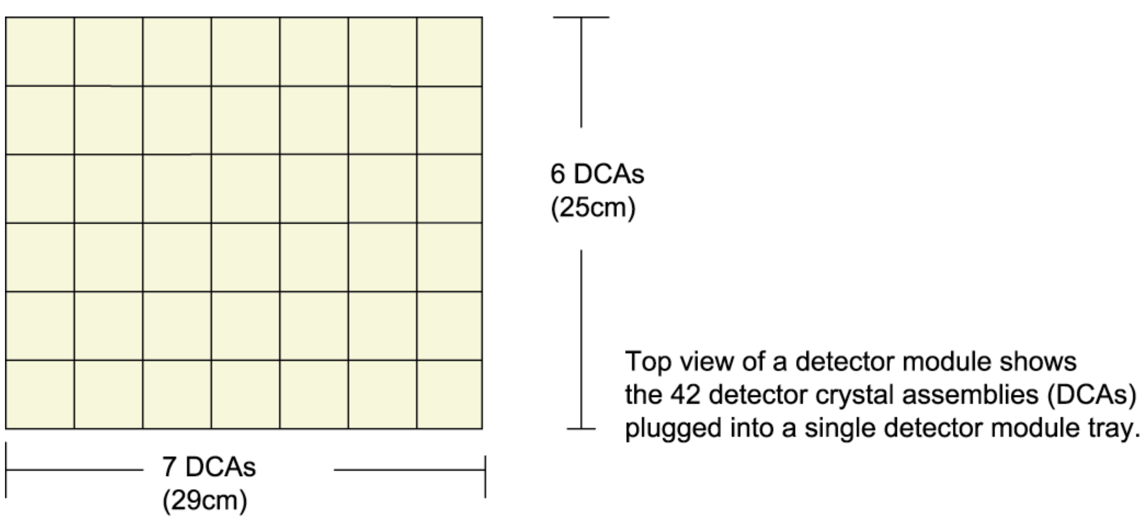


Figure 7-7. Top view of a detector module made up of 42 detector crystal assemblies (DCAs).

Key detector parameters for the baseline design are detailed in Table 7-6 although it should be noted that details are likely to change during the detector development work to be performed over the next two years.

Table 7-6. EXIST instrument detector parameters.

Pixel Pitch	**0.125 cm**
CZT crystal size (2 x 2 per DCA)	**42.0cm**
DCA Pixels per crystal	**1024**
DCAs per detector module	**42 (6 x 7)**
Pixels per detector module	**43008**
Detector modules per sub-telescope	**4**
Sub-telescope per telescope	**9**
Pixels per telescopes	**1.55×10^6**
Total number of telescopes	**3**
Total number of pixels for instrument	**4.65×10^6**

7.4.1.3 Structure

Each telescope is a fully integrated, self-supported unit. CFRP honeycomb panels are used to provide a 'box-like' outer structure. A CFRP grid structure supports the masks and DMs. CFRP struts between the DM grid and the mask grid provide additional mask support and raise frequencies within the structure. Minimal analysis has been done to date on the structure; finite element analysis is needed on the revised model of the instrument as generated during the IMDC exercise. No issues are anticipated but sizing of the support elements cannot be completed until analysis is in place. A conservative approach to mass estimates has been used to reflect the state of the mechanical analysis. There are no thermal or stability issues within the telescope modules themselves. There are concerns about problems with acoustic coupling that will require some engineering attention in the next design iteration.

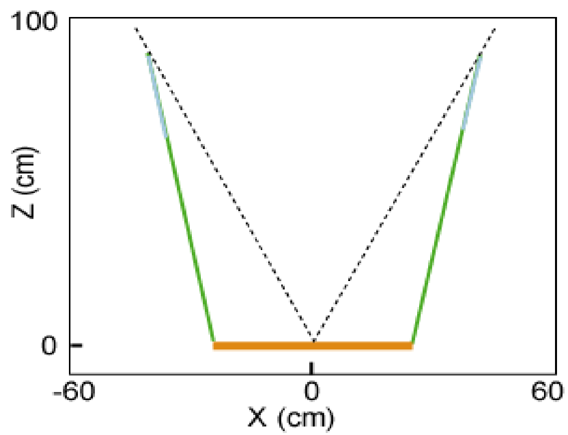
The overall instrument support structure itself (the structure that holds the 3 telescopes and mates to the S/C bus) has now been verified to meet all Delta IV requirements with first lateral mode of 12.4 Hz and a first axial mode of 46.2 Hz. Mass of the baseline structural design is detailed in Table 7-7.

Table 7-7 Mass of telescope structural components.

Side panel structure mass (kg)	110
Back panel mass (kg)	24
Shield support struts mass (kg)	22
Mask support mass (kg)	100
Total structure mass (kg)	**256**

7.4.1.4 Shields

A 2 x 2 array of DMs makes up a single ST. A ST has a 50° by 58° FoV defined by side shields and has a separate digital processing unit to handle the 1024*42*4 = approximately 172,000 pixels contained within this FoV. A ST is a complete functional unit capable of delivering a digital data stream to a central processor or directly to the S/C.



Field of view of an EXIST sub-telescope (2 x 2 detector modules) is shown by the dashed lines.
The side shields are 90 cm long.
This side view is of the 'X' direction, and represents a 25 cm detector module width and a 50 degree FOV FWHM.

Figure 7-8: Schematic view of the EXIST shielding configuration.

Side shields are arranged so that a 'ST', which consists of 2 x 2 DMs, sees a FoV of 50 x 58 degrees full width half-maximum (FWHM). The 3 x 3 STs are themselves mounted at offset angles of 20° and 25° to give the combined fully coded FOV of 60° x 75°. Back shields are required to veto photons or particles coming from below. Side shields are partially active (scintillator crystals, baseline CsI) and partially passive (W-Sn-Cu graded shield; top approximately 1/3) to minimize active shield dead time. A trade study on active/passive fraction and detailed shield geometry is to be completed during instrument trade studies. A nominal value of 70% active 30% passive is assumed for mass and power purposes in the current study. Active shield readout is by photo-multiplier tubes or photodiodes. Detailed simulations are needed to determine actual number of tubes needed. The baseline design, based on prior experience with similar systems, suggests 4 readouts per side panel (2 top, 2 bottom). CsI is the baseline material for active shield. BGO is a viable alternative although it's higher efficiency must be traded against the substantially higher cost. Rear shields are thicker, 2 cm thick CsI, to shield the major source of background, which comes from the direction of the Earth and locally produced spallation induced events from the S/C structure.

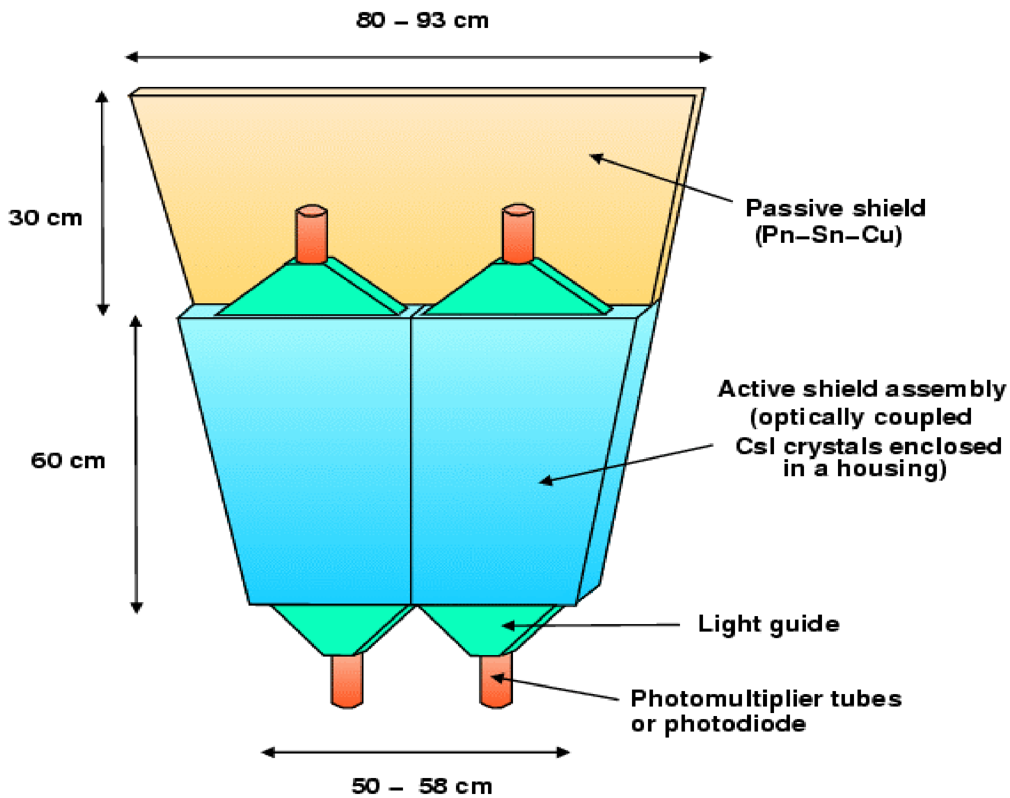


Figure 7-9. Concept layout for EXIST collimating side-shields (passive-active).

Readout is performed by PMTs or photodiodes. Detectors for each telescope are entirely shielded from all directions. Any penetrations of the shield have the effect of increasing background and should be minimized.

Table 7-8. Shield subsystem parameters.

Shield area (sq m per telescope)	12.312
Active shield thickness	0.800
Passive shield thickness (cm)	0.185
Active Shield density (g/cc) (CsI)	4.510
Passive Shield density (g/cc) (Al)	16.800
Active Shield fraction	0.600
Side shield mass per telescope (kg)	419.593
PMT's per shield side panel	4.000
Side Shield PMT's required per telescope	96.000
Rear shield x dimension	174.000
Rear shield y dimension	175.000
Rear shield thickness	1.300
Active Shield density (g/cc) (CsI)	4.510
Back shield mass per telescope (kg)	178.528
Total shield mass per telescope (kg)	**598.100**

7.4.1.5 Readout & Digital Processing

Each detector crystal assembly, 1024 pixels, is read out by an ASIC bonded to the CZT crystals of the DCA through a coupling board (see Fig. 7-6). A DM Data Handling Unit (DMDHU) collects the data from each of 42 detector crystal assemblies in a DM. Each ST contains (4) DMDHUs. Each ST is functionally independent and is controlled by a ST Control Unit (STCU). The STCU performs initial processing of the data (receiving data from the Shield Interface Unit (SIU) and handling the event veto logic), monitors rates for bursts and transients and performs initial positioning for bursts within a ST FoV.

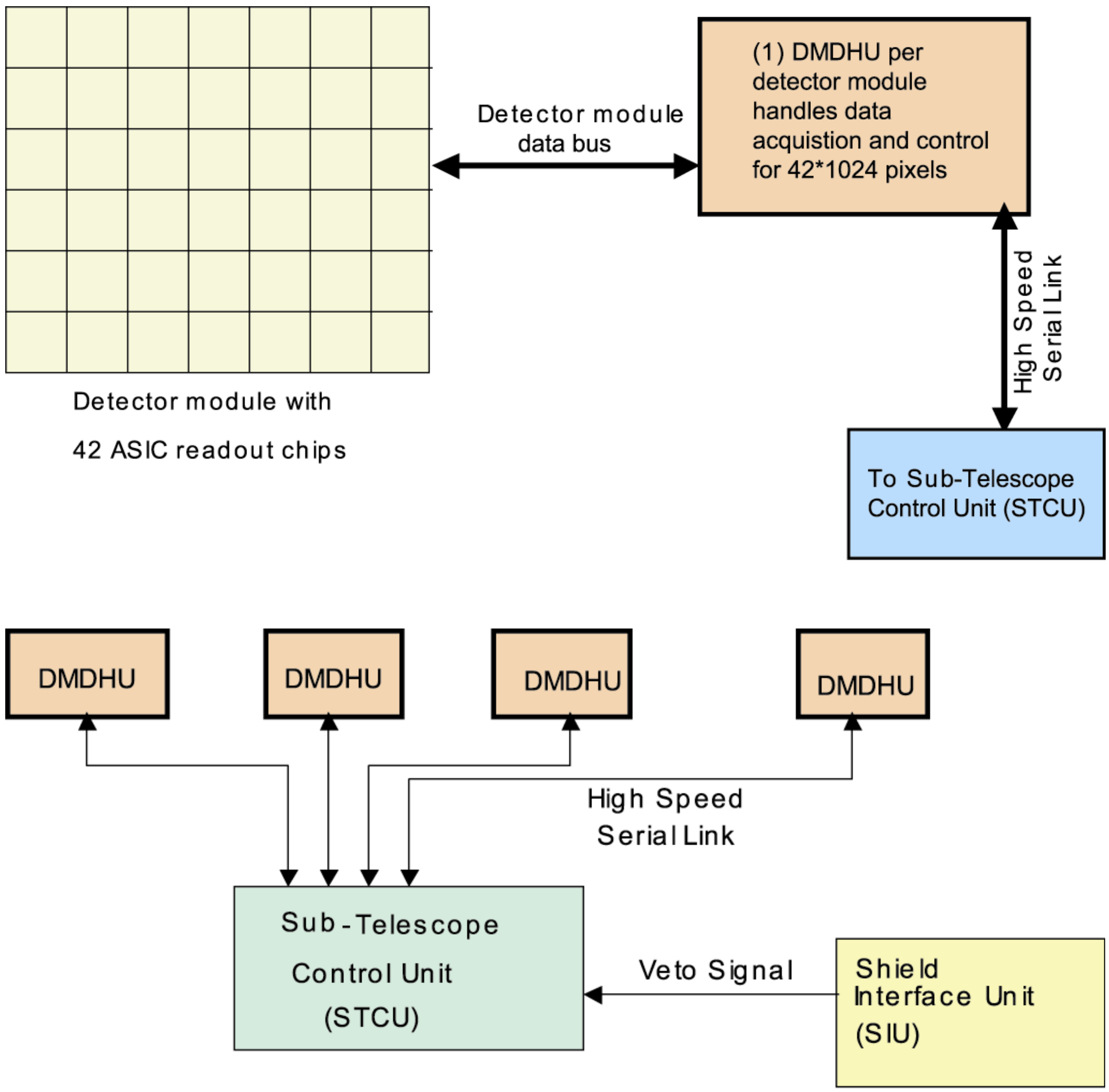


Figure 7-10. Instrument electronics functional block diagram.

7.4.1.6 Thermal Control

The HE Telescope Module thermal system consists of flight-proven techniques and hardware items. Heat is transported from a detector to radiators mounted on the ram (or wake) side of the instrument via Variable Conductance Heat Pipes (VCHP's), which can decrease the detector/radiator coupling to control temperatures and dramatically reduce detector heater power requirements.

The instrument utilizes standard thermal control techniques (VCHP's, heat pipes, heaters, MLI blankets, etc.) to meet thermal requirements. The radiators are heat pipe panels to improve radiator efficiency and enhance VCHP performance. The radiators are painted white to reduce absorption of solar and albedo flux, and all other external surfaces are covered with MLI. The radiators are coplanar to allow proper heat pipe panel operation under gravity, thus allowing full thermal system testing. The estimated mass is approximately 101kg (65kg heat pipes & panels, 34kg MLI blankets) and will require 40W for VCHP control.

Analysis/Modeling

Thermal analysis of the instrument shows that the area required to dissipate 600W of instrument power is 6.3m^2, assuming a 5C max detector temperature and a hot-biased environment. Readably available area on the wake- or ram-facing side is about 7.6m^2, and the radiators could be further enlarged to provide more margin.

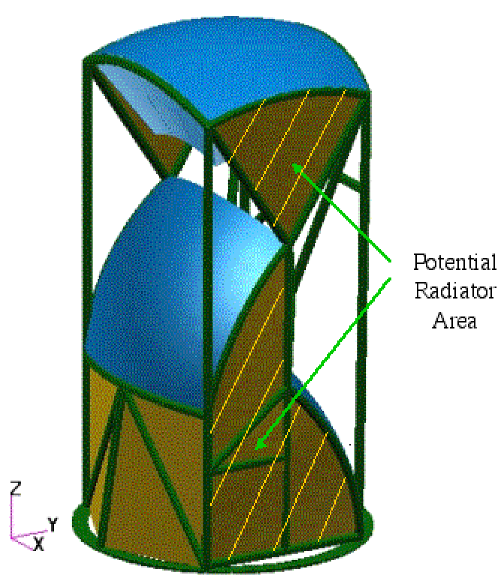


Figure 7-11. Instrument thermal radiator locations.

GSE

Ground cooling is required to keep the detectors at their operating temperature while they are being tested in air.

Alternate Concepts and Trades

The VCHPs could be deleted to reduce cost. Operational heater power of about 300W would then be required to maintain survival temperatures on detectors during cold environments.

Use of heat pipes on radiators could be deleted to save money, although mass would increase to provide adequate thermal conductivity and radiator size.

7.4.1.7 Software

Flight software (S/W) and data handling for the EXIST instrument is recognized as a significant challenge. Several layers of S/W are required. The first significant layer, at the DMDHU level, is primarily firmware that will deliver valid events to the STCUs. Close integration between this S/W team and the electronic hardware teams will mitigate risk, schedule impacts and total costs. For the next layer up, at the STCU, the major S/W challenge is the development of rapid algorithms that are able to sense and coarsely localize transient events, such as GRBs, and rapidly communicate the onset of an event to the TCPU, allowing coordination between the several STs that will see a typical high-energy transient event. The development of this on board image reconstruction S/W, a crucial science driver for the mission, will require extensive S/W validation. This effort is planned to include code reviews, self-test suites for each package, comprehensive test suites for the full simulation and reconstruction codes, high standards for documentation, and mock data challenges. The mock data challenges will include the preparation of a large sample of simulated events that can be used by the instrument operations center (IOC) to test their codes, databases and procedures.

The S/W on the TCPU, which must integrate results from each of the nine STs and communicate with the S/C bus, is relatively standard and is expected to present lower risk than at the STCUs. A flight S/W test plan, S/W management plan and peer level reviews throughout the S/W development process will validate the design of the S/W team efforts.

7.4.2 Interfaces

7.4.2.1 Mechanical

The three telescopes are mounted to an instrument support structure that holds the telescopes in the proper orientation and provides the interface to the PAF and S/C. The three EXIST telescopes mount to the instrument support structure via four hard points near the mask plane. Additional structure to support the aft-end of the telescope (DM end) is added to eliminate a ‘pendulation’ mode. The instrument support structure mounts to the top of a Delta IV PAF via 4 hard points on a circular interface flange.

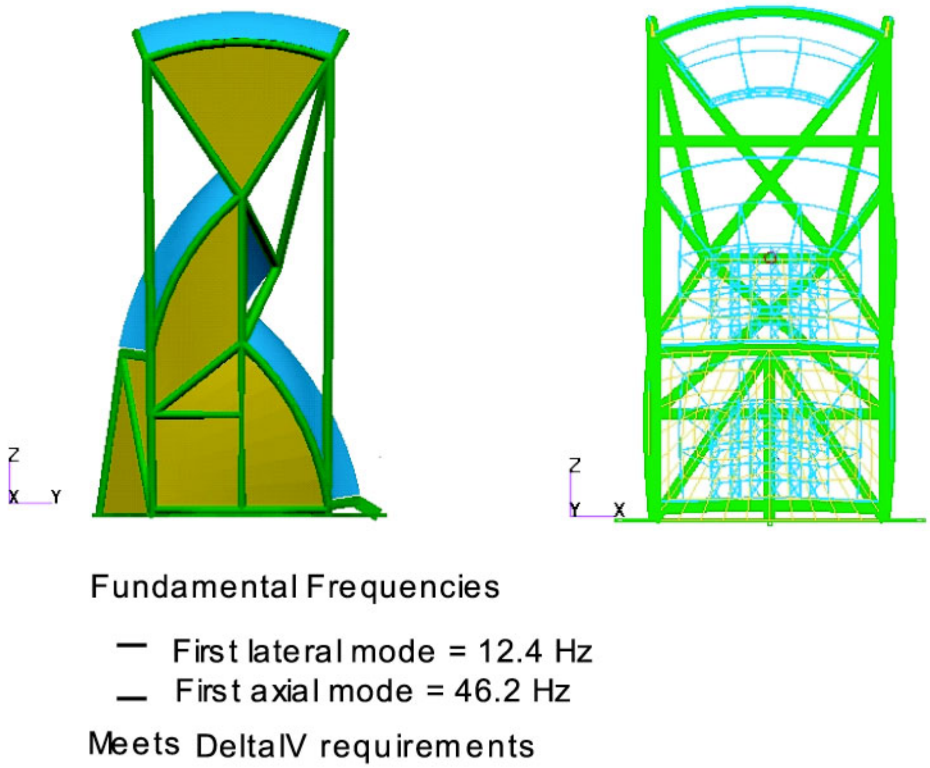


Figure 7-12. Instrument support structure.

