EPIC Interferometer

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the EPIC Interferometer Team

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Response to Request for Information

NRC Beyond Einstein Program Assessment Committee

Instructions for Responding

The panel requests that mission teams respond to the following questions as completely as possible. However, we fully recognize that the missions are at different stages of definition, and answers may not be available for many of the more detailed questions. For example, a specific spacecraft implementation may not have been selected, and so many details cannot be provided. In this case it is sufficient for the panel to understand the overall spacecraft complexity and requirements. We have attempted to indicate below where details are optional.

We also request that you please ensure that any written responses or diagrams that you include do not include ITAR-controlled information. The NRC will consider your response as public information and available to the public, if requested.

1. Science and Instrumentation

Please answer the following as completely as possible:

1.1 Describe the scientific objectives and the measurements required to fulfill these objectives.

The primary scientific objective is to detect and characterize the amplitude of gravitational waves released during the inflationary epoch. These waves are expected to leave an imprint on the power spectrum of the polarization of the 2.7 K cosmic microwave background (CMB). We will measure this spectrum to the sensitivity limit allowed by foreground radiation over a range of spherical harmonics from $\ell = 2$ to 600. We anticipate the foreground limit will correspond to a tensor/scalar ratio of T/S = 0.01. Precision measurements of all the Stokes parameters will be made over the full sky at frequencies from about 30 GHz to 300 GHz to allow the subtraction of these foreground signals.

1.2 Describe the technical implementation you have selected, and how it performs the required measurements.

EPIC observes the sky directly through several scaled, close-packed arrays of corrugated horn antennas. These antennas have extremely low sidelobes and low instrumental cross-polarization. The signals from these antennas are processed simultaneously in two different ways to recover the CMB power spectrum. In one mode of operation, we interfere signals from different antennas to measure the visibility for each baseline. Each visibility selects a narrow range of ℓ values and has no response to very low monopoles. In the second mode, we interfere signals from each antenna with other signals from the same antenna (autocorrelation) to form a correlation polarimeter. This latter mode has lower angular resolution than the first, but can measure large spatial features (low-ℓ). Both modes operate simultaneously to measure the CMB power spectrum from $\ell = 2$ to 600 with a full-sky observation. This range of ℓ space is dominated by the gravitational lensing signal at high ℓ and includes both the reionization bump at $\ell \sim 10$ and the peak at $\ell \sim 100$ due to primordial tensor modes.

In both cases, the detectors are cold bolometers. Bolometers have the advantage of operating over the entire range of millimeter wavelengths of interest for CMB studies. In addition, they have comparable sensitivity to coherent receivers below 90 GHz and better sensitivity above 90 GHz. The high-frequency sensitivity advantage improves in low background environments (balloons and space). Because there are no amplifiers, the main challenge to this approach is combining the signals from the multiple antennas without sacrificing signal-to-noise.

In EPIC the signals from an array of N close-packed, circular corrugated horn antennas are coupled to each of $4N$ bolometers simultaneously. The beam combiner is a Fizeau combiner (or interferometer). The signals reaching each bolometer are multiplexed in such a way that a portion of the visibility of each baseline appears at each bolometer. When the signals are combined the resultant sensitivity is comparable to that of a filled-dish with an array of bolometers coupled to the same number of modes (N) on the sky (for more details, please see January 2007 response to committee request for information).

1.3 Of the required measurements, which are the most demanding? Why?

The primordial tensor mode polarization signal is very faint – likely below 100 nK. The measurement requires a combination of raw sensitivity and exquisite understanding and control of systematic effects. These measurements must be made at a variety of millimeter wavelengths in order to separate the CMB signal from foreground contaminants, primarily from our own galaxy.

1.4 Present the performance requirements (e.g. spatial and spectral resolution, sensitivity, timing accuracy) and their relation to the science measurements.

Angular resolution of ~ 1 degree is required to measure both the reionization "bump" near $\ell \sim 10$ and the primordial tensor mode peak at $\ell \sim 100$. Broad spectral resolution ($\Delta\nu/\nu \sim 30$ %) from 30 to 300

GHz is required for foreground removal. System sensitivity of ~ $1\mu K/s^{1/2}$ (combining all detectors in each frequency channel) is required to reach the tensor mode signal that corresponds to a tensor/scalar ratio of 0.01, presumably at the limit allowed by the foregrounds.