Preliminary analyses of the instrument support structure and telescopes show positive margins of safety for Delta IV static loads. The primary lateral and axial modes are sufficiently high that, when coupled to the S/C bus, the observatory should not have any difficulty meeting the launch vehicle requirements of 8 Hz lateral and 30 Hz axial.

7.4.2.2 Electronics

Data flows from each of three Telescope Control and Processing Unit (TCPU) to the S/C for storage and later transmission. Burst and transient alerts originate in the TCPUs and are communicated to the S/C over 1553 bus for immediate transmission. Commands are handled on the 1553 bus. Regulated +28V power flows from the S/C to the TCPUs and is controlled/distributed for each telescope by the TCPU.

7.4.3 Instrument Integration and Test

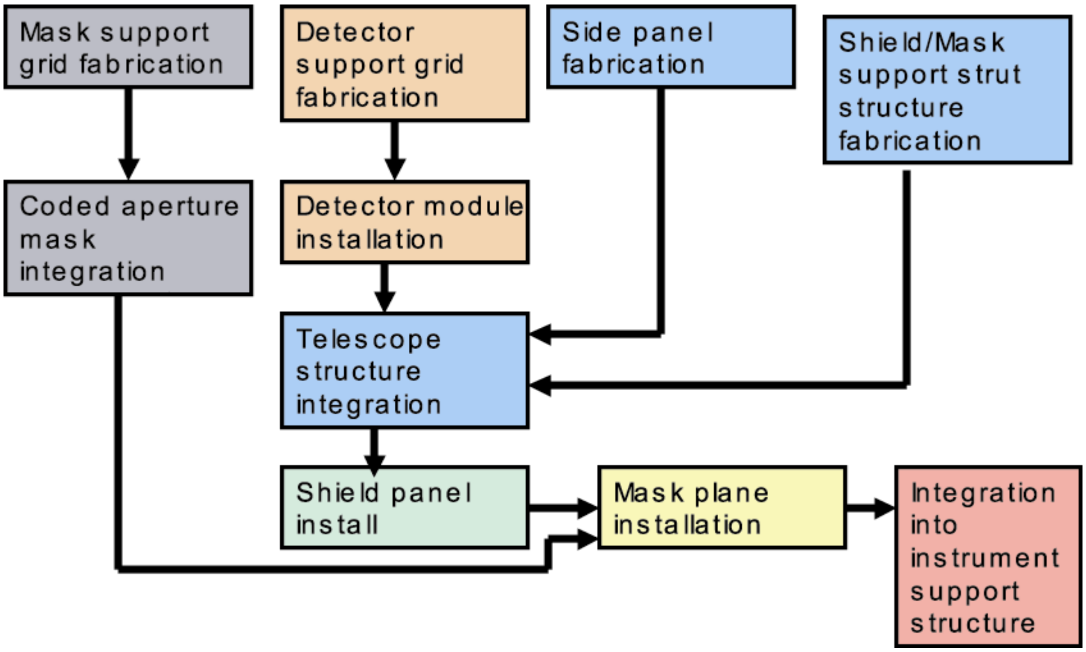


Figure 7-13. Instrument integration flow.

7.4.3.1 Instrument Level Testing

Component and subsystem testing occurs throughout the instrument build phase. Beginning with the DCAs, electronic functionality is tested at each integration step. Once the DCAs are inserted into the DM or DMs, subsystem environmental testing, including thermal vacuum and acceptance level vibration testing is performed along with continuing functional testing. As the DMs are integrated into a ST, an STCU simulator will provide continued functional and performance testing of the STs.

Primary instrument level testing is done at the telescope level. Each telescope unit is a sizable and functionally independent module. Performance validation, full instrument level vibration, thermal cycle, thermal balance and thermal vacuum testing will follow assembly of the STs into a telescope, and integration with the TCPU. Because of the large size of the EXIST instrument once assembled, it is anticipated that all instrument level environmental testing will occur at the telescope level. Observatory level testing, once the instrument and S/C are integrated, is discussed in the subsequent section.

The overall telescope support structure is independently validated using non-destructive examination (NDE), analysis, and proof testing. The size of the structure makes testing of the flight unit problematic although this will continue to be studied as the design matures.

7.4.3.2 Observatory Level Testing

Observatory level environmental testing levels is a significant challenge for the EXIST program. Because of the size and mass of the instrument, once assembled, no GSFC facilities are suitable for a full suite of environmental tests although suitable facilities are available at TRW in Redondo Beach, Lockheed in Palo Alto, and Loral Space Systems in Mountain. View. The EXIST mission philosophy currently emphasizes a full suite of tests at the telescope and S/C level with many of the observatory level test requirements to be met by analysis. Final determination of the suite of tests required will be deferred until selection of S/C and integrator vendor selection.

7.4.4 Instrument Ground Support Equipment (GSE)

7.4.4.1 MGSE

Substantial mechanical fixturing will be required for handling the instrument at the ST level and above. The masks, a major component of the mass of an assembled telescope, are tiled to ease assembly but will require handling and shipping fixturing. The detector sub-assemblies are packaged in individual storage and shipping containers as are the shield panels and their support components.

7.4.4.2 EGSE

The key components of the EGSE are needed early in the program. The first item is a DMDHU simulator so that DMs can be tested in flight-like configuration. Somewhat later in the program an STCU simulator is needed as individual telescopes are being assembled. Once the S/C vendor is selected, a dual channel S/C interface simulator will be needed.

7.4.4.3 Shipping Container

The instrument will be shipped at the telescope level where the size of the shipping container is compatible with normal modes of transport. The telescopes will be integrated as needed into the instrument support structure that will also be shipped in a dedicated container.

7.5 Spacecraft Bus

7.5.1 Mechanical/Structural

The EXIST mission will require a custom built S/C designed to accommodate the significant size and mass of the instrument. Based on the current instrument configuration, the S/C bus structure mass will be no more than 692 Kg, and the S/C bus will measure approximately 4.4m in diameter and 1.8m high. There will be sufficient volume and mass margins to accommodate the propulsion module and all other S/C subsystems. The structure shall be stiff enough so that the primary dynamic modes of the observatory will meet the Delta IV Heavy launch vehicle requirements of >8Hz for the first lateral mode and >30 Hz for the first axial mode.

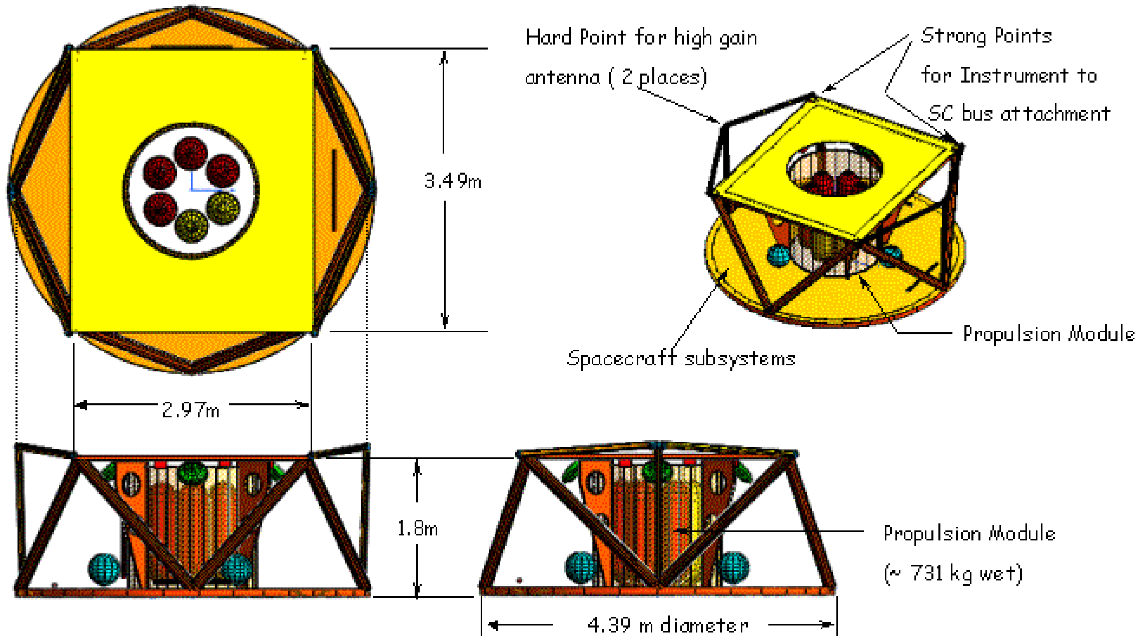


Figure 7-14. Spacecraft Bus Configuration

7.5.1.1 Interfaces

Instrument Attachment

The instrument truss structure weighing no more than 1000 kg will attach to the S/C bus at multiple points around the instrument mounting ring. This will insure good mechanical coupling between the instrument and the S/C. Since the instrument is not particularly sensitive to external structural distortions at the S/C interface, no special flexuring or other means of strictly controlling alignment of the instrument/S/C interface is foreseen. Side panels in between the truss structure will be added as required. This will allow a stiff interface capable of withstanding launch loads.

Mounting locations, cable routing, thermal and structural modeling, and fields of view for star tracker accommodation will be addressed in an ICD to be developed jointly between the S/C and instrument teams.

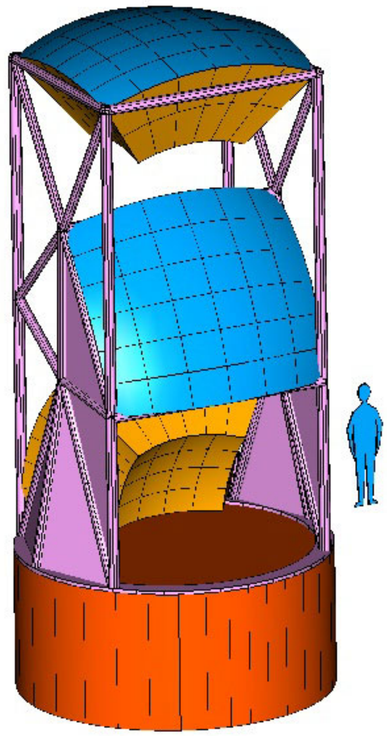


Figure 7-15. Instrument Module to S/C Bus Support Structure

Launch Vehicle Adapter

A standard Delta IV 4394-5 payload attachment fitting (PAF) will be used as the interface between the Delta IV launch vehicle and the S/C.

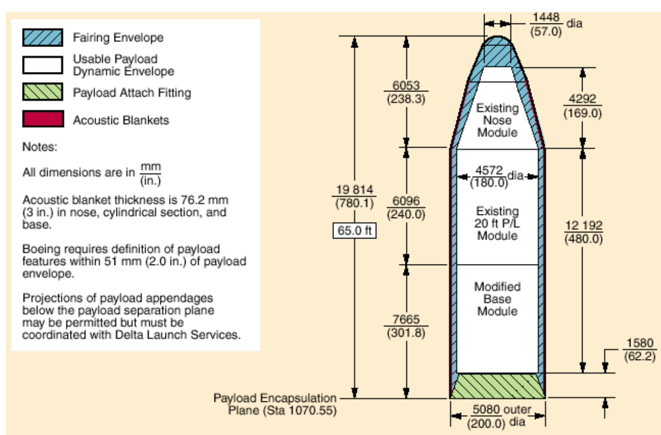


Figure 3-11. Delta IV Heavy 5-m-dia by 19.8-m-Long Metallic Fairing Payload Envelope—4394-5 PAF

Figure 7-16. Launch Vehicle: Delta IV, Fairing: 19.8m x Ø 5m, static envelope.

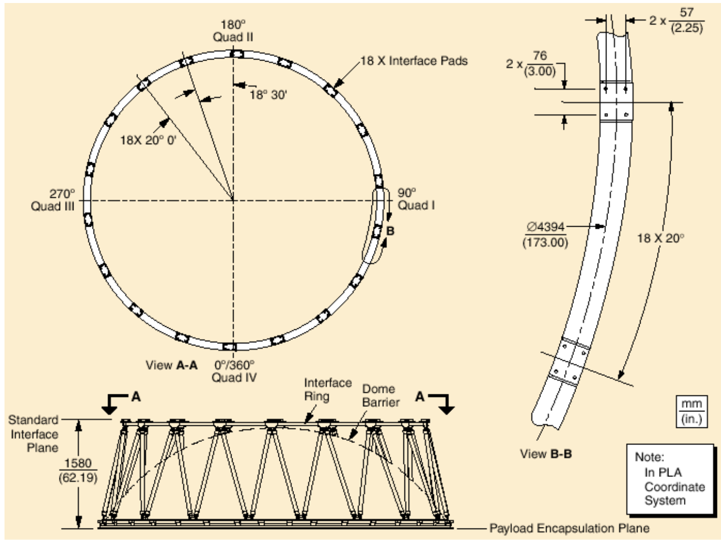


Figure 5-16. Delta IV EELV 4394-5 PAF

Figure 7-17. Payload Attach Fitting 4394-5 (Ø 4394 mm).

7.5.1.2 Structural Loads Analysis and Testing

Qualification of all flight hardware will be achieved through a combination of analysis and testing to protoflight levels. All structure worthiness will be demonstrated through detailed stress and dynamic analysis.

All mechanical design will analytically be proven capable of withstanding the specified limit (flight level) load times the appropriate factor of safety (FS) without failure. The following criteria will be implemented during structural qualifications:

- 1.4 ultimate w/ test qualification
- 2.0/2.6 yield/ultimate qualification by analysis
- 1.4/1.6 yield/ultimate tested Beryllium structures
- 1.5 ultimate composite structure
- Minimum Axial Frequency: 30 Hz
- Minimum Lateral Frequency: 8 Hz
- Secondary Structural Loads above 35 Hz

EXIST structural design assumes a hard mount at the separation plane without consideration for PAF and separation system compliance to meet Delta IV Heavy mechanical interface requirements, including a steady state axial acceleration of 6 G's and allowable launch mass of 8800 kg to an orbit of 500 km and 22° inclination from the Eastern Test Range.

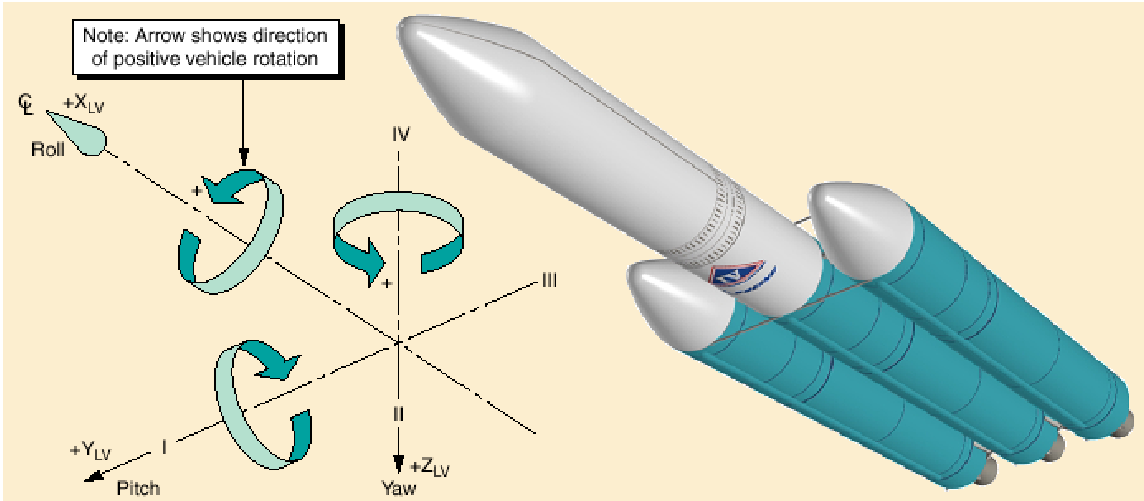


Figure 7-18. Coordinate system for the EXIST observatory based on Delta IV Planners Guide

7.5.1.3 Alternate Concepts and Trades

The current mechanical/structural configuration of the instrument is the result of an accommodation study performed by the instrument design team. A set of six approaches to accommodate the science requirements with various coded aperture configurations was examined. The primary constraint was the volume available in Delta-class launch shrouds, total mass, and detector focal plane area, particularly at the higher energies. Designs were considered optimal to maximize the total achieved field of view (FOV) and thus both instantaneous coverage of GRBs as well as total sky coverage for the survey. The lowest mass, minimal volume configuration is the baseline presented here. Special attention was given to the placement and configuration of the SA panels with respect to obstructing the FOV coverage (see Fig. 7-20, for which the 75° width of the FoV is shown only at the center of the 180° fan-beam).

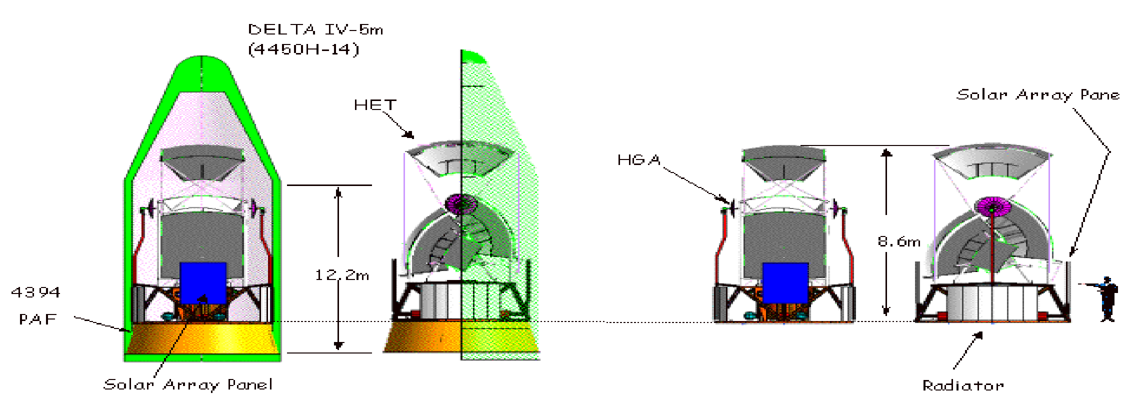


Figure 7-19. EXIST HET, S/C Bus, HGA option and SA panel accommodation within Delta IV.

There are alternate geometries, generally described as rotationally symmetric levels of telescopes, which have some mechanical advantages if the total detector area requirement is lowered. Configurations where the LE response is boosted by auxiliary 'low-energy' telescopes were studied both during instrument design trade studies and during the IMDC run. The scientific advantages offered by the additional sensitivity at LE, and the lessened demand on broad dynamic range from the detectors, were outweighed by the complications incurred by this design (primarily a requirement for deployable mechanisms and additional power) and were subsequently eliminated from the baseline design.

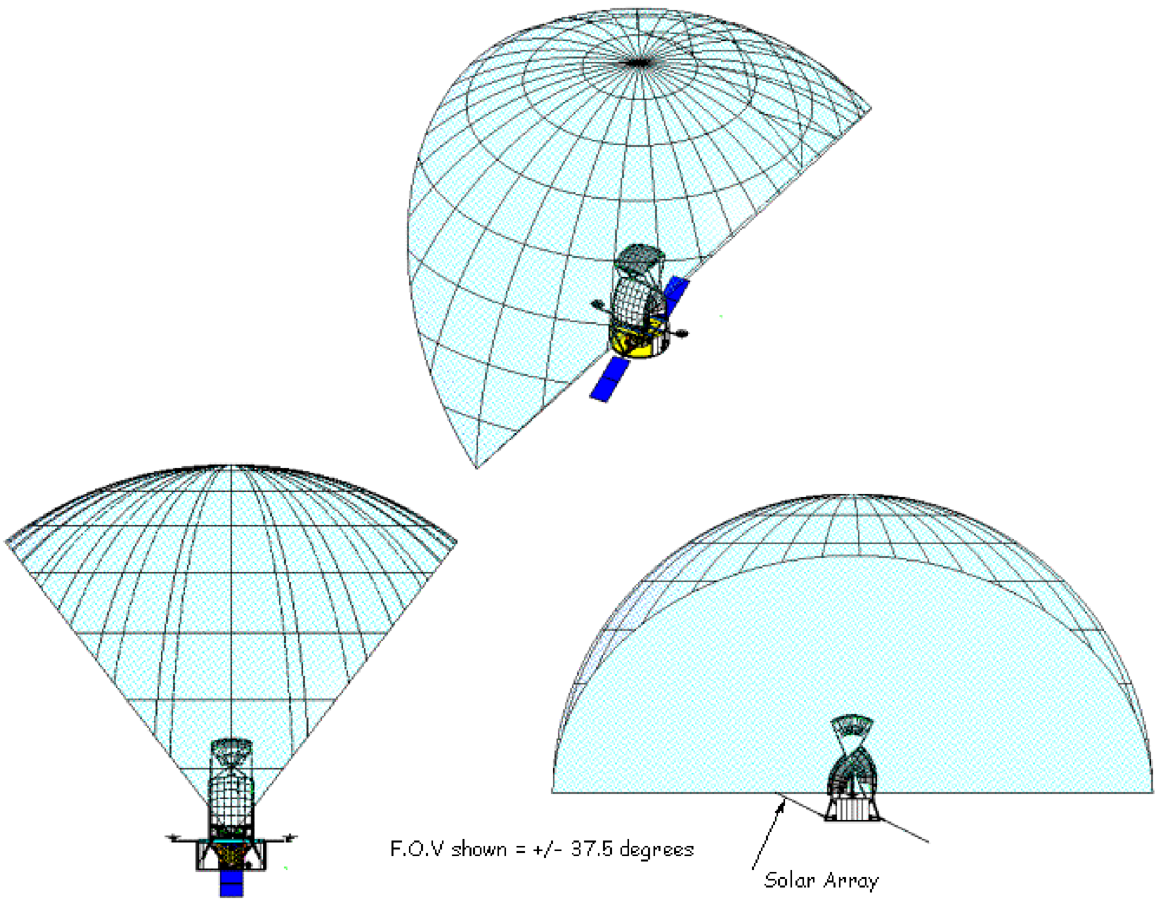


Figure 7-20. Field of View Coverage and Solar Panel Configuration Assessment

7.5.2 Electrical Power Subsystem

The Electrical Power Subsystem (EPS) provides conversion, generation, storage, control, and distribution of unregulated power for the operation of all the EXIST satellite subsystems and components. It is a Direct Energy Transfer (DET) system, which converts solar energy to electrical energy and provides it directly to all S/C loads at an unregulated voltage that varies from 22-32 V. Power balance, battery charge control, power safing, and ground power interfacing are all functional elements of this system. Power system TLM is gathered converted and provided to the Command and Data Handling (C&DH) Subsystem as part of the housekeeping data TLM stream.

When in sunlight, solar energy is gathered by a pair of deployed rectangular Solar Array (SA) panels and is then converted to electrical power at a voltage determined by the battery (approximately 30V). This is applied to a main bus that supplies all loads with their operational power requirements at all times as well as providing charge to the battery. The main bus is routed through a power distribution unit that is split into two parts. The essential bus is an unswitched bus that provides power to essential S/C components such as the communications receiver, C&DH Subsystem, Attitude Control Subsystem (ACS) and survival heaters. The non-essential bus supplies switched power to the instrument as well as the operational heaters. Fault protection is provided to non-essential loads through the use of fuses or re-settable circuit breakers.

The EXIST energy storage will be provided by a single 100AH Nickel Hydrogen (NiH_2) battery and will be sufficient to meet the energy needs of the S/C during the launch ascent phase and eclipse phases of the LEO orbit. In addition the battery will provide power during peak load periods when SA power is inadequate.

The Power System Electronics (PSE) will maintain battery charging and health. The PSE will monitor battery temperature, pressures, current and voltage and maintain state of charge through a combination of means. A Voltage/Temperature (VT) controller as well as an Ampere Hour Integrator (AHI) and Trickle Charge Controller (TCC) will work in unison to maintain an optimal state of battery health.

The PSE will also match array output power to load requirements through the operation of a full shunt system with Pulse Width Modulation (PWM) providing fine control. Excess current, beyond that required for S/C loads and battery charging, is shunted from the array through a series of parallel electronic switches several of which are pulsed at a rate and duty cycle that produces energy balance.

The PSE also provides load switching, fault protection, and safing functions. Electronic switches provide control of loads on the non-essential bus while short detection circuitry monitors these loads for over current conditions and removes power if such a condition is detected.

In the case of an anomalous condition where the battery state-of-charge drops below a certain level or the battery voltage is low, the power system will act to remove non-essential loads and trigger safing actions until the condition is cleared.

Table 7-9. Load analysis for EXIST observatory

Exist Load Analysis		Average Day, Watts	Average Ni, Watts	**Average Watts**	Survival Pwr	Peak Pwr	Launch Pwr
Total Power	Watts	1437	1437	**1437**	770	2575	721
Inst Margin	**30.00%**	196	196	196	59	270	59
Bus Margin	**30.00%**	136	136	136	119	324	108
Obs Power		1105	1105	**1105**	593	1981	555
Science Loads		652	652	652	196	900	196
Instrument Pwr		652	652	652	196	900	196
Spacecraft Loads		453	453	**453**	397	1081	359
Communications		43	43	43	22	171	22
C&DH		49	49	49	49	49	49
ACS		244	244	244	222	543	222
Prop		30	30	30	30	225	30
Power		36	36	36	36	36	36
Mechanisms		16	16	16	3	22	0
Structural		0	0	0	0	0	0
Thermal		35	35	35	35	35	0

Note: The power system is sized assuming a 30% load margin as indicated. Default for instrument survival power is 30% of average.

The Power Subsystem consists of the SA, battery, and PSE, with the physical characteristics as shown in Table 7-10.

Table 7-10. Physical Characteristic of Power Subsystem Hardware Components

Exist Power System			Dimensions (M)		Mass (KG)			
Item	**#**	**Height**	**Width**	**Length**	**Vol/Area**	**Mass**	**Total Vol/Area**	**Total Mass**
PSE	1.00	0.22	0.28	0.64	0.04	19.15	0.04	19.15
Solar Array	2.00		1.50	4.65	6.98	40.33	13.95	80.65
Battery	1.00	0.36	0.66	0.81	0.19	81.00	0.19	81.00
Harness								20.00
								200.80

7.5.2.1 Solar Array

The SA will consist of two 1.5 X 4.7 meter deployed panels with single axis drive canted at 20°. The geometry is important since there will be significant shadowing during part of the orbit and the length of the array allows some power to be generated by the partially shadowed panel. The SA will provide 3500 W Beginning of Life (BOL) and 3300 W End of Life (EOL) power to support a 1500 W orbital average load. Triple Junction GaAs solar cells with an average efficiency of 27% are baselined. Total panel mass including solar cells, diode boards, connectors, wiring and substrate is estimated at 81 kg.

Table 7-11. Energy balance analysis.

Energy Balance Analysis	
Pl (W)	1436.5
Td (Min)	58.6
Te (Min)	36.0
Nsald	0.9
Nbtld	0.8
Nsabat	0.8
Incident Angle	20.0
Pa (W) EOL	**3204.3**
Pa/Pl	2.2

Table 7-12 Solar Array panel sizing.

SA Panel Area Analysis	
SA Pwr EOL	3204.3
TJGaAs W/MM EOL	260.0
TJGaAs W/MM BOL	275.0
Cell Area	12.3
Packing Factor	0.9
Total Panel Area	**13.7**
Sa Pwr BOL	**3389.1**

7.5.2.2 Battery

The EXIST energy storage will be provided by one 100AH 22 cell NiH_2 IPV battery. An orbit period of 94 minutes with a maximum 36-minute eclipse time is assumed. The sun should always be within 20° of the solar panel normal during the entire mission life. Battery power will primarily be required during the 26,000 expected eclipse cycles but also during the launch phase up through SA deployment and sun acquisition. It will be utilized during peak load periods at a limited duty cycle and during safing events should the observatory experience off nominal attitude configurations. Nominal discharge voltage of this battery will be around 28V rising to 30V when charged. The battery will provide voltage, current, temperature and pressure information to the PSE to provide charge control and determine state-of- health. Battery assembly dimensions will be approximately 36cm x 66cm x 81cm with a mass of 81 kg.

Table 7-13. Battery DOD analysis.

Battery DOD Analysis	
S/C Load	1436.5
Battery Capacity (AH)	100
Battery V	29
DOD (AH)	30
DOD %	30%

7.5.2.3 PSE

The EXIST PSE will be based on the MAP design. It is a DET system. Power is provided to the loads through switched and unswitched services. Battery charge control (AHI, CC, VT & TC) is achieved in S/W with some hardware backups. The system supports the following battery TLM: current, voltage, half voltage, temperature and pressure. Battery relay and electronic load switching is done by the PSE (see Figure 7-21). Seven SA segments are sequentially shunted as necessary with a PWM converter driving two other segments for fine power control. One SA segment is not shunted and is directly attached to the bus. Additional engineering will have to be done to size the system for the EXIST load and configure switching, fusing and safing for its unique requirements. PSE dimensions are estimated at 22 x 28 x 64cm with a mass of 19 kg. The PSE is designed to a functional rather than component-level redundancy standard.

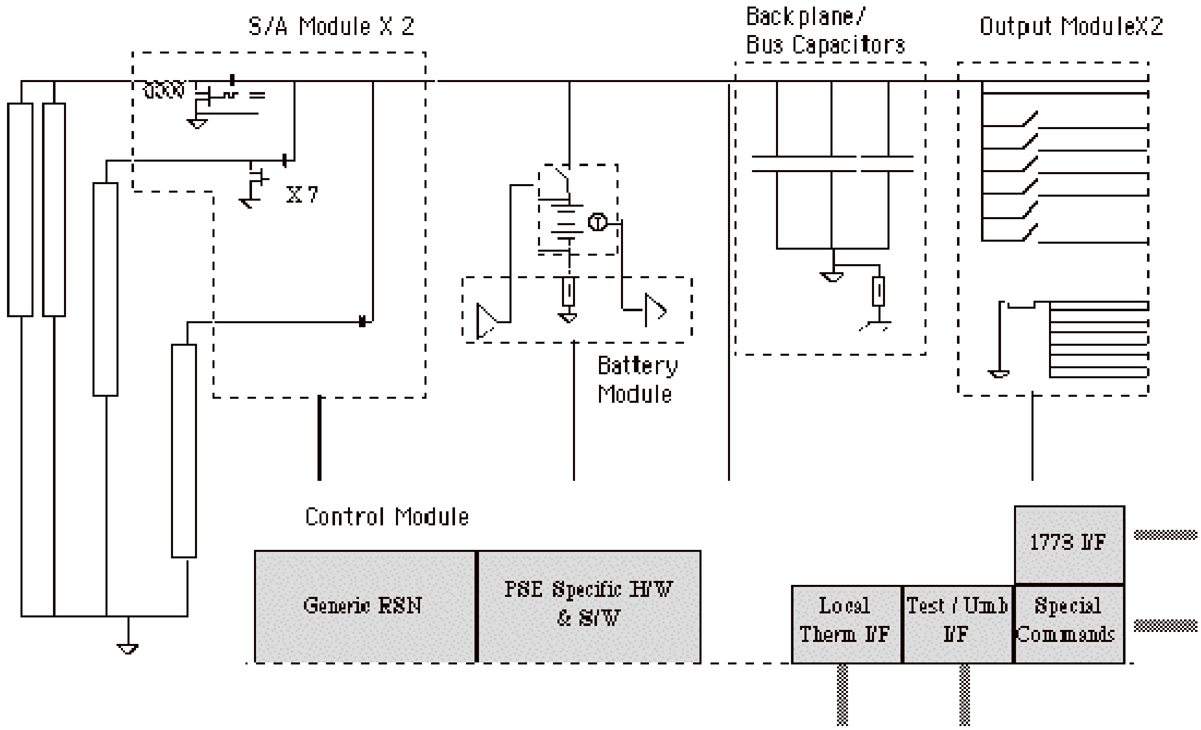


Figure 7-21. Electrical power system diagram.

Table 7-14. Typical power system telemetry.

PSE Telemetry		
Every 4 Seconds	Every 8 Seconds	Every 32 Seconds
<u>Fast Telemetry</u> Critical Voltages, Currents	**<u>Medium Telemetry</u>** Other Voltages, Currents Status and Control Signals	**<u>Slow Telemetry</u>** Other Status Temperatures
Battery Current Battery V Bus Current 1 & 2 Bus V Solar Array Module Current Command Counter	Battery Current Battery Differential V Battery Pressure Chassis Current PSE Current Solar Array PWM Control Solar Array PWM Status LVPC Load Current SSPC Status 1,2,3, Solar Array Segment Mask Control Mode Desired Current for V Control Desired V for V/T Level Battery State of Charge	Battery Relay Status Solar Array Panel 1-6 Tempo Battery Temp Module Temps LVPC Trip Level LVPC Arm & Fire Masks Watchdog Reset Count Reset Command Count Battery Current In Battery Current Out

The following table lists the specifications and performance of the EXIST Electrical Power System.

Table 7-15. Specifications and performance of electrical power system.

Parameter	Spacecraft Specification	EPS Performance
Bus V	24 – 34 V	22 – 35 V
EOL Load Capability	1500W	1500 W
Design Life	5 Years	5 Years
Energy Storage	Support all ops	Support all ops*

* Limited duty cycle

7.5.2.4 Interfaces

The EPS interfaces to any S/C components that require unregulated main bus power through its output modules. Individual loads will be either switched or unswitched through the module depending on system requirements. This usually includes most components on the S/C except for the passive thermal control system. In addition, commands and TLM are provided by an interface to the C&DH Subsystem through a MIL-STD-1553 bus protocol.

Test connectors will be provided at the PSE to allow stand-alone testing of the box through fabrication and qualification. The NiH_2 battery will also be provided with a test connector to allow monitoring at the individual cell level. The observatory will be provided with SA and battery arming plugs to allow total isolation of S/C systems from power sources. These arming plug locations will also serve as ports for the introduction of GSE power from battery and SA simulators. A separate port will be provided for umbilical power and hard-line TLM of critical power system parameters.

GSE using agreed upon protocols will be provided to insure full functional testing of the EPS at the box development level. The GSE will consist of computers, interfaces and power supplies necessary to verify functionality.

At the S/C level SA and battery simulators will be provided to allow full up and flight-like testing of the observatory in all modes of operation and through all environmental test conditions including mission orbital simulation.

7.5.2.5 Alternate Concepts and Trades

EXIST may be able to take advantage of additional technological advances in the power systems area. One possibility for mass reduction is the use of ultralight SA technology. This uses a flexible material as a solar cell substrate and a lightweight deployment system. The array folds into a compact package for launch and deploys into a circular umbrella like configuration. This technology is very mature with test articles having been flown and a qualified system built for a Mars lander mission. The mass estimate for a complete ultra light A system for EXIST would be 21 kg. vs the currently estimated 81kg.

Another method of reducing the size and mass of the SA would be by the use of Quad Junction Solar Cells. These cells are currently in development though not expected to be available for another 5-7 years. Their use would reduce the total array area required by perhaps 25% of the current estimate.

The use of a Lithium Ion vs. NiH2 battery could yield a significant reduction in power system mass. Lithium Ion is aggressively being developed and is being proposed for several full sun low depth of discharge (DOD) missions at this time. More testing in the Low Earth Orbit (LEO) cycling regime will be required however before the technology could be considered reliable for a high cycle life mission such as EXIST. Use of Lithium Ion batteries would drop the battery mass from 80 to about 50kg.

Work is also proceeding on Structural Batteries where the active energy storage elements are packaged into the structure of the S/C itself rather than as separate units. Though still in its infancy this technology could yield significant mass savings in the future.

7.5.3 Thermal Control Subsystem

Three S/C bus thermal zones are needed to meet mission thermal requirements. The NiH battery is isolated from other components, with its own radiator of approximately 1.1 m^2 and heater control system requiring 30W power to maintain its required 0°to 10°C temperature range. Most other components, with temperature ranges of –10°to 40°C, are mounted to the S/C deck. The deck is conductively coupled to the S/C bus radiator with an area of about 5.3m^2. The propulsion system components (lines, tanks, valves, etc.) are individually controlled to within 15°C via heaters, thermistors, and thermostats and will require 35W power in the operational mode.

The S/C bus utilizes standard thermal control techniques (heat pipes, heaters, blankets, etc.) to meet thermal requirements. The S/C deck and radiators are heat pipe panels. The radiators are painted white to reduce absorption of solar and albedo flux, and almost all other external surfaces are covered with multi-layer insulation (MLI). The total mass of this system is estimated at approximately 36kg (25kg heat pipe panels, 9kg MLI blankets) and will use an average of approximately 65 watts, primarily for battery and propellant tank heaters.

7.5.3.1 Analysis/Modeling

Thermal analysis of the S/C bus has shown that the required surface areas for the S/C bus and battery radiators are 5.3m^2 and 1.1m^2, respectively. Available area in the most favorable orientations (wake- or ram-facing) is about 12m^2, so the bus has substantial radiator margin.

7.5.3.2 GSE

Ground cooling is required to keep the detectors at their operating temperature while they are being tested in air. After installation, flight batteries must also be kept cool to maintain life expectancy.

7.5.3.3 Alternate Concepts and Trades

Use of heat pipes on radiators and S/C deck could be deleted to save money, although mass would increase to provide adequate thermal conductivity.

7.5.4 Attitude Control Subsystem (ACS)

The EXIST ACS is a zero-momentum system with very large actuators to accommodate EXIST's immense disturbance inputs, as described in the following sections.

During primary science mode operations, the EXIST ACS is required to maintain the S/C within 1° of zenith. In addition, it must support roll and pitch slews for inertial pointing on targets of opportunity within 60° of zenith, completing each slew within 45 minutes. Although the attitude accuracy requirement is rather loose, the attitude knowledge requirement is tight: 5 arc seconds (1 sigma) about all three axes. In addition to science operations, the ACS must also support nulling of launch vehicle tipoff rates, attitude control during thruster maneuvers, and a safe hold mode (SHM).

EXIST employs a zero-momentum ACS with star trackers and an inertial reference unit (IRU, or "gyro") as its primary science-mode sensors. It uses reaction wheels to control the attitude, with continuous unloading of secular torques using magnetic torque rods. These actuators must be rather large to compensate for maximum disturbance torques (primarily atmospheric) of approximately 0.030 N-m, and to support the required slew rates. These severe disturbances result from the large offset between the CM and the center of pressure (CP), a by-product of a heavy instrument mounted far above the S/C SAs. Unfortunately, the SAs cannot be mounted near the instrument without obstructing its FoV. The atmospheric torques have both a cyclic component (due to rotation of the SAs with respect to the ram direction) and a secular component (based on the average CM-CP offset during an orbit). Gravity gradient torques also act on the observatory, but they are an order of magnitude smaller than atmospheric torques. Solar radiation torques are two orders of magnitude smaller than atmospheric torques.

The attitude knowledge requirement of 5 arc seconds (1 sigma) represents the limit of what can be achieved using off-the-shelf star trackers. End-to-end pointing knowledge is also driven by our ability to verify and maintain the alignment between the instrument detectors and the star trackers. An on-orbit calibration should be performed, with the instrument observing a target with a known position with respect to the stars in the Fob of the tracker(s). The on-orbit calibration will be available each orbit from bright X-ray sources (e.g. Crab nebula, Cygnus X-1). A detailed alignment budget will be developed later during the formulation phase.

If tighter pointing knowledge were needed, one option would be to use a very sophisticated imaging system in place of standard star trackers. The Aspect Camera Assembly (ACA), developed by Ball Aerospace for the Chandra AXAF S/C, would be one candidate. However, the ACA, or any similar device, would also significantly increase the cost of the ACS, with some impact on mass and power as well.

The Attitude Control Electronics (ACE) contains a PiVoT GPS receiver card, which receives inputs from GPS antennas on the observatory to determine its orbit. These orbit solutions are used in ACS algorithms and are available to other subsystems that require orbit knowledge.

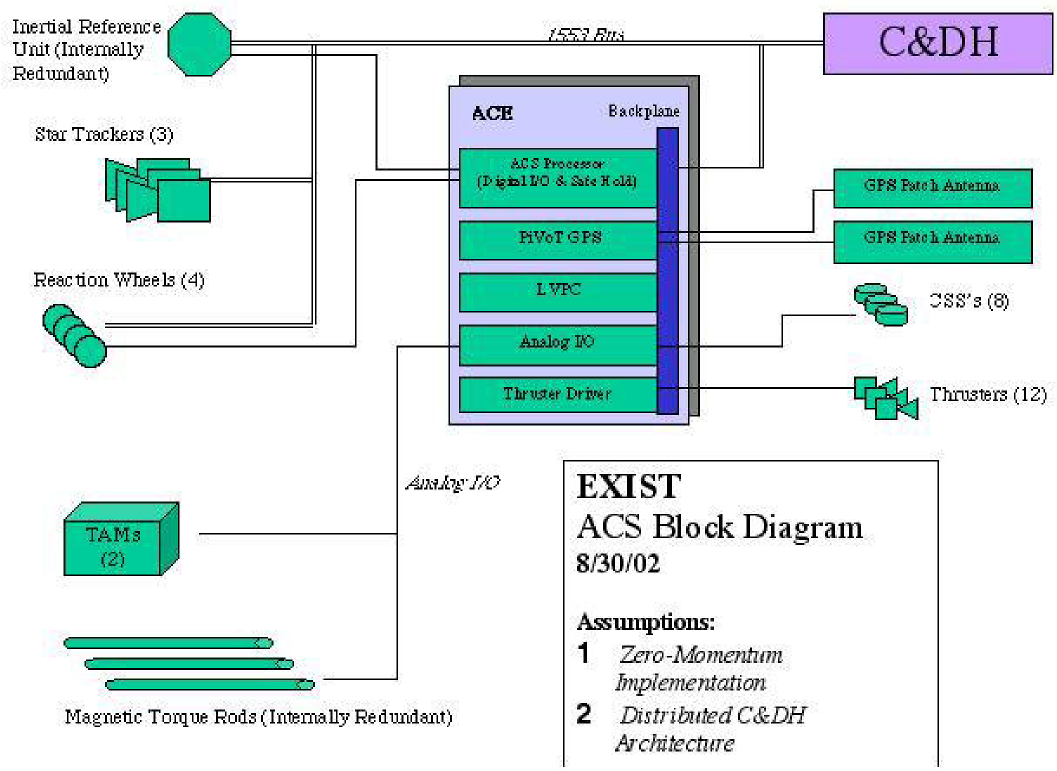


Figure 7-21. EXIST ACS block diagram.