1.5 Describe the proposed science instrumentation, and briefly state the rationale for its selection.

EPIC consists of 16 fundamental modules (See figs. 1-1, 1-2, 1-3, 1-4, 1-5). Each module is a cluster of 64 close-packed corrugated horn antennas. The modules are scaled in size so that they have identical beam patterns on the sky.

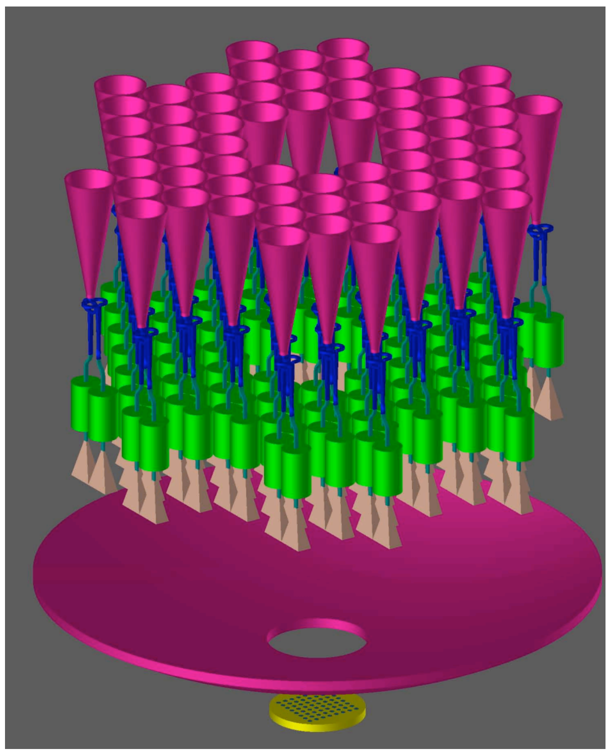

Figure 1-1. A possible configuration for an interferometric module for EPIC. The array views the sky through a close-packed cluster of 64 corrugated horn antennas. The two polarizations (either linear or circular) are split by an ortho-mode transducer and individually phase-modulated (Fig. 1-2). The beams are then combined with a Fizeau combiner in the form of a cold, compact, on-axis Cassegrain telescope. Note that the distances between the antennas, primary mirror and detector array are not to scale. Interference fringes formed by the various antenna baselines appear on the bolometer array in the focal plane of the telescope. The superimposed fringes are separated from each other using a phase modulation sequence that uniquely encodes each visibility (Fig. 1-3). EPIC could be made of a cluster of these fundamental modules, with multiple copies operating at frequencies from 30 GHz to 300 GHz.

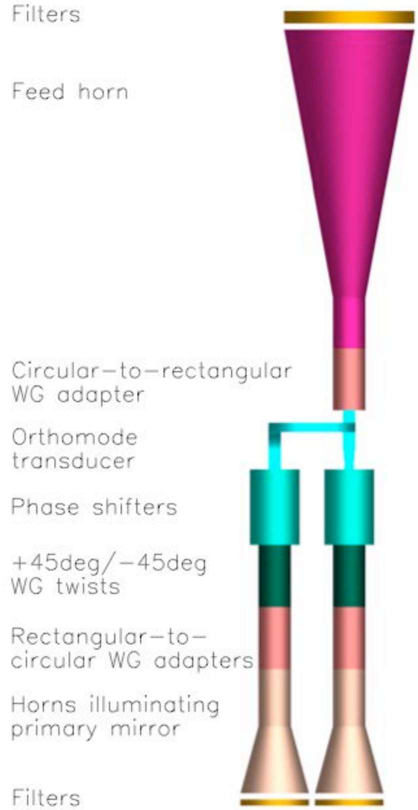

Figure 1-2. Input unit (IU). Two polarizations are separated using an orthomode transducer and are rotated in waveguide (WG) so that the two polarization vectors are aligned. A +/- 90 degree phase modulation is introduced in one of the arms and the two signals are directed at the Fizeau combiner. The interference of the two signals from an IU results in a correlation receiver, instantaneously sensitive to the Stokes U parameter. The interference of signals from different IUs results in an interferometer.

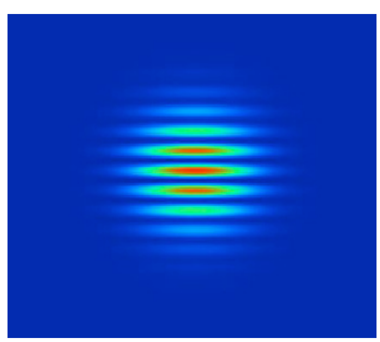

Figure 1-3. Simulation of fringe patterns formed in the focal plane of the Fizeau beam combiner from a single baseline.

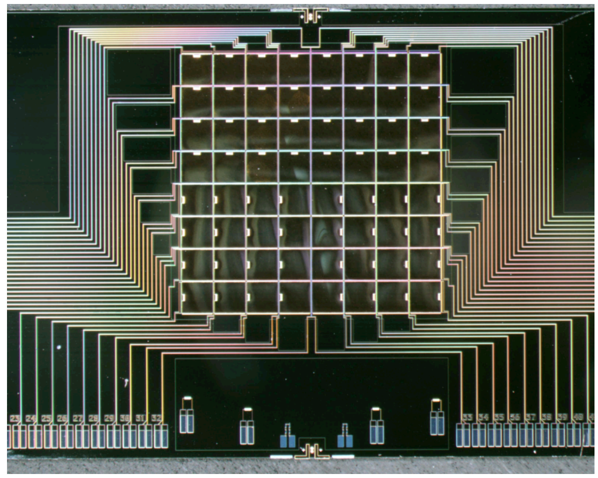

Figure 1-4. Backshort-under-grid (BUG) bolometer array (courtesy NASA/GSFC) that could be used in the focal plane of each EPIC module. Signal on each bolometer element is measured with a superconducting transition edge sensor (TES). To Nyquist sample the fringe patterns in EPIC, arrays with 4 x 64 = 256 pixels are required.