7.5.4.1 Control Modes

The following is a summary of the ACS Control Modes:

Science mode – Three-axis stabilized, zenith, or inertial pointing.

- Gyro and star trackers for attitude determination.
- Wheel speed modulated to control attitude.
- Magnetic torquer bars (MTB) used to unload momentum. (3)

Rate null/Sun acquisition—null the rate and point solar array normal to the sun.

- Coarse sun sensors (CSS) and IRU as sensors.
- Rate null using thrusters.

Safehold Mode—Same as Rate null/Sun acquisition, except:

- Independent processor and software.
- Reaction wheels instead of thrusters.

Delta V mode—Perform thrust maneuvers for orbit maintenance or deorbit.

- Gyro as primary sensor.
- Thrusters provide both delta-velocity and attitude control actuation.

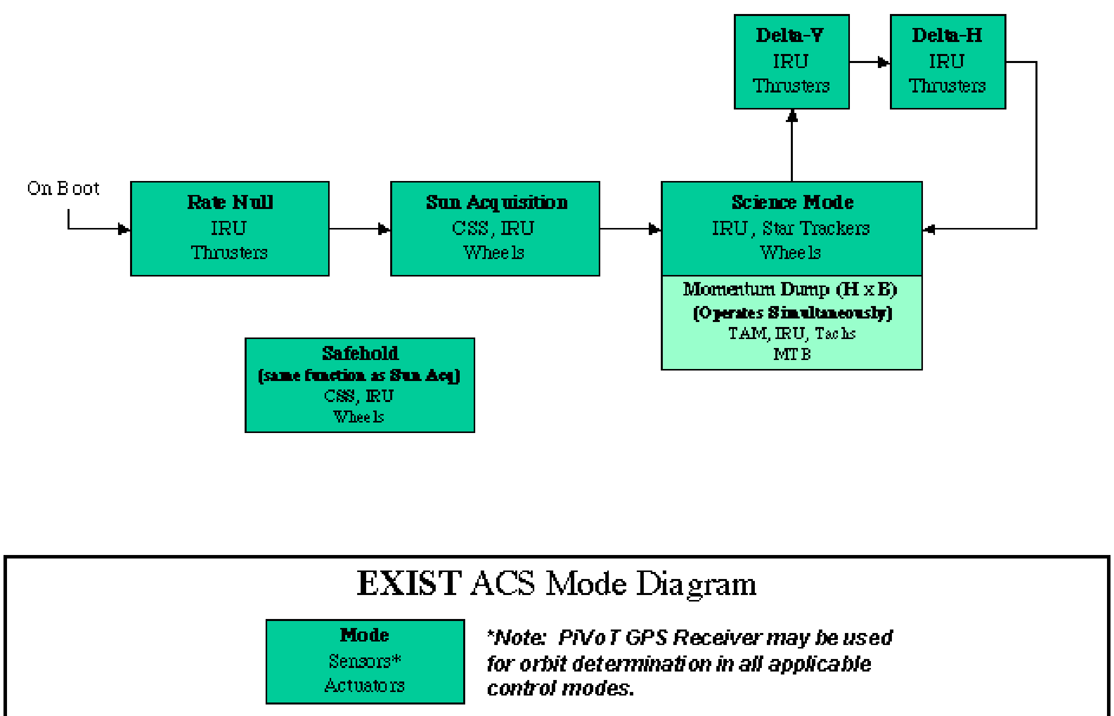


Figure 7-22. EXIST ACS mode diagram.

7.5.4.2 ACS Hardware

The current mission profile provides for reboost when the S/C altitude decreases to no less than 450 km. At this altitude, the maximum atmospheric density can conservatively be estimated as 1.2×10^{-11} kg/m^3. These aerodynamic torques are by far the greatest disturbance acting on the EXIST observatory. As a result of all disturbances, momentum builds up at a rate of approximately 47 N-m-s per hour. This is an extraordinarily high rate, forcing selection of the largest torque rods in the Ithaco catalog. These rods, which saturate at a magnetic dipole of 3200 A-m^2 (2600 A-m^2 maximum linear range), are flying on the Hubble Space Telescope (HST). Each rod is 2.44 meters (8.0 feet) long, with a mass of 45.4 kg (100 lbm). A safety factor of 2 was applied to the calculated secular torques in order to ensure adequate control authority margins. Performing reboost maneuvers more frequently, thereby increasing the minimum mission altitude and decreasing the maximum atmospheric density could achieve additional design margin.

The cyclical component of observatory momentum oscillates between $\pm$ 8 N-m-s with a period equal to half the orbital period. However, the momentum wheel size is actually driven by the slew requirement. The wheel suite must absorb 32.3 N-m-s of momentum during a minimum-torque slew. This translates into approximately 23 N-m-s per wheel during a roll or yaw slew, assuming the wheels are mounted in a 45° pyramid about the pitch axis. When built for optimum mass, the selected wheels have a momentum capacity of 50 N-m-s, which exceeds the requirement by a factor of two. The ACS hardware with mass and power estimates is listed in Table 7-16.

Table 7-16. ACS Hardware List

Exist ACS Hardware List						
			Total	Total Power	Total Power	Total Power
			Mass	Orbit Avg	Peak	Safehold
Components	Model	Quantity	(Kg)	(W)	(W)	(W)
Attitude Control electronics (ACE), Internally Redundant	(Based on GSFC Heritage, with added GPS Receiver)	1	20	40	46	40
Coarse Sun Sensors	Adcole 11866	8	0.0368	0	0	0
IRU, Internally Redendant	Litton SIRU	1	5.5	22	40	20
Star Trackers	Ball CT-602	3	20.73	20	20	0
Magnetometers	Smex-lite	2	1.36	0.6	0.6	0.6
Engine Valve Drivers (EVDs)	(Based on TRMM EVD)	2	10	0.53	0.53	0.53
Magnetic Torquers	HST/GRO (Ithaco)	3	136	60	60	60
Reaction Wheels	Honeywell HR14X	4	34	100	375	100
GPS Patch Antennas	TBD	2	0.9	0.5	0.5	0.5
		TOTAL =	229	244	543	222

*Assume two wheels are operating at peak power @ 6000 RPM, with the other two wheels at steady-state power.

7.5.4.3 Algorithms/Software

The ACS Analysis Team will work in concert with the Flight S/W Team in developing the control algorithms and S/W that control the observatory attitude. Automatic code generation—which was used to produce roughly 30% of the ACS S/W on the Microwave Anisotropy Probe (MAP), and may be used more extensively on the Solar Dynamics Observatory (SDO)—is an attractive option for EXIST as well.

Almost all of the ACS S/W will reside with the rest of the flight code in the central C&DH processor. The only exception is SHM, which will reside in the Attitude Control Electronics (ACE) processor, to ensure independence. All sensors and actuators required for SHM will have a direct interface with the ACE, allowing attitude control to be maintained even in the event of a failure that interrupts communications over the main S/C data bus.

Autonomous fault detection and correction (FDC) algorithms will be employed to take remedial action in the event of hardware failure, unintended operation, or unexpected disturbance.

7.5.4.4 GSE

ACS testing at the board, box, subsystem, and S/C levels will utilize a hybrid dynamic simulator (HDS) to allow closed-loop operation of the hardware and S/W. The HDS will model the S/C dynamics and simulate the observatory's response to actuator operation. In addition to the HDS, simulators of hardware in other subsystems may be employed for ACS performance or interface testing. Alternate Concepts and Trades

Table 7-17. ACS trade studies performed.

Trade	Options	Preliminary Result
Momentum Unloading Method	1. Magnetic Torque Rods; 2. Thrusters	Chose magnetic torque rods. Momentum unloading can be performed autonomously and constantly, without interfering with science operations. Torque rods use no consumables (i.e. they do not limit spacecraft life). Propellant required for five years of momentum unloading is greater than the mass of the baseline torque rods.
Attitude Control Method	1. Zero Momentum; 2. Momentum Bias	Chose zero momentum system. Momentum bias system provides adequate pointing accuracy for primary (zenith pointing) science mode, but cannot support 60° slews during mission. Previous study (IMDC, November 2001) had selected momentum bias due to absence of a slew requirement at that time. Note: although attitude knowledge requirement is very tight (5 arc sec), attitude control requirement is very loose (1°).

7.5.5 Propulsion

EXIST employs a bi-propellant propulsion subsystem. The EXIST propulsion subsystem must null tipoff rates, perform reboost maneuvers to maintain the 500 $\pm$ 50 km altitude, and execute an end-of-life controlled re-entry maneuver. The total delta-velocity requirement is 231 m/s, not including attitude control firings. The following table summarizes the propellant budget, with a 10% penalty added to all Delta-V maneuvers to account for attitude control firings:

Table 7-18. Propulsion budget summary.

Requirement	Delta-V	Isp	Ox/Fuel	S/C Mass	Prop Used	Fuel Used	Ox Used
	(m/s)	(sec)	Ratio	(kg)	(kg)	(kg)	(kg)
Tipoff	n/a	240	1.65	8800	6.8	2.6	4.3
Launch Altitude Dispersions	0	315	1.65	8793.2	0.0	0.0	0.0
Drag Makeup	111	315	1.65	8793.2	310.6	117.2	193.4
Drag Makeup ACS	11.1	240	1.65	8482.6	39.9	15.1	24.9
Disposal	120	315	1.65	8442.7	321.9	121.5	200.4
Disposal ACS	12	240	1.65	8120.8	41.3	15.6	25.7
Residuals			1.65	8079.4	10.7	4.0	6.7
Total	254.1				731.3	275.9	455.3

The propulsion baseline is a bi-propellant system using MMH fuel and NTO oxidizer. This type of system was chosen over monopropellant hydrazine (N2H4) because the inferior performance of monopropellant thrusters would result in prohibitive increases in propellant mass and tank volume. A bi-propellant system using anhydrous hydrazine and NTO was also considered but rejected due to packaging concerns with the lower oxidizer/fuel ratio of a N_2H_4/NTO combination results in a very large fuel tank. If the use of a carbonaceous fuel (MMH) is unacceptable for contamination reasons, then this decision can be re-visited.

Based on a S/C separated mass of 8800 kg, the total propellant required is 731 kg, consisting of 276 kg of MMH and 455 kg of NTO. The selected mixture ratio is an industry standard that conveniently allows the fuel and oxidizer tanks to be of equal volume. Assuming that the total system contains two propellant tanks (one for each species), the volume of each tank must be at least 20,600 cubic inches (0.338 cubic meters). The best candidate tank appears to be Pressure Systems Incorporated (PSI) model 80350-1, a 35-inch (89-cm) diameter titanium vessel using a surface-tension device for propellant extraction. Each tank has a volume of 22,450 cubic inches (0.368 cubic meters) and a mass of 13.14 kg maximum.

The system also must contain two cylindrical pressurant tanks, each with a minimum volume of 1600 cubic inches (0.0262 cubic meters). The Lincoln Composites Model 220123-1, with a volume of 3010 cubic inches (0.493 cubic meters) offers reasonable volumetric margin. This is a cylindrical, composite-overwrap pressure vessel with a diameter of 13.2 inches (33.5 cm), a length of 25.4 inches (64.5 cm), and a mass of 7.5 kg.

Because the propulsion system must operate throughout the mission, the system provides completely independent pressurant manifolds for each propellant species. This absolutely prevents mixing of oxidizer and fuel vapors, which might otherwise cause over-pressurization and/or damage to the pressurant manifold.

7.5.5.1 Hardware

Figure 7-24 presents a schematic of the EXIST propulsion subsystem. All components will be constructed primarily of titanium, minimizing the use of stainless steel to prevent the formation of iron adduct in the oxidizer manifold. Figure 7-23 shows 12 thrusters, a typical quantity for a spacecraft of this class. However, the number of thrusters, in addition to their sizing and placement, will not ultimately be determined until later in the formulation phase.

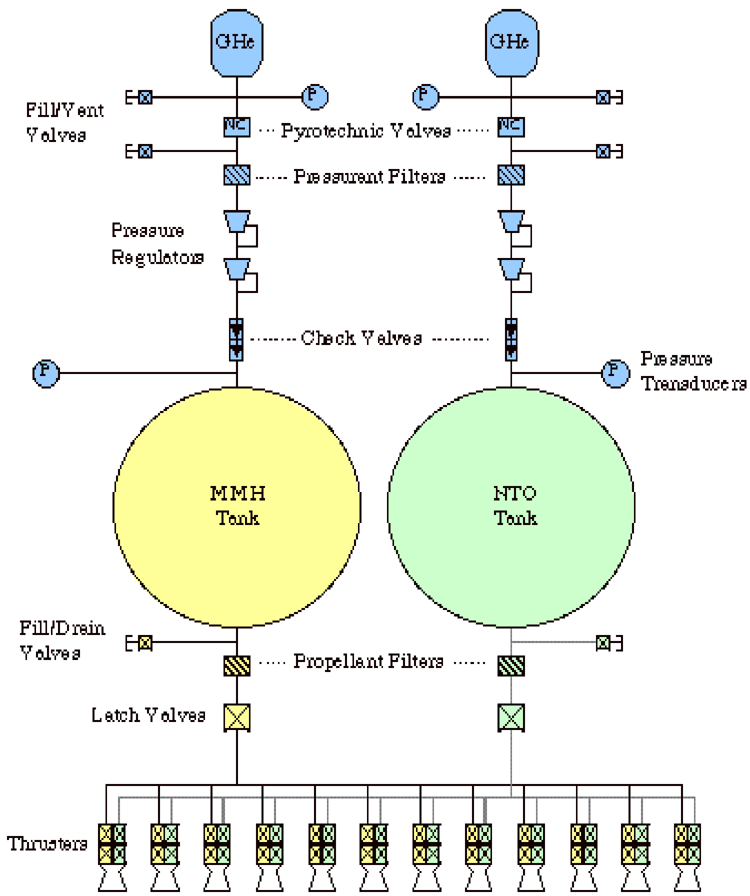


Figure 7-23. Propellant schematic diagram.

The mass and power consumption of each component is provided in the table below. Note that these figures include all propulsion heaters:

Table 7-19. Mass and Power

		Power (W)		
Component	**Mass (kg)**	**Orbital Average**	**Peak @ 28 Vdc**	**Dimensions / Comments**
Pressurant Tanks (2)	15	0.0	0.0	33.5 cm diameter x 64.5 cm length
Propellant Tanks (2)	26.3	15.0	30.0	89 cm diameter
Biprop Thrusters (12)	12.0			1 kg per thruster
Valve heater		30.0	60.0	Heater power only; Orb Avg = 50% Duty Cycle
Injector heaters		12.0	24.0	Heater power only; Orb Avg = 50% Duty Cycle
Command			80.0	4 thrusters x 20 W
latch valves (2)	1.3			
Heaters		0.5	1.0	Orb Avg = 50% Duty Cycle
Command			20.0	2 valves x 10 W
tank filters (2)	2.0	0.5	1.0	Heater power only; Orb Avgas = 50% Duty Cycle
Pressuring filters (2)	1.0	0.0	0.0	
Pyrotechnic valves (4)	0.6	0.0	0.0	Used only once, shortly after separation
Pressure regulators (2)	3.4	1.0	2.0	Heater power only; Orb Avg = 50% Duty Cycle
P-ducers (4)	1.0	1.0	1.5	Excitation voltage plus heater power; Orb Avg Heater = 50% Duty Cycle
Check valves (2)	0.3	0.5	1.0	Heater power only; Orb Avg = 50% Duty Cycle
Fill & drains (6)	1.8	2.0	4.0	Heater power only; Orb Avg = 50% Duty Cycle
Lines/fittings & heaters	7.4	10.0	20.0	Heater power only; 15% of component mass
Brackets & misc	6.5	0.0	0.0	10% of (tank+component) mass
Propellant	731.0	0.0	0.0	
Nitrogen pressurant	3.0	0.0	0.0	
Dry Mass	63.6			
Totals	797.6	72.5	224.5	Does not include latch valve command power

7.5.5.2 GSE

The propulsion subsystem can be built and tested using standard pressure panels and electrical driver boxes. Testing will take longer than for a monopropellant system, due to the presence of two separate propellant feed systems. Propellant loading must be accomplished with two separate sets of GSE, one for each species.

7.5.5.3 Alternate Concepts and Trades

The following is a list of trade studies performed:

Table 7-20. Propellant trade studies performed. Command Data Handling (C&DH)

Trade	Options	Preliminary Result
Propulsion System Type	1. Monopropellant 2. Hydrazine (N2H4) and Nitrogen Tetroxide (NTO) Bipropellant 3. Monomethyl Hydrazine (MMH) and NTO Bipropellant	MMH and NTO Bipropellant. Monopropellant system cannot realistically meet mission total impulse requirements. MMH/NTO combination is easier to package than N2H4/NTO combination due to propellant mixture ratios and densities. Instrument is not sensitive to contaminants from bipropellant exhaust plumes.

The Command Data Handling (C&DH) subsystem processes the commands received from the ground, and the data from the satellite subsystems and the instruments. It also manages the time-keeping functions. The following paragraphs describe the functional implementation, the hardware components, and the interfaces of this subsystem.

The C&DH subsystem receives the commands from the Communication Subsystem in Pulse Code Modulation format at 2kbps, and performs all decoding and validation functions such as the inversion detection and correction, the code-blocking, the S/C ID verification, and the checksum verification. It then processes and distributes the commands to all S/W and hardware subsystems and the instruments. The C&DH is capable of processing both real-time and stored commands.

The C&DH subsystem collects science data from the instruments; packetizes and assembles the data into frames with Reed-Solomon short code (255,245). The data is then stored on orbit in the recorder.

The C&DH subsystem collects the housekeeping data from the satellite and the instruments, and formats the data in frames at a rate up to 8kbps. The housekeeping data is available in real-time during ground contacts, and is stored at all times for dumping to the ground. The subsystem also monitors the housekeeping data and responds to out-of-limit conditions.

During ground contacts, the science data is retrieved from the recorder memory, the errors are detected and corrected, and the short code is stripped. Corrected science data is then encoded with Reed-Solomon long code (255,233), and optionally with 1/2 rate Convolutional Code and/or Pseudo-Random (PS) Code for transmission in RF X-Band. Housekeeping data is similarly retrieved, and encoded for transmission in the RF S-band.

The C&DH subsystem provides the mechanism for synchronizing S/C time to UTC. It distributes the time and stamps the data with the synchronized time.

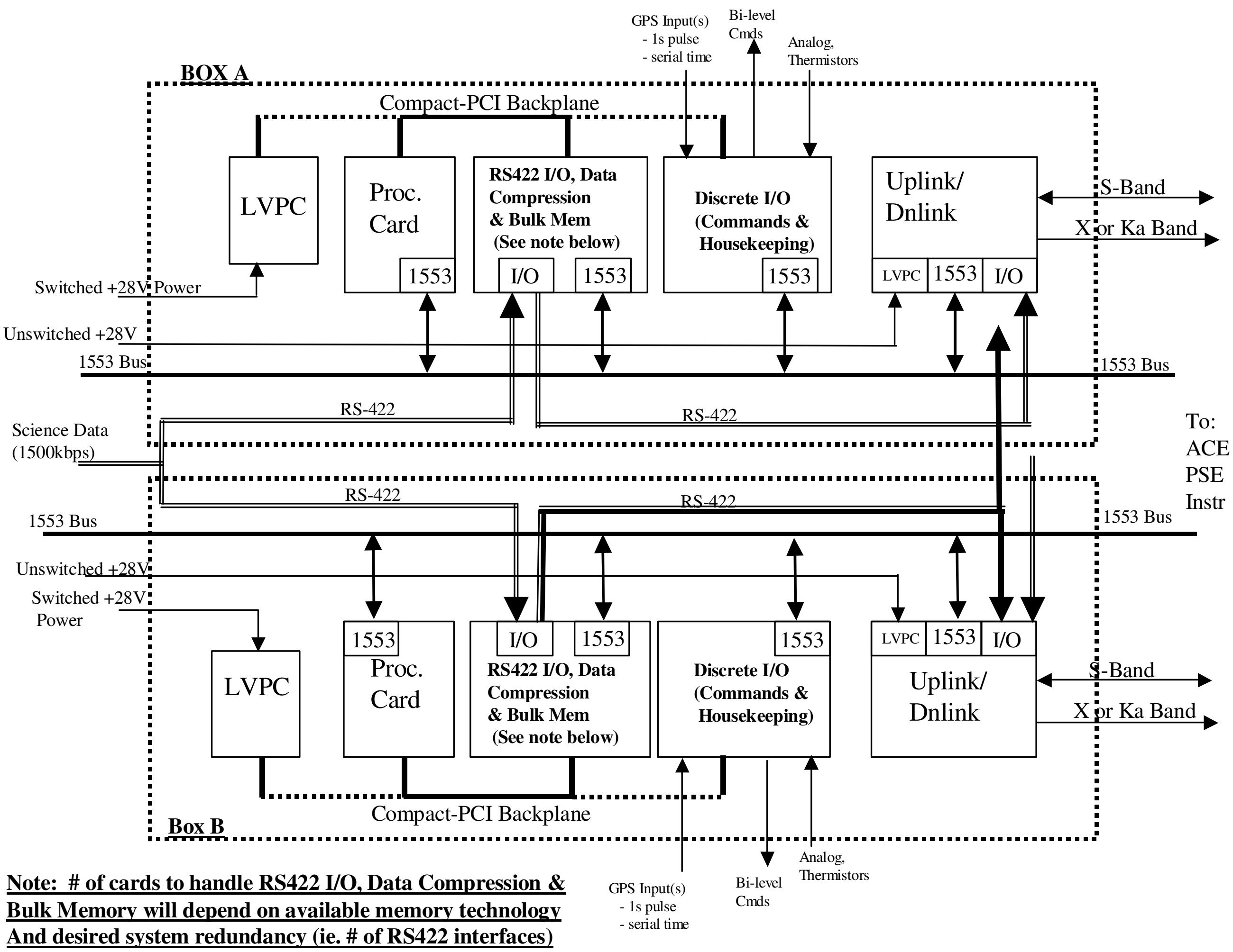


Figure 7-24. Command & Data Handling (C&DH) subsystem block diagram.

7.5.5.4 Hardware

The C&DH for the EXIST Mission shall consist of two separate boxes (Primary and Redundant) with cross-strapped uplink/downlink interfaces and a MIL-STD-1553 S/C bus to maximize redundancy to meet the five year mission requirement. Only one box shall be powered-on at a time with the exception of the uplink/downlink cards. These cards shall always be powered to support redundancy.

Each box shall conform to the following mission-specific specifications:

- Capability to accept and process GPS time inputs to meet timing accuracy requirements of 0.1ms absolute and 0.001ms relative for time correlation purposes.
- 70Gbits of Solid-state Data Storage Capability to meet requirement of storing up to 1 day's worth of science data at the Science Survey Rate of 1500kbps that is compressed 2:1
- 1500kbps RS-422 Interfaces to each of the three EXIST TCPUs.

Each box will contain the following cards:

- Uplink/Downlink
- Processor
- Instrument Interface and Bulk Memory
- Housekeeping I/O
- Low Voltage Power Converter (LVPC)

The Uplink/Downlink card receives commands from the RF S-band subsystem, validates them, and forwards them to the processor for execution. Hardware decoded command capability also resides on this card. It receives TLM data from the processor, encodes it and sends it to the RF S-band and X-band subsystems. The Uplink/Downlink card serves as a remote terminal (RT) on the MIL-STD-1553B bus. This card also contains an LVPC to maintain a continuous power-on mode to support C&DH.

The Processor card controls all TLM gathering, command execution, and out-of-limit detection and reaction. It provides a platform for the flight S/W and attitude control processing. This card is an off-the-shelf radiation-tolerant single-board computer card with a compact-PCI backplane. The processor card communicates to all other cards through the MIL-STD-1553 bus where it serves as the bus controller.

The Instrument Interface and Bulk Memory card performs the functions of receiving science data from the instruments and stores TLM data between ground contacts. This card contains hardware compression capability and a compact-PCI backplane for communication with the processor card. It also contains a MIL-STD-1553 interface where it serves as a RT. This card may need to be split into two cards depending on the complexity of the instrument electrical interface, the availability of high-density radiation-tolerant DRAM, and any added complexity needed to support instrument redundancy requirements.

The Housekeeping I/O card performs all housekeeping command and TLM gathering functions. This includes relay pulses for power switching and deployables, analog sampling of temperatures, voltages, and currents where needed to monitor S/C and instrument health, and receiving GPS time information from an external GPS receiver. This card serves as a RT on the MIL-STD-1553B bus.

The LVPC card converts unregulated 28 Volts power from the Power Subsystem to the regulated voltages as required within the C&DH.

The C&DH accepts science data from three telescope TCPUs. Figure 7-22 shows a block diagram that supports full redundancy where each of three redundant TCPUs are cross-strapped to both C&DH boxes.

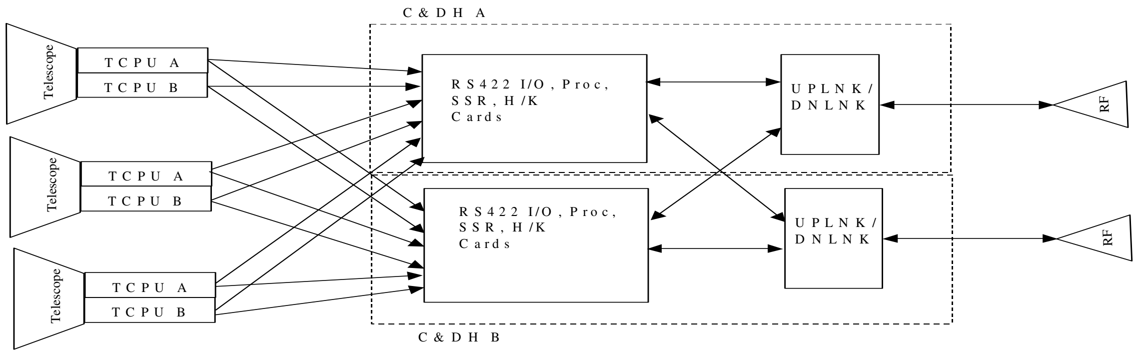


Figure 7-25. Block diagram for C&DH showing system redundancy and cross strapping.

Mass Estimation

The estimated mass of each box is as follows:

Table 7-21. Mass of C&DH components.

Component	Mass (kg)
Uplink/Downlink	1.3
Processor	1.0
Bus Interface/Memory	2.3
Housekeeping I/O	1.3
LVPC	1.4
Backplane	0.4
Chassis	4.0
Total	11.7

Mass estimation for the individual cards and backplane is based on MIDEX/MAP, Swift BAT, and EO-1 WARP measured and/or estimated masses for electronics components with equivalent functions. It should be noted that the card dimensions for each program are different. As a result, an 80% margin is included in the chassis estimate, which is based on the SWIFT BAT chassis.

Therefore, the total mass of the C&DH, excluding harnessing is 23.4kg.

Power Estimation

The estimated power consumption for each box is shown below.

Table 7-22. Power budget for C&DH components.

Component	Avg Power (watts)
Uplink/Downlink (incl LVPC efficiency)	6
Processor	12.5
Bus Interface & Memory	9.0
Housekeeping I/O	2.5
Backplane	0.0
Subtotal	30.0
LVPC 70% eff	13.0
Total	43.0

Power estimate for each card, except the Bus Interface & Memory card, is based on MIDEX/MAP, Swift BAT, EO-1 WARP, and NGST measured and/or estimated power for electronics components with equivalent functions. The proposed design combines the Bus Interface and Memory functions on one card. The 9W figure is a compromise based on the power estimates for separate Memory and I/O cards from the aforementioned programs.

The estimated actual average power consumption if both boxes are on would be 86W. If one box serves as a cold spare but with its uplink/downlink powered, the minimum C&DH average power consumption would be 43.0 + 6.0 = 49W.

7.5.5.2 Data Rates

Table 7-21 Data Ingest Rate

Spacecraft Level Requirement	Daily Average (kbits/s)
Science	1500
Instrument Housekeeping	4
Spacecraft Housekeeping	4
Total	1508

The science data will be 2:1 losslessly compressed

Spacecraft Data Downlink Rate

The C&DH shall support X-band and S-band downlink at the following rates:

Table 7-24. Spacecraft Data Downlink Rate

Downlink	Rate (kbits/s)
S-band (S/C housekeeping)	2,4,8,16,32
X-band	20-30Mbps

The C&DH shall support S-band uplink rates of 2 kbits/s.

Processing Requirements

Science Data Processing
This will be further defined with the instrument design.

Uplink Command Processing
Telecommand protocol will be determined during later design phases. Uplink command decoding, verification, distribution and execution.

Downlink Data Processing
TLM protocol is TBD during later design phases. The C&DH subsystem will implement Reed-Solomon, Cyclic Redundancy Code (CRC), Psuedo-Random (PS), Convolutional Encoding. Each may be bypassed.

Spacecraft Data Processing
The spacecraft will perform housekeeping TLM monitoring and out-of-limits response as well as maintenance and distribution of S/C time (accurate to 10 ms). The C&DH subsystem will correlate S/C time to ground time (accurate to 1 ms). The C&DH subsystem will also perform Error Detection and Correction (EDAC) for data storage and recorder management. The C&DH shall provide a hardware platform for Attitude Control System (ACS) processing.

Spacecraft Data Storage Requirement
The C&DH can store 1 days worth of instrument and S/C data. This translates to nearly 70 Gbits for storage of data, short Reed-Solomon check bit data, and Hamming Code error detection and correction (EDAC) check bit data. The C&DH supports a nominal 7 to 8 ground contacts per day and provides simultaneous record and playback capability.

7.5.5.3 Interfaces

The C&DH Subsystem interfaces with the Communication Subsystem for the ground commands, and the engineering and science data downlinks. It also interfaces with all subsystems for distribution of commands and collection of housekeeping data through the MIL-STD-1553 bus. Unregulated nominal 28 Volts DC Power is supplied by the Electrical Power Subsystem. The ACS supplies raw attitude subsystem data to the C&DH Processor for attitude data processing.

7.5.5.4 GSE

Ground Support Equipment will include:

- A TLM and command workstation,
- A front-end data system and
- Any required Interface Boxes to support Command and TLM activities.

Two Ground station systems would be required to support individual box-level I&T activities.
.
Miscellaneous C&DH subsystem interfaces (one set per box) including:

- Instrument TCDU interfaces
- Analog I/O interfaces for testing Housekeeping operations
- Transponder simulator
- Processor Flight-S/W load and debug/diagnostic interfaces.

7.5.6 Flight Software

The S/C flight S/W resides in the C&DH, ACS, and possibly other subsystems that have processors. EXIST imposes no unique requirements on the flight S/W. The flight S/W will reuse (in part) heritage S/W configured for other missions.

The flight S/W receives real time and stored commands from the ground. It verifies that they are received without error, and processes them, stores them, and/or distributes them as appropriate. The S/W assembles the S/C housekeeping data from the subsystems and generates the housekeeping data to be sent to the ground.

The flight S/W manages the onboard storage of data using a file system. A standard protocol will be used to transfer files to the ground. File transfers will also be used for data from the ground to update onboard tables (e.g., locations of the TDRS S/C) or update onboard S/W.

The flight S/W monitors the health of the S/C and the instrument and implements corrective action for critical items that cannot wait for ground intervention. The corrective actions will typically place the instrument or the observatory in safe mode, a quiescent power positive mode, until operators on the ground can analyze the problem and restore normal operations.

The flight S/W provides attitude determination and control. It points the instrument to accomplish the sky survey or the target observation. As necessary, it points the SAs and antennas as required for operations. The flight S/W distributes information on the orbital position, attitude and time to the instrument. Position and time are provided by the GPS receiver.

The flight S/W provides other autonomous functions. It will accept burst alerts from the instrument and send them to the ground over the TDRS demand access link. This function will have been proven by several previous missions (for example, Swift and GLAST). It will monitor the position information and reconfigure the instrument for South Atlantic Anomaly (SAA) excursions.

7.5.6.1 Development versus Off-the-Shelf

The flight Software will be implemented using existing S/W to the extent feasible. The S/W will include commercial off-the-shelf operating systems and S/W that has been used on previous missions for similar functions (for example, safe mode or TLM formatting). A small amount of S/C S/W may be developed, based on the implementing organizations previous experience. For example, the burst alert message handling is not used on all missions, but will have been implemented by several S/C developers prior to EXIST. If these developers also develop EXIST, it can be reused, if another developer builds exist, the function would be a new function.

7.5.6.2 S/W Testing, Simulators

The flight S/W includes the simulators, test beds, and other equipment required to develop, test, and maintain the S/W through the end of the mission. The C&DH S/W should be developed first. Early availability of the C&DH S/W will support the development of the ACS and instrument S/W and ease the integration of all of the flight S/W.

7.5.7 RF Communications Subsystem

The communication system would consist of an X-Band subsystem for science data, S-band subsystem for ground commanding, GPS for position determination and timing, and TDRS Return Demand Access for immediate notification of gamma ray bursts similar to that employed by SWIFT. The possibility of Ka band with a HGA is an option that can be further explored. A new Low Power Transceiver (LPT) is under development and is anticipated to be space qualified and available at the time of EXIST.

7.5.7.1 Science data downlink

Science data acquisition can be achieved using an X-Band science data downlink to the ground stations at 20 Mbps with an omni antenna and one contact per orbit. At a 700 Kbps (compressed) continuous data rate, the link will need 3.4 minutes/orbit to dump the stored science data. Ground stations at Malindi, Hawaii, Maspalomas, Kourou, and Perth can provide this support. (Note: Malindi & Kourou do not indicate current X Band capability but it is planned to have this capability prior to EXIST).

7.5.7.2 Telemetry and Commanding

S-Band TLM and Commanding to Ground station (and/or TDRS for launch & emergency support) will be provided at 8 Kbps (TLM) and 2 Kbps (CMD).

7.5.7.3 Gamma Ray Bursts

Gamma Ray Burst announcements can be done using TDRS Return Demand Access capability 1.0 kbps. This capability is continuously available and similar capability is being emplolyed on the SWIFT mission to be launched in fall of 2003.

7.5.7.4 GPS

A GPS is included for position knowledge & timing. There will be sufficient on-board storage provided for one day.

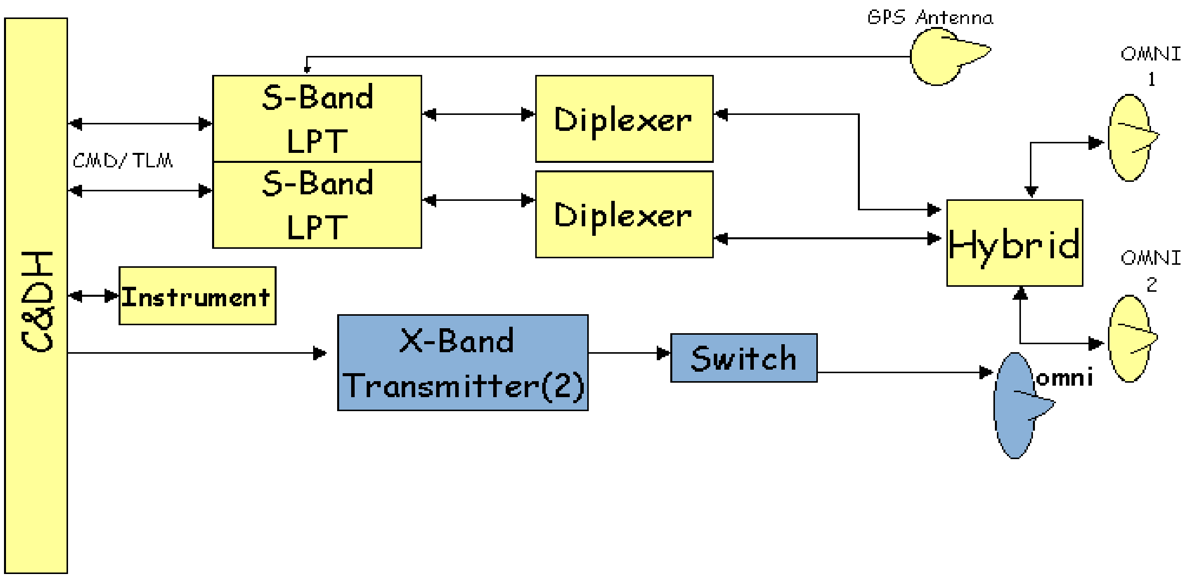


Figure 7-26. RF communication block diagram.

7.5.7.5 Alternate Concepts and Trades

S-Band

- Need 2 antennas to enable recovery in case of loss of control & launch phase support
- Best location is nadir/zenith

X-Band

- Need a single shaped omni located on nadir side

Ka-Band

- Need a single shaped omni located on nadir side
    - As of this date none have been built but does not look like major design issue

Ka Band

- Two 1m steerable antennas mounted on sides should have sufficient view to TDRS
- Could be similar to EOS–AM X-band design

7.6 System Integration and Test (I&T)

An I&T Manager who has a working knowledge of all aspects (electrical, mechanical, thermal, science objectives, etc) of the system to be taken through the I&T process will be assigned to the EXIST Project. The EXIST I&T Manager will have responsibilities which include process planning from high level flow to detailed daily operations, organization of the I&T team, scheduling of resources and personnel for each task, development of I&T plans and procedures, implementation and control of all I&T activities. To properly perform these responsibilities, the EXIST I&T Manager will be involved in the planning and early design stages (planning phase) of all space flight items. In this phase, the I&T Manager will assure that the EXIST I&T requirements are understood and incorporated in the design process. During the actual I&T process (implementation phase), the EXIST I&T Manager will direct the I&T team and approve all I&T test plans and procedures. The I&T Manager will be the sole point of contact for the EXIST I&T operations at the I&T facility, and will often be the single point of contact for launch site operations.

7.6.1 Observatory Integration Process

The EXIST Observatory I&T process will consist of two major phases: the Planning Phase and the Implementation phase.

7.6.1.1 Planning Phase

The EXIST planning phase will occur in conjunction with the early stages of EXIST space flight item planning, design and development. Activities that may be undertaken in this phase include, high level EXIST I&T flow definition, details of major assembly, test items, and sequences. An I&T flow will determine the planned sequence of assembly and test events, and reflect a logical flow and realistic duration for activities. It will be developed in association with the EXIST Project management for coordination of scheduled deliveries and proper funding. It may be modified by the Project through the incorporation of program philosophies (risks and tradeoffs). The EXIST I&T flow is a dynamic document and may change depending upon actual circumstances (e.g., late deliveries of hardware or S/W), changes in management philosophies, budgetary constraints, etc. Figures 7-2/ and 7-28 depict the proposed I&T flow at a broad level and at a detailed S/C level.

Cost planning for the defined I&T flow will be an early task in I&T planning. This task will insure that proper funding for the identified activities is obtained. Funding will include some allowance for retesting of failed components, delivery delays, unexpected shift work, launch delays and other unplanned events inherent in the implementation phase of the I&T process. The amount set aside for such purposes will be in proportion to the assumed risk associated with the particular space flight item, selected launch vehicle and importance of the overall project to NASA.

Set-up and equipping facilities to be used in the integration process will also be performed early in the I&T planning. This task includes set-up of necessary infrastructure such as communications and data lines, air handling and temperature control, cleaning facilities and office space. New equipment for use in these facilities will be selected and procured during this phase.

EXIST I&T FLOW

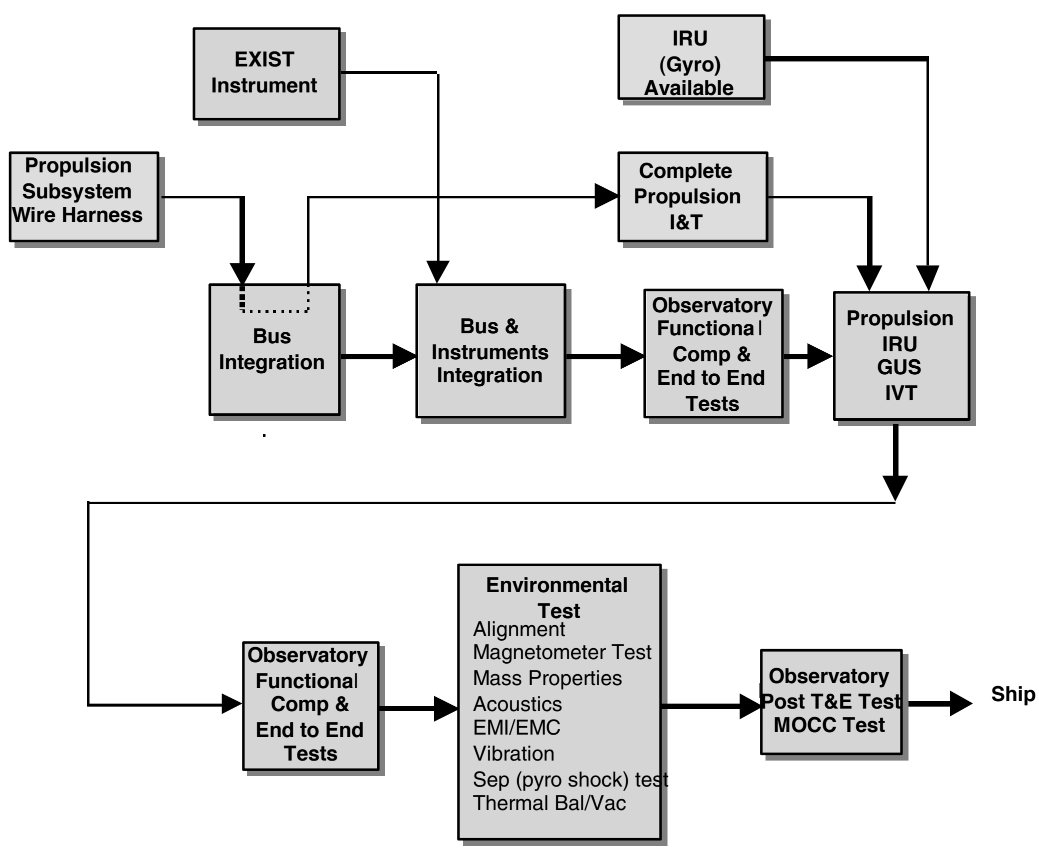


Figure 7-27. EXIST Observatory I&T flow.