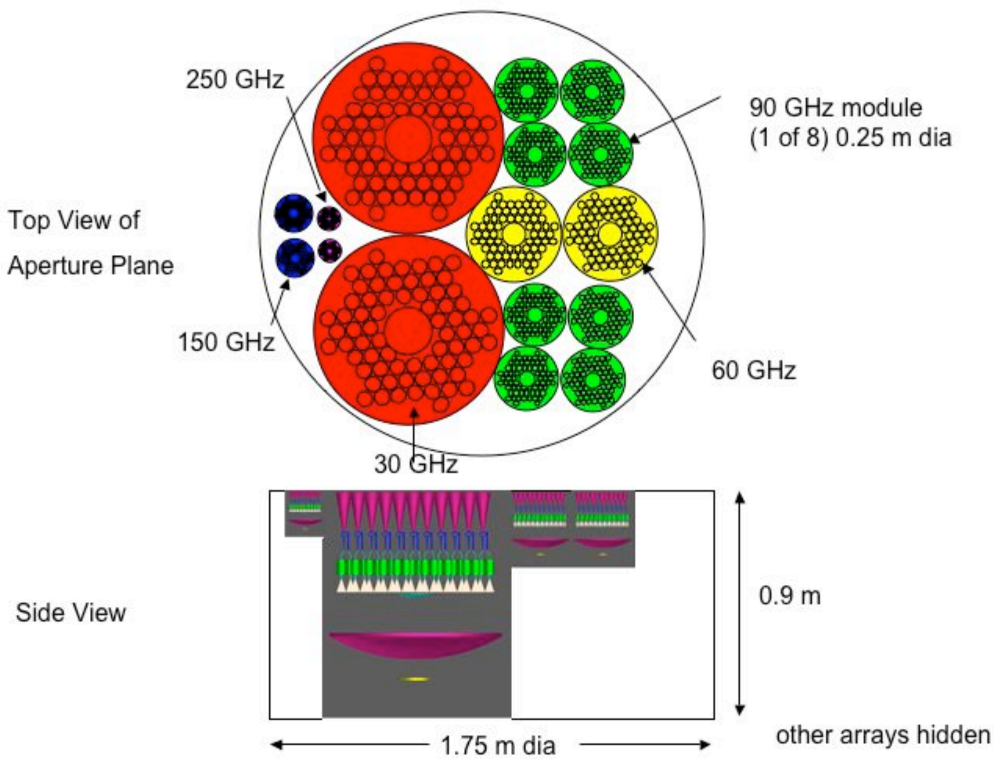

Figure 1-5. EPIC instrument array layout. The arrays are cooled to 2 K by a liquid helium bath. Detector arrays are cooled to ~ 100 mK by an adiabatic demagnetization refrigerator.

1.6 For each performance requirement, present as quantitatively as possible the sensitivity of your science goals to achieving the requirement. For example, if you fail to meet a key requirement, what will the impact be on achievement of your science objectives?

Figure 1-6 shows the estimated sensitivity of EPIC to CMB polarization. The requirement for achieving angular resolution of 1 degree determines how well EPIC can measure the peak in the primordial power spectrum that is faintly visible at $\ell \sim 100$. Full-sky coverage is required to measure the reionization peak down to $\ell = 2$. The errors on the data points scale linearly with the stated sensitivity requirements.

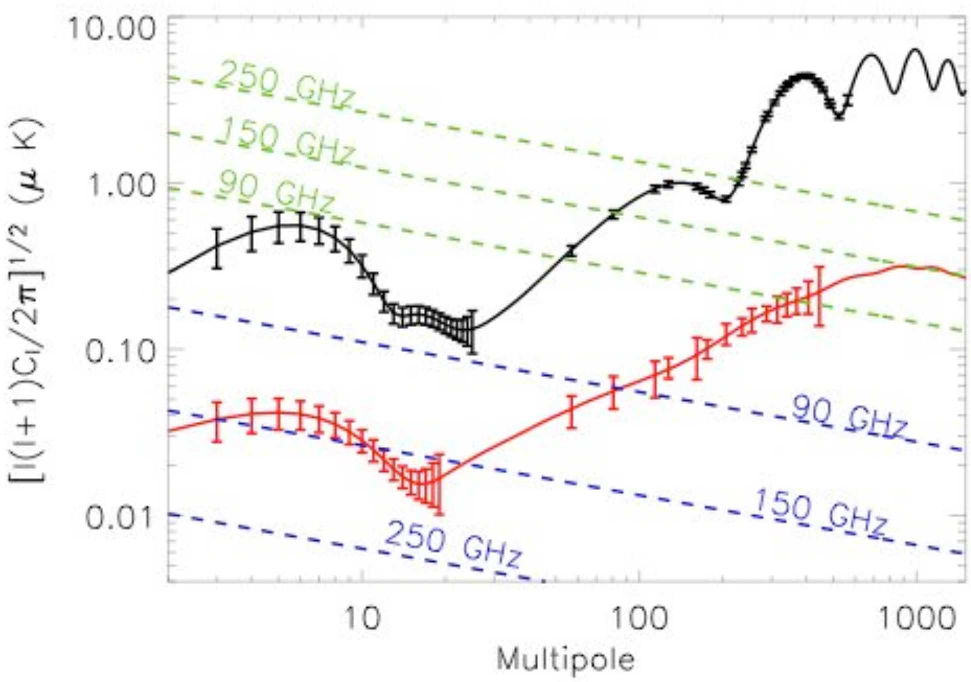

Fig. 1-6. Estimated sensitivity of EPIC to CMB polarization. *E*-mode (black) and *B*-mode (red) polarization power spectra are shown. The power spectra are based on the best-fit model from WMAP. The tensor-to-scalar ratio is taken to be 0.01. Errors (1σ) assume one year of integration sampling the full sky uniformly. The configuration assumed here includes 1024 feed horns, with 512 sensitive to 90 GHz, the primary science channel; the other 512 feed horns, sensitive to 30, 60, 150 and 250 GHz, are for measuring and removing foregrounds and are not included in this estimate. The dotted lines show the expected levels of polarized dust emission and the dashed lines show the expected levels of polarized synchrotron emission at 90 GHz, 150 GHz and 250 GHz based on the WMAP results. EPIC operates both as an imaging instrument and an interferometer; low-ℓ points come from operating the interferometer as single-beam correlation radiometers while high-ℓ points come from operating the instrument as an interferometer.