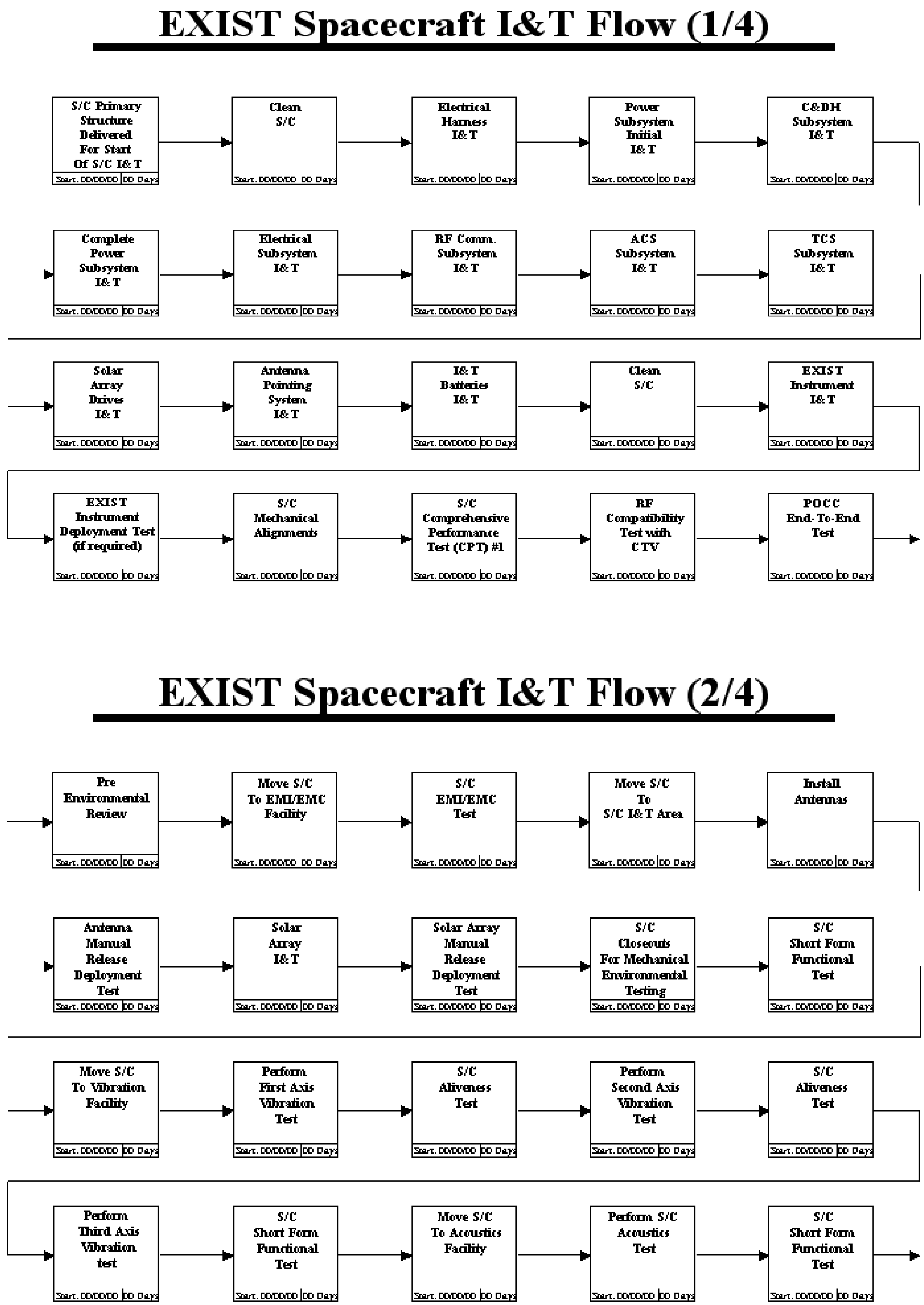
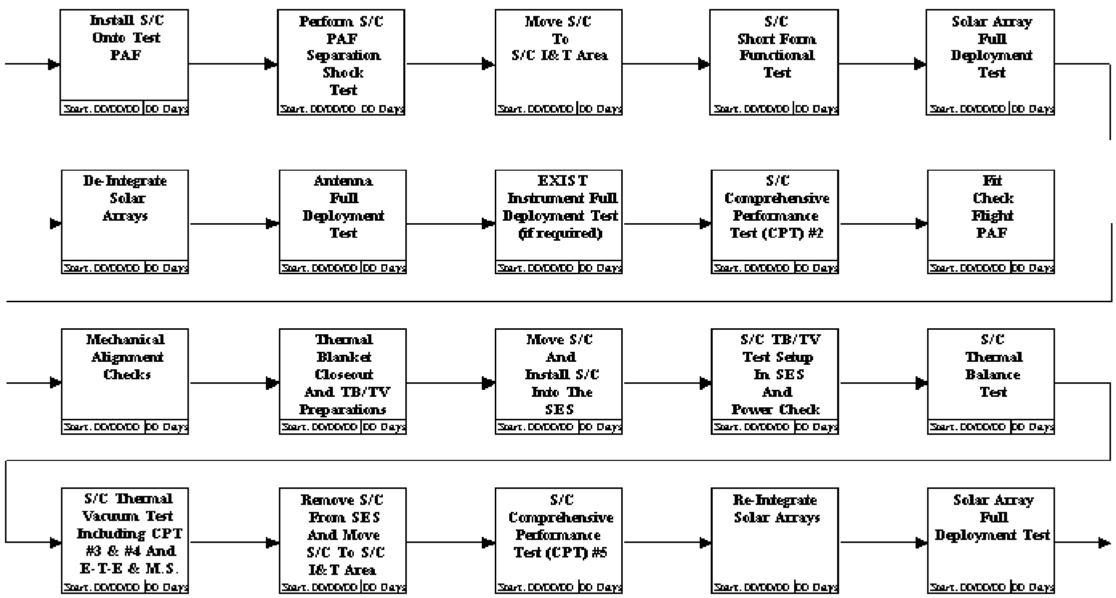
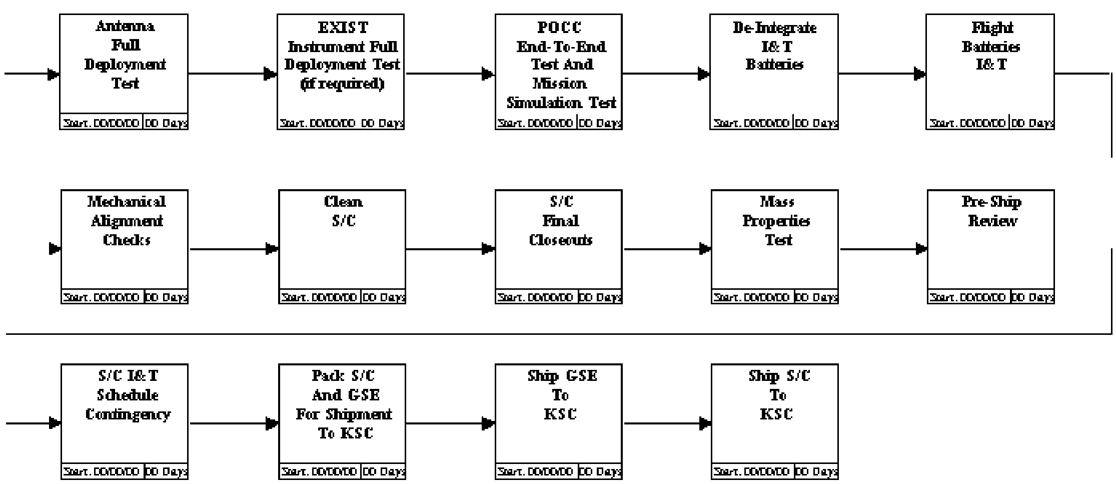


Figure 7-28. Details of EXIST spacecraft I&T flow.

EXIST Spacecraft I&T Flow (3/4)



EXIST Spacecraft I&T Flow (4/4)



7.6.1.2 Implementation Phase

The EXIST I&T Manager will develop and submit the I&T Plan, which outlines the intended I&T process to be used in the implementation phase, for approval by the EXIST Project in this phase. This plan is a valuable document for all EXIST discipline support personnel to use in planning for the implementation phase of I&T. The I&T Manager will work with EXIST discipline and instrument personnel to gain a clear understanding of the tasks involved, and uncover tasks and potential problems that had not previously been identified. All decisions and support needed to implement the I&T plan will be finalized before the start of the implementation phase. The I&T plan is a dynamic document, and it may change depending upon actual circumstances (late deliveries of hardware or S/W, changes in management philosophies, budgetary constraints, *etc*.) Furthermore, the EXIST I&T plan will be used by other project organizations to help in planning, or to request services. In the former case, discipline and project support personnel will make staffing, budget and logistic plans and design GSE based on the I&T plan. For the latter, services including logistics support and launch site services will be requested based on this document.

The EXIST I&T implementation phase will begin as early as possible. The implementation phase consists primarily of executing the I&T plan. Since I&T is a dynamic process, frequent and often major changes will occur, the EXIST I&T Manager will ensure that the space fight item successfully completes the I&T process regardless of any changes or complications that may occur. To mitigate risk, alleviate schedule problems, or for other engineering reasons, limited I&T may be performed on Engineering Test Units (ETU) or flight back-up spares. In these cases, the I&T process is the same as for flight hardware except that it may be appropriate to skip some activities such as mechanical integration (if performing electrical checks for example).

The ground system will be involved in as many tests as feasible, either directly or passively tapping into the TLM data, to test interfaces and ground system functionality and to train the operations team.

7.6.2 Observatory Level Testing

Observatory level tests will be performed to verify the EXIST observatory functionality. The figure below shows the relative test complexity and duration as well as general description of the tests.

7.6.2.1 Comprehensive Performance Test (CPT)

The EXIST Comprehensive Performance Test (CPT) will be developed to

- Verify that the EXIST observatory is ready for flight
- Verify that the EXIST observatory meets all testable requirements
- Identify any hardware or S/W system level interface/interaction problems
- Detect any problems induced by environmental testing

The CPT will test all of the EXIST observatory operational modes and configurations. The CPT plan will be accessed against the EXIST observatory verification matrix, and modeled after actual mission sequence scenarios. To implement CPT, STOL (or an equivalent language) procedures will be developed to automate test execution and data collection. The EXIST CPT will be performed multiple times, including pre-environmental, thermal vacuum, pre-ship, and pre-launch testing.

7.6.2.2 Functional Test

The EXIST Functional Test will be a subset of the CPT test procedure, allowing for re-use of test developed for the CPT. It is a streamlined standalone test of basic observatory functionality. It will be used to verify observatory test setup, verify all interface paths on the S/C and GSE, and full functionality of all hardware components. In other words, it will be used to verify that hardware is fully functional prior to a test, or was not damaged after a test. For the Functional Test, all components will be powered on, and all hardware operational modes tested to verify commanding, TLM, and interfaces in the process.

7.6.2.3 Aliveness Test

The EXIST Aliveness Test will be a basic test of the observatory operation. It will be used to verify that EXIST S/C is “alive” and operational. It is intended as a quick setup and test verification, to be followed by Functional Test or CPT at a later point in time. For the Aliveness Test, all components will be powered on, and then basic commands and critical TLM points will be verified.

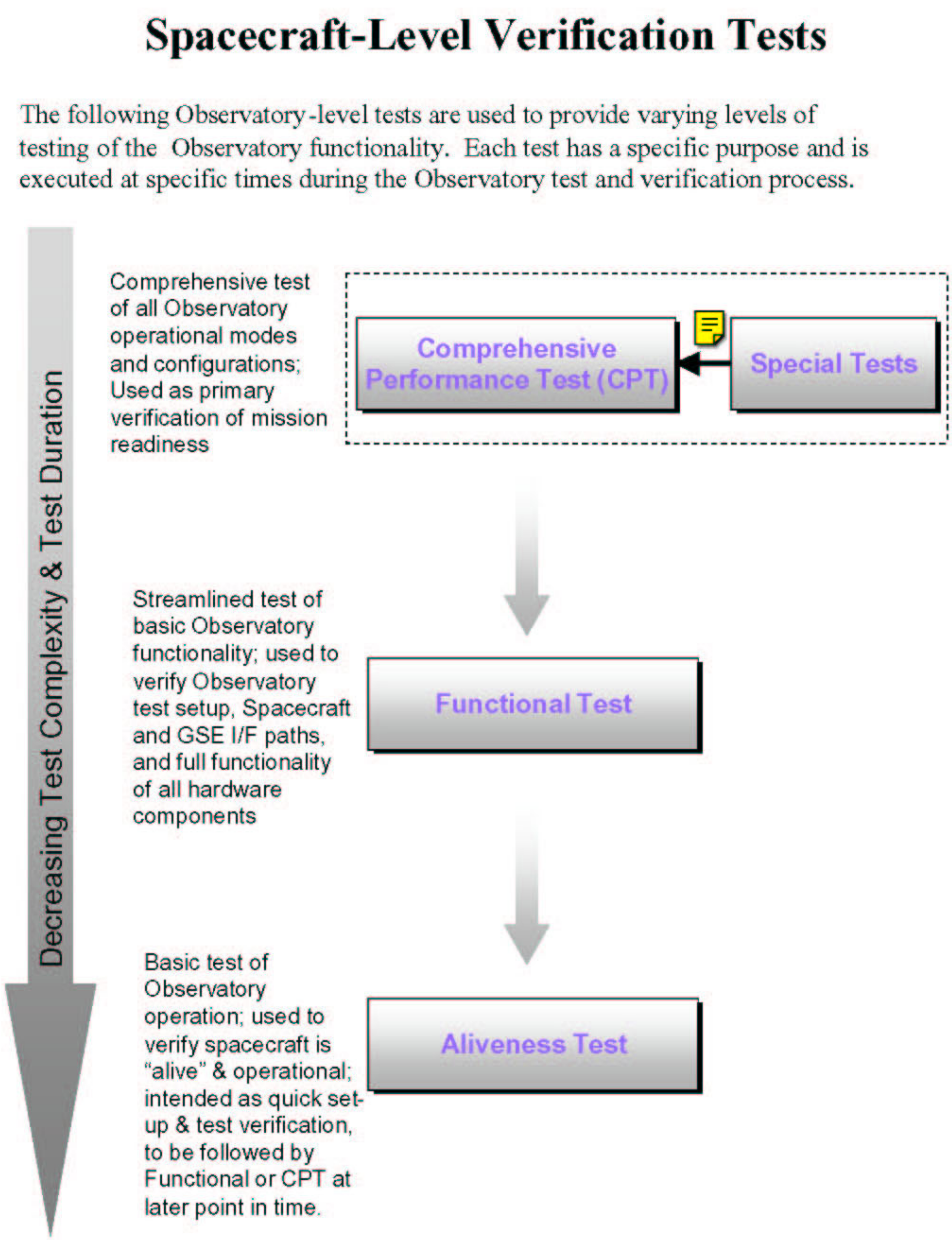


Figure 7-29. Verification test complexity description.

7.6.3 Environmental Test Program

The EXIST I&T Plan will include a detailed environmental testing plan to assure that we allow an exhaustive testing of the hardware to wring out all hardware and operations issues prior to launch. The environmental testing will include alignment, EMI/EMC, magnetics, thermal balance/thermal vacuum, mass properties, vibration acoustics, mechanical shock, and any other unique tests. Sequence of these tests is presented in the I&T Process Flow diagrams.

7.7 Mission Assurance (Safety, Reliability, and Quality)

The EXIST Project will plan and implement an organized Mission Assurance and Safety Program that encompasses all flight hardware and S/W from program initiation through launch operations. In addition, this program will assure the integrity and safety of the flight instrument and observatory, the ground system S/W, and the hardware that interfaces with flight equipment. The Mission Assurance and Safety Program will encompass the many multi-facets of systems performance validation.

7.7.1 Reliability

EXIST S/C bus will require a fully redundant system in order to achieve its required mission lifetime of 5 years with no Single Point Failures preventing achievement of science objectives. Deployable mechanisms pose a greater risk. Currently the only deployables are SAs and HGA. Each of the three telescopes are independent modules with their own processor and communication line to the S/C bus. In the event that a telescope completely fails, the remaining telescopes can still independently operate although sky coverage will be degraded by 30% (fully-coded imaging; 15-30% for partially coded imaging). There will an attempt to cross-strap as many telescope critical subsystems in order to share or switch between them. Reliability analyses will be performed concurrently with design so that identified problem areas can be addressed for timely consideration of corrective action. Several analyses are discussed in the following sections.

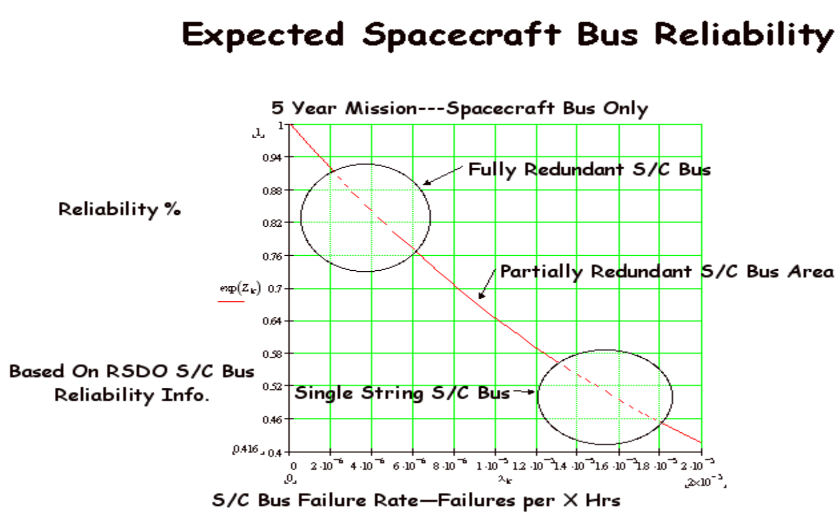


Figure 7-30. Spacecraft bus reliability.

7.7.1.1 Failure Modes and Effects Analysis and Critical Items List

A Failure Modes and Effects Analysis (FMEA) and Critical Items List (CIL) will be performed early in the design phase to identify system design problems. As additional design information becomes available the FMEA/CIL will be refined.

Failure modes will be assessed at the box level for the instrument to bus interface. The failure mode will be assigned a severity category based on the most severe effect caused by a failure. Mission phases, for example, launch, deployment, on-orbit operation and retrieval, will be addressed in the analysis.

Severity categories will be determined in accordance with the following table:

Table 7-23. Failure severity categories.

Category	Severity Definition
1	Catastrophic Failure modes that could result in serious injury or loss of life (flight or ground personnel), or loss of launch vehicle.
1R	Failure modes of identical or equivalent redundant hardware items that, if all failed, could result in category 1 effects.
1S	Failure in a safety or hazard monitoring system that could cause the system to fail to detect a hazardous condition or fail to operate during such condition and leads to Severity Category 1 consequences.
2	Critical Failure modes that could result in loss of one or more mission objectives as defined by the GSFC project office.
2R	Failure modes of identical or equivalent redundant hardware items that could result in Category 2 effects if all failed.
3	Significant Failure modes that could cause degradation to mission objectives.
4	Minor Failure modes that could result in insignificant or no loss to mission objectives

FMEA analysis procedures and documentation will be performed in accordance with documented procedures. Failure modes resulting in Severity Categories 1, 1R, 1S or 2 will be analyzed at greater depth, to the single parts if necessary, to identify the cause of failure.

Results of the FMEA will be used to evaluate the design relative to requirements (for example, no single instrument failure will prevent removal of power from the instrument). Identified discrepancies will be evaluated by management and design groups for assessment of the need for corrective action.

The FMEA will analyze redundancies to ensure that redundant paths are isolated or protected such that any single failure that causes the loss of a functional path will not affect the other functional path(s) or the capability to switch operation to that redundant path.

All failure modes that are assigned to Severity Categories 1, 1R, 1S and 2, will be itemized on a Critical Items List (CIL) and submitted with the FMEA report. Rationale for retaining the items will be included on the CIL.

7.7.1.2 Parts Stress Analyses

Each application of electrical, electronic, and electromechanical (EEE) parts, will be subjected to stress analyses for conformance with the applicable derating guidelines. The analyses will be performed at the most stressful values that result from specified performance and environmental requirements (e.g. temperature, voltage) on the assembly or component. The analyses will be performed in close coordination with the peer reviews (and thermal analyses, and it will be required input data for component-level design reviews.

7.7.1.3 Worst Case Analyses

Worst Case Analyses will be performed on circuits where failure results in a severity category of 2 or higher. The most sensitive design parameters, including those that are subject to variations that could degrade performance, will be subjected to the analysis. Analyses or test or both will demonstrate adequacy of margins in the design of electronic circuits, electromechanical and mechanical items.

The analyses will consider all parameters set at worst case limits and worst case environmental stresses for the parameter or operation being evaluated. Depending on mission parameters and parts selection methods, part parameter values for the analysis typically include the following: manufacturing variability, variability due to temperature, aging effects of environment, and variability due to cumulative radiation. The analyses will be updated in keeping with design changes.

7.7.2 Systems Safety

The system safety program will be initiated in the concept phase of design and continue throughout all phases of the mission. GSFC will certify safety compliance prior to the Pre-Ship Review (PSR). An initial safety assessment will focus on the propulsion, thermal and power systems as the most likely source of hazard to personnel and equipment. The system safety program will accomplish the following:

- Provides for the early identification and control of hazards to personnel, facilities, support equipment, and the flight system during all stages of project development including design, fabrication, test, transportation and ground activities.

- Address hazards in the flight hardware, associated S/W, GSE, operations, and support facilities, and conform to the safety review process requirements of NASA-STD-8719.8, “Expendable Launch Vehicle Payloads Safety Review Process Standard”.

- Meets the system safety requirements of EWR 127-1 "Range Safety Requirements Eastern and Western Range" and KHB 1710.2, "Kennedy Space Center Safety Practices Handbook".

- Meets the baseline industrial safety requirements of the institution, EWR 127-1, applicable Industry Standards to the extent practical to meet NASA and OSHA design and operational needs, and any special contractually imposed mission unique obligations.

7.7.3 Orbital Debris Assessment/End-Of-Life

An Orbital Debris Assessment will be prepared or the information required to produce the assessment consistent with NPD 8710.3, Policy for Limiting Orbital Debris Generation and NSS 1740.14, Guidelines and Assessment Procedures for Limiting Orbital Debris

The EXIST mission will complete its mission life by utilizing controlled re-entry. The mission is designed to include enough resources to conduct re-entry at the end of the mission life.

8 Mission Operations and Ground System Concept

8.1 Mission Operations Concept

The EXIST science operations has two modes, survey (scanning) and targeted (inertial pointing). EXIST is in survey mode most of the time, observing the entire sky once per orbit. In survey mode, the instrument points towards zenith throughout the orbit. Targeted mode will be used for targets of opportunity and for selected other objects. The instrument will point at the target whenever it is unocculted by the Earth. During occultation, a secondary target may be observed, or the observatory may revert to survey mode. Targeted mode will be used infrequently in the first year of the mission but increasing thereafter. The wide-FoV allows survey science to continue during targeted observations as well as many targets to be observed simultaneously during targeted observations.

Targets of opportunity will occur approximately once per month. When a transient phenomenon is identified from EXIST data or by another observatory, the project scientist will review candidates and select those to be observed. The target will be acquired within a few hours, allowing time for commands to be generated and checked. EXIST will observe the target of opportunity for the specified time, returning to survey mode or pre-planned target mode when the target is occulted by the Earth.

The instrument will detect gamma ray bursts. Information about these bursts will be sent to the ground within a few seconds to allow for follow-up observation by other observatories or selection as an EXIST target of opportunity.

The instrument will stop generating data and transition to a low power mode during excursions through the South Atlantic Anomaly (SAA). SAA excursions will occur over approximately 10% of the orbit.

EXIST will perform an orbital maneuver approximately once per year to maintain its altitude between 450 and 500 km. At the end of the mission, the propulsion system will be used to safely dispose of the observatory into the Pacific Ocean.

Burst alerts (<3 arcmin burst positions and initial spectra verses time) will be sent to the ground in real time over low bandwidth communications links. The bulk of the data will be sent to the ground through TDRS Demand ACCESS Services. The data will be dumped at relatively high rate and then sent back to the science or mission operations center over commercial communications links. The data will typically be delivered for full processing 3 to 16 hours after it was acquired.

The EXIST instrument and S/C will be capable of monitoring their own health and safety. In the event that they detect a problem, they will transition to a safe mode. The S/C will use the same communications path as the burst alert to notify the ground of the problem.

Ground operations will also be automated to the extent cost effective. The mission and science operations are expected to require staffing during normal working hours. Automated systems would monitor the observatory and the ground system, and alert an on-call operations team member in the event that a problem was discovered.

After launch and checkout, the Mission Operation Center (MOC), Instrument Operations Center (IOC), and Science Support Center (SSC) are staffed during working hours only. MOC personnel are on call in the event that an anomaly occurs, significant amounts of data are lost, or a target of opportunity is declared. The IOC personnel are on call for instrument anomalies. The SSC personnel are on call for targets of opportunities.

8.2 Ground System Concept

EXIST will use existing multi-user ground stations to recover the bulk science data and to uplink routine commands. The communications system is baselined to downlink data at 20 Mbps using X-band. EXIST generates about 60 gigabits of data per day (compressed), which require 7 or 8 contacts to transfer to the ground. Figure 8-1 shows the ground system concept.

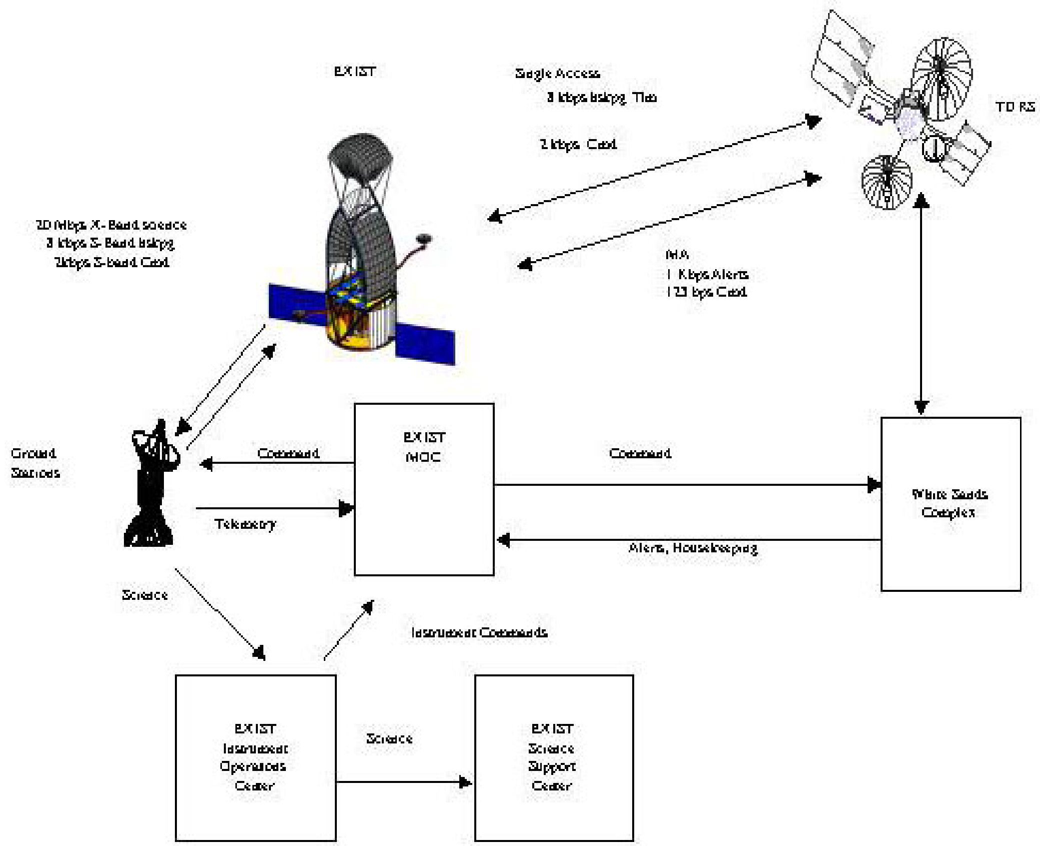
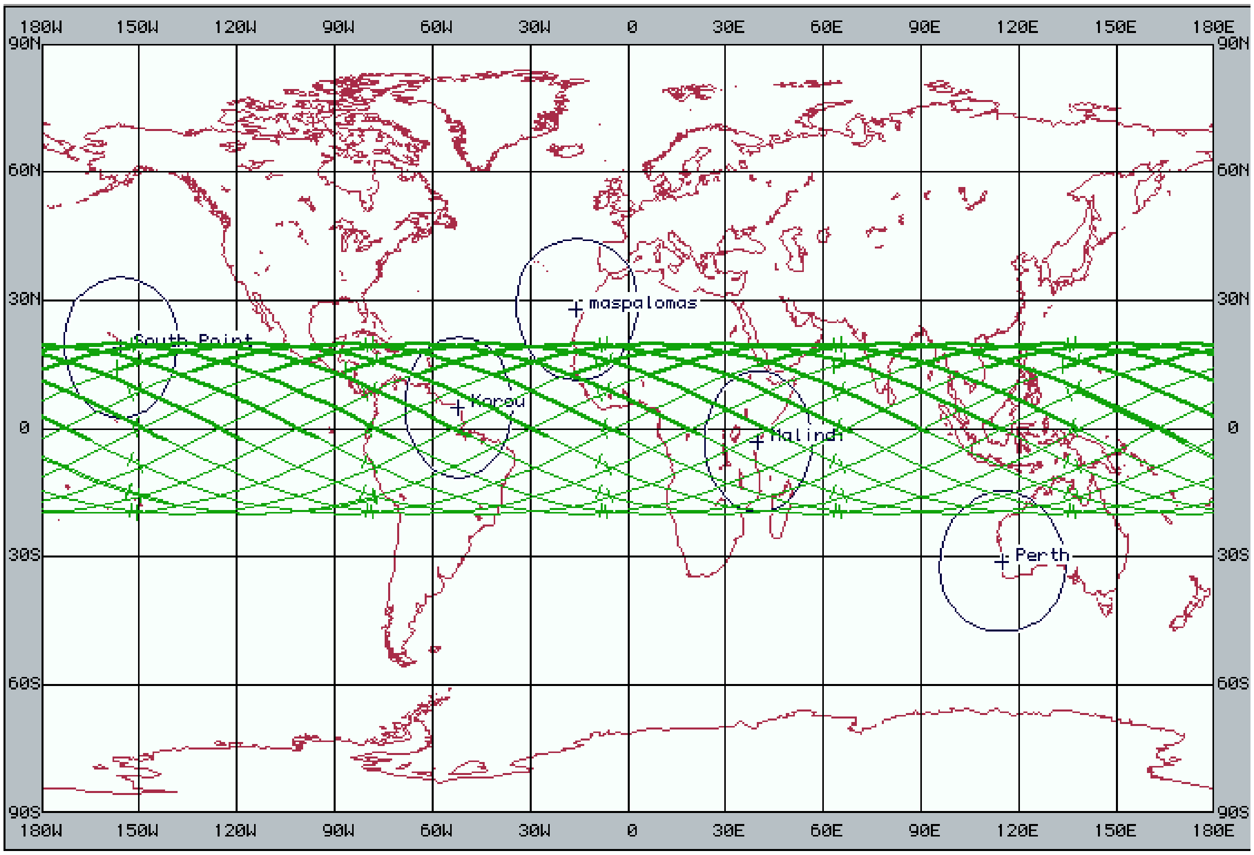


Figure 8-1. EXIST ground system concept.

8.2.1 Space/Ground Link

Figure 8-2 shows some potential ground station locations. At least two stations will be required to recover the data. The S/C and the ground station use a file transfer protocol to transfer the files to the ground station without error.



(EXIST: inclination= 20 deg, alt=500 km
Stations: Hawaii, Kourou, Maspalomas, Malindi, Perth)

Figure 8-2. Potential ground station locations.

The MOC will monitor the downlink automatically using status data from the ground station. It will alert an operations team member if the data is not received correctly. The science data will be sent after the contact to the IOC at a lower rate. The data will be delivered to the IOC within 24 hours of acquisition by the instrument. This time will be influenced by the location of the stations, the time between contacts, and the bandwidth available between the station and the SSC.

The burst alerts will use the TDRSS Demand Access Service. This service provides continuous return link coverage. The Demand Access Service is always listening for a transmission from EXIST. It acquires the signal within seconds and sends the data to the Mission Operations Center. The MOC will send the message to the Ground Communication Network (GCN) for immediate dissemination to other observatories and to the IOC and SSC. The Demand Access Service will also be used by the S/C to alert the operations team of any onboard anomalies.

EXIST will also use TDRSS for space/ground communications during special activities, such as post launch checkout and orbital maneuvers. TDRSS may be used for target of opportunity commands if a ground station contact is not available.

8.2.2 Mission Operations Center

The MOC will operate the S/C, send and receive command and TLM loads to the S/C and instrument, and perform health and safety monitoring. The MOC receives the alert messages from the S/C, processing the health and safety alerts and sending the burst alerts to the GCN. The MOC schedules ground station contacts and generates predicted orbit data for the IOC and the ground stations. The MOC accepts flight S/W loads from the S/C flight S/W maintenance function and from the IOC. The MOC plans and evaluates orbital maneuvers.

The MOC will contain a simulator that will be used to test and train the ground system prior to launch and to test new procedures and new flight S/W after launch.

8.2.3 EXIST Science Center

The SSC will perform higher-level science data processing and archiving, and manage special instrument observations. The SSC will support the data processing and investigations conducted by the science team guest observers. Among the tasks planned for the Science Support Center (SSC) will be the identification of targets of opportunity, production data (high-level) processing of the entire data set, generation of high-level data analysis tools, and creation and maintenance of the public data archive.

8.2.4 EXIST Instrument Operations Center

The IOC will support the operation of the instrument, perform low level data analysis and provide those data to the SSC, and perform higher level data analysis to support the science investigations performed by the instrument team. The IOC will be responsible for carrying out the following tasks both prior to and during flight: nominal instrument operations, instrument calibration, instrument monitoring, production and maintenance of operations S/W, support of the Mission Operation Center, maintenance of the instrument flight S/W, and production of data analysis S/W. Following launch, the IOC will be responsible for the production of low-level standard data products useable by the general community, verification of flight data, and processing of data to support the instrument team's investigations.

9 Future EXIST Mission Trades and Design Studies

This mission study has identified a number of additional concept refinement, mission trade and risk mitigation studies which should be conducted. This section summarizes these findings and recommends work to be performed in the next stage in the EXIST concept development.

9.1 Instrument

The EXIST instrument design is based on engineering work performed in Goddard's Instrument Synthesis and Analysis Laboratory (ISAL) in May 2000 assuming EXIST would fly as an attached payload to the International Space Station. Subsequently, NASA Headquarters Office of Space Science suggested that EXIST should be considered as a free-flying, low inclination mission. This study did not address instrument modification from the original space station baseline to the free-flyer. Design iteration through the ISAL should be pursued early in the next stage of the mission study.

EXIST needs technology development in a number of areas as described in section 6. Specific technology needs include very large area CZT detector arrays and read-out electronics, high-speed on board data processing systems, and advances in coded aperture mask technology.

Additionally, the following instrument issues should be addressed by further study:

1) Detector functional and environmental verification. Environmental tests may be somewhat difficult due to size (lifting/handling/test fixtures/test facilities). Special facilities and/or EGSE would be required.
2) Co-alignment of telescopes, and of telescopes to ACS sensors' reference frame. Maintain alignment over mission life and temperatures.
3) Calibration of instrument modules.
4) Thermal control and stability over the full temperature range.

9.2 Spacecraft Bus

RSDO deferred making an EXIST bus recommendation from their existing catalog until conclusion of RSDO On-Ramp IV. The current catalog of buses cannot accommodate the larger EXIST payload and instrument mass. An RSDO provided bus could be a significant cost saving over a customized bus. Industry survey and bus studies should be conducted to identify compatible commercial off-the-shelf buses, through RSDO if feasible, or through a broader RFI if the RSDO catalog is not a practical approach at this time.

Additional spacecraft bus trade studies should be carried out. Specifically, the following trades should be considered:

1) Explore ramifications of launching "upside down". This would alleviates launch vehicle CG concerns, allow for a longer spacecraft and possibly a different solar array solution.

2) Assess new technology low-power transceiver (currently under development and considered low-risk). Consider alternatives including combining communications and

GPS receivers in one package. Review alternate solutions that might be viable at the cost of some additional mass and power.

3) Consider different solar array panels and drives implementation. Alternatives include:
   - Employ a 2-axis drive with flat panels aligned along the velocity vector. This would ensure perfect sun pointing at all times and would have a most favorable ballistic coefficient. It would be well adapted to the shape of payload fan-beam. However, this would be a complicated design.

   - Employ a 1-axis drive with panels canted to “mid-beta angle” and aligned normal to the orbit. This is the simplest traditional approach but must augment the solar array area for cosine loss and minor shadowing issues. The solar array shaft would be located at the very bottom of the spacecraft to clear fan-beam FOV, producing a very large disturbance torque moment arm.

4) Assess a Multi Pump Capillary Pumped Loop (CPL) system for instrument thermal control. The Multi-CPL system pushes the current state-of-the-art. The first space-based demonstration of a multiple-evaporator CPL system was the CAPL-3 mission on STS-108 (launched 11/29/01).

5) Spacecraft jitter should be studied for impact to science requirements. Wheels, solar array drives, thruster operations, thermal snap, and fuel slosh are potential jitter sources.

9.3 Launch Vehicle

The Delta-IV is a new launch vehicle whose initial flight occurred on November 20, 2002 during the final editing of this report. A review should be conducted of Delta IV launch vehicle performance capabilities to a desired inclination of less than 28° which reflects actual launch experience as well as modified EXIST payload mass and CG. This review would be coordinated with KSC and Boeing.

Evaluate co-manifest or ride sharing opportunities on a similar or larger launch vehicle. There is a potential for cost or mass savings. It may be advantageous to use the Delta IV Heavy launch vehicle to gain an even lower orbit inclination.

9.4 Mission Reliability

A sensitivity analysis should be conducted to determine the costs and science return benefits of various mission lifetime requirements and goals. A 3-year required mission life with a 5-year goal is considerable less costly than a 5-year required life with a 10-year goal. However, significant science production in this spectral range and sensitivity would be highly desirable well into the foreseeable future.

Further evaluate full redundancy versus selective redundancy to achieve required and goal operational mission lifetime in terms of cost, mission performance (i.e. science data and sky coverage) and reliability rates. Accelerated lifetime and failure testing of new components is needed. EXIST employs new instrument design packaging and new CZT technology detectors.

The proposed Hamamatsu Photo Multiplier Tubes testing indicate redundancy is needed in this area. Customized versus off the shelf spacecraft bus.

Other mission reliability issues or trade studies that should be addressed include:

1) Determine if ability to adjust operating voltage to extend life should be considered. Variable voltage would address electronic part degradation.

2) Conduct preliminary FMEA to determine credible single point failures. Determine mission critical and at risk subsystems. Assist in reliability analysis.

3) Identify impact of South Atlantic Anomaly (SAA) on electronic part selection. Determine SAA affects, such as single event upsets, on mission science data processing and storage.

9.5 Propulsion

Several propulsion subsystem trades have been identified for further study. These trades include:

1) "Standard" vs "Ultralight" weight composite fuel tanks. There is little or no flight heritage on ultralight tanks. Additionally, there may be qualification costs for ultralight tanks. However, the lower mass could result in significant savings.
2) Lower ISP (310 sec) Bi-propellant. Study available bi-propellant candidates.
3) Bi-propellant (e.g., N_2H_4/NTO) verses Mono-propellant (e.g., Hydrazine) studies.

9.6 Mechanical/Structure

Preliminary analysis indicates that EXIST structure with long axial trusses and shear panels can meet launch vehicle mechanical requirements. Fundamental frequencies can meet Delta IV requirements. Gross stresses in truss structure appear reasonable. However, there are opportunities and rationale for further optimization of truss and panel design. Material trade studies for structure should be pursued. Alignment and mass requirements may allow use of higher coefficient of thermal expansion (CTE) materials, which may be less expensive or stronger than current design.

Details on detectors mounting, and resulting stresses should be analyzed thoroughly. How detectors are mounted will affect overall stiffness and stresses. Mass properties of the actual detectors should be added to the finite element model (FEM) to produce more realistic dynamics.

Current model uses simplified lumped masses, which may produce unconventional dynamics results. More realistic mounting to spacecraft bus should be incorporated and analyzed. Interface loads will need detailed analysis.

9.7 Power

This study report has identified a number of power subsystem trades for further study. These trades include:

1) Perform a trade to look at counter rotating IPACS (3-axis flywheel) to combine ACS with energy storage. This will provide a back up for the batteries (NiH2) and possibly reduce the battery size.
2) Consider alternate battery types and sizing based on mission lifetime requirements. 100 AH NiH_2 requires 29,000 cycles at 5 years; 39,000 cycles at 7 years with a 34% depth of discharge. A life test should be done on the battery design to ensure it will meet the cycle life requirement with normal eclipse seasons.
3) Triple Junction Gallium Arsenide (TJGaAs) solar cells at 28% efficiency are expected. EXIST should consider this and other advances in battery technology in mission concept formulation study.