1.7 Indicate the technical maturity level of the major elements of the proposed instrumentation, along with the rationale for the assessment (i.e. examples of flight heritage, existence of breadboards, prototypes, etc).

Corrugated horn antennas have heritage from COBE and are TRL 9. The orthomode transducers for frequencies below 100 GHz have been used in WMAP and are TRL 9. OMT's up to 300 GHz have been built; we are not aware of the flight heritage for these devices. The phase modulators are the most challenging part of the EPIC design. Ferrite phase modulators have been used in the ground-based BICEP and MBI instruments; TRL is probably 6. Alternative phase modulator technologies (i.e. MEMS switches or varactor-diode controlled non-linear transmission lines) are at a lower level of readiness. The Fizeau combiner is a conventional Cassegrain telescope and poses no technical challenges. The arrays of bolometers required in the focal plane can be either NTD Ge (TRL 8, heritage from Planck, Herschel or TES bolometers (TRL 6, heritage from SCUBA, GBT). Appropriate readout electronics have been developed for these programs. All of these parts are under being tested by the Millimeter-wave Bolometric Interferometer (MBI), a ground-based test-bed for the EPIC technologies.

The cryogenics include a superfluid liquid helium cryostat (TRL 9, heritage from Spitzer, ISO, Herschel, COBE) as well as a single-shot ADR (TRL 9, heritage from the XRS instrument on ASTRO-E2).

1.8 Briefly describe the overall complexity level of instrument operations, and the data type (e.g. bits, images) and estimate of the total volume returned.

Instrument operates continuously in scanning mode. Signals from each bolometer pixel are sampled at 10 Hz at 16 bits and are demodulated on the ground. This produces a continuous data rate of 830 kbps (including 25% contingency). These data are transmitted to ground approximately once per orbit.

ADR is recycled approximately every 24 hours.

1.9 If you have identified any descope options that could provide significant cost savings, describe them, and at what level they put performance requirements and associated science objectives at risk.

We have not identified any descope options.

1.10 In the area of science and instrumentation, what are the three primary technical issues or risks?

1. phase modulator technology

2. cryogenics

3. removal of foreground contamination – need to demonstrate that this can be done adequately using a combination of measurements in image space and visibility space.

1.11 Fill in entries in the Instrument Table to the extent possible. If you have allocated contingency please include as indicated, if not, provide just the current best estimate (CBE).

See table below.

1.12 Optional details – If you have answers to the following detailed questions, please provide:

For the science instrumentation, describe any concept, feasibility, or definition studies already performed (to respond you may provide copies of concept study reports, technology implementation plans, etc).

EPIC is the subject of a NASA-supported mission concept study. The study period began 7 May 2004 and will end 6 May 2007. We will provide a report to NASA by 6 August 2007 and can provide the same report to the committee at that time. A conference paper on the EPIC concept has been published (Timbie, P. T., Tucker, G. S., Ade, P. A. R., Ali, S., Bierman, E., Bunn, E. F., Calderon, C., Gault, A. C., Hyland, P. O., Keating, B. G., Kim, J., Korotkov, A., Malu, S. S., Mauskopf, P., Murphy, J. A., O'Sullivan, C., Piccirillo, L, and Wandelt, B., D. "The Einstein Polarization Interferometer for Cosmology (EPIC) and the Millimeter-wave Bolometric Interferometer (MBI)," New Astr. Rev. 50(11-12), 999 (2006).)

For instrument operations, provide a functional description of operational modes, and ground and on-orbit calibration schemes.

Describe the level of complexity associated with analyzing the data to achieve the scientific objectives of the investigation.

Provide an instrument development schedule if available.

Provide a schedule and plans for addressing any required technology developments, and the associated risks.