9.8 Flight Dynamics

There are several considerations in flight dynamics, which should be reviewed. These items include:

1) Later launch date versus mission altitude. In 2013, the EXIST observatory would experience less solar activity induced atmospheric drag allowing a lower altitude with same resources.
2) Launch dispersion versus initial orbit altitude. Consider the required spacecraft V needed to correct for launch vehicle dispersion as opposed to the impact of insertion higher or lower than nominal.
3) Maneuver operations versus thruster sizing. Using fewer maneuvers can reduce costs, though higher thruster performance is required.
4) Autonomous orbit determination and maintenance versus the system resource impacts needed to implement and operate autonomously. This will affect propulsion, power, C&DH, and operations.

9.9 RF Communications Subsystem

Several considerations in RF Communication have been identified for further study, including:

1) LPT has yet to be space qualified but should be qualified well in advance of the EXIST mission. There is action ongoing by NASA to qualify the LPT within next few years. The current TRL is 4, a very low risk. A fallback option is to use an existing space qualified transceiver with a separate GPS receiver. There would be an increase of approximately 4 kg in weight and 5 watts DC power for the GPS receivers.

2) For the Ka Band alternative, a Ka Band shaped omni needs to be built and qualified. This will involve non-recurrent engineering costs but the development should not be high risk. The rest of design is considered minimal risk. Currently, there is no Ka Band frequency allocation direct to ground for space research missions. It is being applied for in WRC ‘03. NASA spectrum managers are cautiously optimistic.

9.10 Ground System

EXIST uses the TDRSS Demand Access Service for burst and health and safety alerts to the ground. This service relies on the first generation of TDRSS spacecraft. These spacecraft are currently projected to operate through at least 2012. There is some risk that this service will not be available for the full mission lifetime. EXIST should monitor plans for the operation of these spacecraft and for any follow-on capability. In addition, EXIST should investigate alternate communication services, such as data relay through Inmarsat or a comparable system.

EXIST operations will require a modest advance in the current state of the practice for operations automation. This advance is expected for other missions between now and the EXIST launch. If this advance does not occur or is perceived as too risky, EXIST may require additional staffing to accomplish the mission.

The availability, location, and capability of low latitude ground stations will change between now and several years before launch. A trade study to evaluate the optimal network will be required.

The data downlink is limited to 20 Mbps by the X-band spectrum allocation. Somewhat higher data rates might be feasible in X-band, but the allocated spectrum is only 50 MHz and there are stringent constraints on out-of-band emissions. An allocation is expected in Ka-band that would allow much higher bandwidths. If the multi-user ground stations are equipped for Ka-band operations, EXIST could have less frequent contacts, reducing the cost and complexity of mission operations.

The MOC, IOC, and SSC are described as separate, stand-alone facilities in this document. The project should perform trades studies to determine the feasibility and effectiveness of co-locating functions, either among these facilities or with functions from other missions.

10 Risk Management

The EXIST risk management approach provides early risk identification, tracking, and mitigation. The risk management plan will be developed and implemented during the mission formulation phase. Risks are categorized by type, and then classified for potential impact severity and likelihood of occurrence. Risks with medium to high impact and a high probability of occurrence require a risk mitigation plan. The risk categories are technical performance, cost, and schedule. Technical performance risk mitigation plans include early breadboards, parallel path development, alternative design development, redundancy, and judicious use of the mission mass and power margin. Cost risk mitigation plans include rescoping the efforts to remain within the original cost allocation, such as accepting a lower level of performance, parallel path development work arounds, or applying some financial contingency. Schedule risk mitigation plans include early breadboards, parallel paths, work arounds, and judicious use of schedule contingency.

The EXIST Project will implement a Continuous Risk Management (CRM) process in accordance with NPG 7120.5A, NASA Program and Project Management Processes and

Requirements. Details of the CRM process along with actions, tasks, and tools specific to the EXIST Project, are to be provided in Risk Management Plan.

There are six primary activities of the CRM process:

- Risk Identification: continuous efforts to capture, acknowledge, and document risks as they are found.
- Risk Analysis: an evaluation of all identified risks to estimate the probability of occurrence, severity of impact, timeframe of expected occurrence or when mitigation actions are needed, classification into sets of related risks, and priority ranking.
- Risk Planning: establishes actions, plans, and approaches for addressing risks and assigns responsibilities and schedules for completion. Metrics for determining the risk status are also defined during this step.
- Risk Tracking: an activity to capture, compile, and report risk attributes and metrics which determine whether or not risks are being mitigated effectively and risk mitigation plans are being performed correctly.
- Risk Controlling: an activity that utilizes the status and tracking information to make a decision about a risk or risk mitigation effort. A risk may be closed or watched, a mitigation action may be re-planned, or a contingency plan may be invoked. Decisions on the appropriate resources needed are also determined during this activity.
- Risk Communicating and Documenting: an overt action to communicate and document the risk at all steps of the CRM process. This can be in the form of an action item log, risk information sheet, risk database, mitigation plan, status report, tracking log, and/or meeting decision.

CRM will be carried out during day to day activities of EXIST by project engineering and management personnel, and discussed during key meetings. The top 20% risks shall have priority for resources to be expended for mitigation. However, all other risks shall be watched or accepted. Watched risks shall have their attributes examined and reported on a monthly basis. Any risks that are identified but not mitigated are considered accepted. It is also understood that not all risks are identified, and it is the intent of CRM to provide the means to handle identified risks.

As a result of EXIST mission studies, several areas of risk have been identified, and to some extent, analyzed in appropriate sections of this report. Many of these risks are considered in the recommended mission trade and design studies outlined in section 9.

11 Schedule and Cost

In conducting a mission concept study, the team assumed the following mission development timeline. It is based on the launch date envisioned by the Decadal Survey that endorsed the EXIST mission. This schedule is used in mission cost estimates.

Table 11-1. EXIST Mission Top Level Schedule

Pre-Formulation	Oct. 2002 – Sept. 2003
Formulation	Oct. 2003 – Sept. 2005
Systems Requirements Review	*Jan. 2004*
Preliminary Design Review	*Mar. 2005*
Mission Confirmation Review/NAR	*Sept. 2005*
Instrument Development	Oct. 2005 – Feb. 2009
Spacecraft Development	Oct. 2005 – Feb. 2009
Critical Design Review	*Oct. 2006*
Observatory I&T	Feb. 2009 – Mar. 2010
Pre-Environmental Review	*Apr. 2009*
Pre-Ship Review	*Mar. 2010*
Ship to Launch Site	March 2010
Launch Readiness Review	*June 2010*
Launch	June 2010

The EXIST schedule assumes that sufficient advance funding will be available for development of instrument technology. The schedule also assumes that the EXIST mission will compete and be selected as the Black Hole Finder Probe for the first of three “Einstein Probe” missions in the “Beyond Einstein Program” to be implemented under the new NASA Space Science Enterprise Strategic Plan.

The total mission cost shown in Table 11-2 has been developed based on FY2002 dollars. Cost estimation was performed as part of the IMDC exercise in November of 2001. Contingency was estimated by sub-system based on the technology readiness level (TRL) and flight heritage of the subsystem components. This estimated cost represents end-to-end mission development, implementation, launch, and operations.

Table 11-2. EXIST Mission Cost.

	FY02$	FY02$ w/contingency
Project Management	$8.8	$11.0
Pre-launch Development	$5.4	$6.8
Instruments	$98.0	$123
Spacecraft	$55.4	$69.2
Mission Systems Engineering	$6.8	$8.5
Integration and Test	$6.8	$8.8
Launch Vehicle	$102.0	$107.0
Ground System Development	**$3.8**	$4.8
Mission Operations – 5 yrs	$23.1	$28.9
Guest Observer Program – 5yrs	$20.0	$20.0
TOTAL COST	**$330.0**	**$387.8**

12 Education and Outreach

12.1 Introduction

As the first deep survey of the sky for BHs and other extreme objects in the universe, EXIST will have broad public appeal. Viewing exciting images in an entirely new band of exploration will fascinate people of all ages. EXIST will reveal unseen objects such as obscured BHs, historical but hidden supernova remnants, flashes of hard x-rays from GRBs signaling the birth of BHs in the distant universe, and cataclysmic quakes from enormously magnetized neutron stars in nearby galaxies. EXIST will be an ongoing movie of the variability of the energetic universe with the potential to capture the public's imagination, to instill a love for science in the general populace, and to energize the learning environment in the science classroom.

The fundamental interaction of gravity, matter and energy that EXIST will study is a natural forum in which to teach students basic physics aligned with the National Science Education Standards. Our Education and Public Outreach goal is, therefore, to promote EXIST science in both the formal and informal education communities, using the web and planetaria as well as the classroom environment.

12.2 Program Specifics

To achieve these goals we will rely on tried-and-tested methods of development and dissemination. For the formal classroom setting, we will create a program in which we train five educators who will work in conjunction with EXIST science and E/PO teams. These educators will be chosen from a nationwide search and will help develop, test and disseminate both printed materials and workshops, becoming "EXIST Educator Ambassadors" throughout the mission's lifetime. They, in turn, will train other educators at local, state and national teachers' meetings, maximizing the impact and leverage of EXIST science. These EXIST Educator Ambassadors will join a growing Ambassadors project (including SEU and GLAST Ambassadors) that can extend across the Astrophysics Division at NASA.

The second part of the formal setting will be to match 4^{th}-9^{th} grade teachers and scientists directly through Project ASTRO, a very successful national program of the Astronomical Society of the Pacific. For nearly ten years they have been linking educators and scientists at 2-day workshops to help them "develop an individualized program to share the excitement of modern astronomy." Working directly with the scientists, teachers will be better able to make the science of EXIST accessible to students, giving EXIST science a crucial boost in the classroom. Also, Project ASTRO has started a new program called "Family Astro" which targets people in a family setting, aiding in the informal dissemination as well.

For additional informal education, we will partner with a science museum (e.g., the Boston Museum of Science or the Maryland Science Center) to develop an interactive planetarium show showcasing EXIST science and the high-energy universe. We will also develop a teachers' guide for this show, linking the informal and formal educational aspects of this effort. Any EXIST Educator Ambassadors involved with museums or planetaria would provide valuable assistance in this area as well, increasing the leverage.

No mission would be complete without a website. An EXIST Education & Public Outreach (E/PO) website will be created to detail the science, planning and development of the mission, as well as showcasing the science, with a large degree of interactivity. Dissemination of formal education materials will also be a major function of the website.

12.3 Assessment And Impact Of E/PO Materials

Dissemination will occur through the NASA Support Network, and we also will actively seek out partnerships with institutions that have been awarded funds through NASA's Minority University Research and Education Partnership Initiative. Additional dissemination will occur through the EXIST Ambassadors Program, the partner museum, the International Planetarium Society, Project and Family Astro, the EXIST E/PO website and through GSFC's Imagine the Universe! Website.

We will continue to partner with WestEd as our external evaluator to ensure that we effectively educate the public with respect to the science and technology of the EXIST mission. Evaluation findings throughout development will allow us to adapt our activities and materials as necessary. WestEd currently evaluates the E/PO efforts of the Swift and GLAST missions, and can extend This effort to EXIST, using surveys, interviews and focus groups to perform both formative and Summative assessment and to also measure the effectiveness of our dissemination efforts

13 Conclusions and Recommendations

This study report represents a first step in development of the EXIST mission concept. Clearly, the report indicates that the EXIST concept is feasible and can be achieved with an acceptable level of technical, cost, and schedule risk. However, this mission study was heavily constrained in time and resources. A continuing EXIST concept study is needed to more fully characterize and develop the instrument and mission concepts, as well as programmatic and science planning. Specifically:

- The EXIST instrument concept should be refined through a second design iteration with the GSFC Instrument Synthesis and Analysis Laboratory (ISAL).
- The instrument detector concept requires further development with prototype detector modules.
- Alternate designs and trades have been identified and should be evaluated for spacecraft subsystem and mission operations concepts. A future EXIST mission study should also include an evaluation and study by industry of a compatible commercially available spacecraft bus.
- A future EXIST mission study should also conduct additional cost trades and analyses as well as consider potential mission partners.

Appendix A: Acronym List

AASC	Astronomy and Astrophysics Survey Committee
ACA	Aspect Camera Assembly
ACE	Attitude Control Electronics
ACS	Attitude Determination and Control System
ACS	Attitude Control Subsystem
AGN	Active Galactic Nuclei
Amp-hr	Ampere Hour
AHI	Ampere Hour Integrator
APD	Avalanche Photo Diode
ASIC	Application Specific Integrated Circuit
ASTRO	Mission Name (not an acronym)
AXAF	Advanced X-ray Astrophysics Facility, Now Chandra
BAT	Burst Alert Telescope
BATSE	Burst and Transient Source Experiment
BGO	Beryllium Germanium Oxide
BH	Black Hole
BHProbe	Black Hole Finder Probe
BOL	Beginning of Life
C	Celsius
C&DH	Command and Data Handling
CA	California
CC	Charge Controller
CDR	Critical Design Review
CFA	Center for Astrophysics
CFRP	Carbon Fiber Reinforced Plastic
CG	Center of Gravity
CGRO	Compton Gamma Ray Observatory
CIL	Critical Items List
CM	Center of mass
CM	Configuration Management
CMD	Command
CP	Center of pressure
CPL	Capillary Pumped Loop
CPL-3	Capillary Pumped Loop-3 (mission on STS-108)
CPT	Comprehensive Performance Test
CPU	Central Processing Unit
CRC	Cyclic Redundancy Code
CRM	Continuous Risk Management
CsI	Cesium Iodide
CSS	Coarse sun sensors
CTE	Coefficient Thermal Expansion
CZT	Cadmium-Zinc-Telluride (CdZnTe)
DCA	Detector crystal arrays
DET	Direct Energy Transfer
DM	Detector module
DMDHU	Detector Module Data Handling Unit
DOD	Depth of Discharge
DOE	Department of Energy
DRAM	Dynamic Random Access Memory
EDAC	Error Detection and Correction
EEE	Electrical, electronic, and electromechanical
EELV	Evolved Expendable Launch Vehicle
EGSE	Electrical Ground Support Equipment
EMC	Electro-magnetic Compatibility
EMI	Electro-magnetic Interference
EOL	End of Life
EPS	Electrical Power Subsystem
E-T-E	End-to-End
ETU	Engineering Test Unit
EVD	Engine Valve Drivers
EWR	Eastern and Western Range
EXIST	Energetic X-ray Imaging Survey Telescope
FDC	Fault detection and correction
FEM	Finite Element Model
FMEA	Failure Modes and Effects Analysis

Appendix A: Acronym List

FoV	Field of view
FRR	Flight Readiness Review
FS	Factor of safety
FTA	Fault Tree Analysis
FWHM	Full width half-maximum
FY	Fiscal Year
GaAs	Gallium Arsenide
GCN	Ground Communication Network
GE	General Electric
GEVS-SE	General Environmental Verification Specification for STS & ELV Payloads
GHe	Gaseous Helium
GLAST	Gamma-ray Large Area Space Telescope
GPS	Global Positioning System
GRAPWG	Gamma-Ray Astronomy Program Working Group
GRB	Gamma-ray bursts
GSE	Ground Support Equipment
GSFC	Goddard Space Flight Center
GUS	Gyroscopic Upper Stage
HDS	Hybrid dynamic simulator
HE	High Energy
HEFT	High Energy Focusing Telescope
HET	High-Energy Telescope
HGA	High Gain Antenna
HST	Hubble Space Telescope
HVPS	High Voltage Power Supply
I&T	Integration and Test
I/O	Input / Output
ICD	Interface Control Document
IDE	Independent Detector Electronics
IMARAD	A company in Israel that manufactures CdZnTe
IMDC	Integrated Mission Design Center
INTEGRAL	International Gamma-ray Astrophysics Laboratory
IOC	Instrument Operations Center
IPACS	Integrated Power & Attitude Control System
IPV	Individual Pressure Vessel
IR	Infrared
IRU	Inertial reference unit
ISAL	Instrument Synthesis and Analysis Laboratory
ISGRI	INTEGRAL Soft Gamma-Ray Imager
ISS	International Space Station
IVT	Independent Verification Test
KHB	Kennedy Handbook
KSC	Kennedy Space Center
LAT	Large Area Telescope
LE	Low Energy
LEO	Low Earth Orbit
LISA	Laser Interferometer Space Antenna
LLNL	Lawrence Livermore National Laboratory
LPT	Low Power Transceiver
LVPC	Low Voltage Power Converter
MAP	Microwave Anisotropy Probe
Mbps	Megabits per second
MCR	Mission Confirmation Review
MDR	Mission Design Review
MGSE	Mechanical Ground Support Equipment
MHz	Megahertz
MIPS	Million instructions per second
MLI	Multi-layer insulation
MMH	Monomethyl hydrazine
MOCC	Mission Operations Control Center
MODA	Mission Operations Data Analysis
MOR	Mission Operations Review
MRR	Mission Readiness Review
MSFC	Marshall Space Flight Center
MTB	Magnetic Torquer Bar

Appendix A: Acronym List

NAR	Non-Advocate Review
NASA	National Aeronautics Space Administration
NDE	Non-destructive examination
NGST	Next Generation Space Telescope
NiH_2	Nickel Hydrogen
NPD	NASA Policy Directive
NRC	National Research Council
NSS	NASA Safety Standard
NTO	Nitrogen tetroxide
NTO	Nitrogen tetroxide oxidizer
OAP	On-orbit Average Power
ORR	Operations Readiness Review
OSHA	Occupation Safety and Health Administration
OSS	Office of Space Science
PAF	Payload attachment fitting
PCI	Power Converter Interface
PDR	Preliminary Design Review
PER	Pre-Environmental Review
PG	Procedure Guideline
PHA	Preliminary Hazard Analysis
PiVoT	Position, Velocity, and Time (model Named for GPS receiver developed by GSFC)
PMT	Photo Multiplier Tube
PMTHV	Photo Multiplier Tube High Voltage
POCC	Payload Operations Control Center
PRA	Probabilistic Risk Assessment
PS	Pseudo-Random
PSE	Power System Electronics
PSF	Point spread function
PSR	Pre-Ship Review
PWM	Pulse Width Modulation
QE	Quantum efficiency
RBD	Reliability Block Diagram
RF	Radio Frequency
ROSAT	Roentgen Satellite
RSDO	Rapid Spacecraft Development Office
RT	Remote terminal
S/C	Spacecraft
S/W	Software
SA	Solar Array
SAA	South Atlantic Anomaly
SDO	Solar Dynamics Observatory
SDR	Systems Design Review
SEMP	Systems Engineering Management Plan
SEU	Structure and Evolution of the Universe
SHM	Safe Hold Mode
SIU	Shield Interface Unit
SNAP	Supernova Acceleration Probe
SR&T	Science Research & Technology
SRR	Systems Requirements Review
SSC	Science Support Center
SSPC	Solid State Power Controller
ST	Sub-telescope
STCU	Sub-Telescope Control Unit
STS-108	Space Transportation System - 108 mission
T&E	Test and Evaluation
TAM	Three Axis Magnetometer
TB/TV	Thermal Balance / Thermal Vacuum
TBD	To be determined
TC	Trickle Charge
TCC	Trickle Charge Controller
TCPU	Telescope Control and Processing Unit
TDRSS	Tracking & Data Relay Satellite System
TJGaAs	Triple Junction Gallium Arsenide
TLM	Telemetry

Appendix A: Acronym List

TRL	Technology Readiness Level
TRR	Test Readiness Review
URA	Uniformly Redundant Arrays
UTC	Universal Time Coordinated
V	Volts / Voltage
VCHP	Variable Conductance Heat Pipe
VERITAS	Very Energetic Radiation Imaging Telescope Array System
VT	Voltage/Temperature
WARP	EO-1 Wideband Advanced Recorder/ Processor
WRC	World Radiocommunications Conference
W-Sn-Cu	Tungsten-Tin-Copper

EXIST Fast Facts

Energy range	10 - 600 keV
Field of View	180º x 75º (fully coded)
Angular Resolution	2-5 arc minutes (10 – 50 arcseconds source locations)
Energy, Temporal Resolution	1-2 keV (<100 keV), 2-6keV (<600 keV); 2 μsec
Sensitivity (5σ, approximately 10^7 s)	0.05 mCrab (10-150 keV); 0.5 mCrab (150-600 keV)
Telescopes, Detectors	Coded aperture, 8 m^2 CZT
Attitude control, Pointing, Aspect	3-axis stabilized, 1º pointing, 5" instantaneous knowledge
Mass	8800 kg
Power	1500 W (on-orbit average)
Orbit	500 km altitude, circular with <22º inclination
Telemetry and Command	1.5 Mbps X-band science data downlink S-band housekeeping downlink/command uplink TDRS demand access for transient event notification
Launch Vehicle	Delta-IV or equivalent
Launch Date	~2010 timeframe
Mission Life	5 years design, 7 years goal

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