The Millimeter-wave Bolometric Interferometer (MBI) is a ground-based test platform for evaluating the EPIC concept. MBI-4 includes 4 antennas at 90 GHz and will be deployed for testing this summer (2007). Members of the EPIC team are submitting a proposal to the NASA APRA program to develop the required technologies. The proposal calls for a test flight of MBI-16 in 2010.

Describe the complexity of the instrument flight software, including estimate of the number of lines of code.

Compare the scientific reach of your mission with that of other planned space and ground-based missions.

Instrument Table

Item	Value/Description
Number and type of instruments	1
Number of channels	16 scaled arrays at 30(2), 60(2), 90(8), 150(2), 250(2) GHz with 20% BW
Size/dimensions (for each instrument)	2.5 m dia x 2.7 m
Payload mass with contingency	1590 kg, 25%
Average payload power with contingency	250 W, 25%
Average science data rate with contingency	830 Kbps, 25%
Instrument Fields of View (if appropriate)	arrays view same 15^0 dia FOV
Pointing requirements (knowledge, control, stability)	1' knowledge, 3' control

2. Mission Design

Please answer the following as completely as possible:

2.1 Provide a brief descriptive overview of the mission design (launch, orbit, pointing strategy) and how it achieves the science requirements (e.g. if you need to cover the entire sky, how is it achieved?).

Circular sun-synchronous orbit, similar to that of COBE. 900 km altitude, 99 deg. inclination, 6 PM ascending node. Boresite is oriented ≈ 94 ◦ from sun and toward local zenith to avoid illuminating instrument apertures with radiation from Sun or Earth. Gives full sky coverage in six months. Spacecraft rotates about boresite at 1 rpm to allow recovery of polarization information and to fill out the u-v plane for interferometer visibility information.

2.2 Provide entries in the mission design table to the extent possible. Those entries in italics are optional. For mass and power, provide contingency if it has been allocated, if not – provide just your current best estimate (CBE). To calculate margin, take the difference between the maximum possible value (e.g. launch vehicle capability) and the maximum expected value (CBE plus contingency).

See table below as well as tables in section 3. Spacecraft Implementation.

2.3 Provide diagrams or drawings (if you have them) showing the observatory (payload and s/c) with the components labeled and a descriptive caption. If you have a diagram of the observatory in the launch vehicle fairing indicating clearance, please provide it.

See section 3. Spacecraft Implentation.

2.4 Overall (including science, mission, instrument and S/C), what are the three primary risks?

1. Interferometric approach to CMB polarization measurement. While interferometers have been used for years for precision CMB measurements, the approach of combining spatial interferometry with incoherent detectors is new. The payoff is potentially improved control over systematic effects compared to an imaging system.

2. Cryogen lifetime. We require a cryogen hold time of a minimum of 1 year on orbit.

Optional detail (provide if available):

- If you have investigated a range of possible launch options, describe them, as well as the range of acceptable orbit parameters.
- If you have identified key mission tradeoffs and options to be investigated describe them.

Mission Design Table

Parameter	**Value**	**Units**
Orbit Parameters (apogee, perigee, inclination, etc.)	900 km circular 99 deg. inclination	
Mission Lifetime	24	mos
Maximum Eclipse Period		min
Spacecraft Dry Bus Mass and contingency	See section 3.	Kg, %
Spacecraft Propellant Mass and contingency	See section 3.	Kg, %
Launch Vehicle	Atlas 5(401)	
Launch Vehicle Mass Margin	See section 3.	Kg, %
Spacecraft Bus Power and contingency by Subsystem		W, %
Mass weighted reuse percentage of payload and spacecraft subsystem components		%
Mass weighted redundancy of payload and spacecraft subsystem components		

3. Spacecraft Implementation

Please answer the following as completely as possible:

3.1 Describe the spacecraft characteristics and requirements. Include, if available, a preliminary description of the spacecraft design and a summary of the estimated performance of the spacecraft.

The design of the Observatory (Figure 3-1) is dictated by the seven top-level requirements listed in Table 3.1-1. Each of the requirements can be met using existing components, hardware designs, or, in the case of the structure, scaling of proven designs and use of established manufacturing processes. From an avionics performance perspective, none of the EPIC parameters necessitate the utilization of unproven hardware or development of new technology.

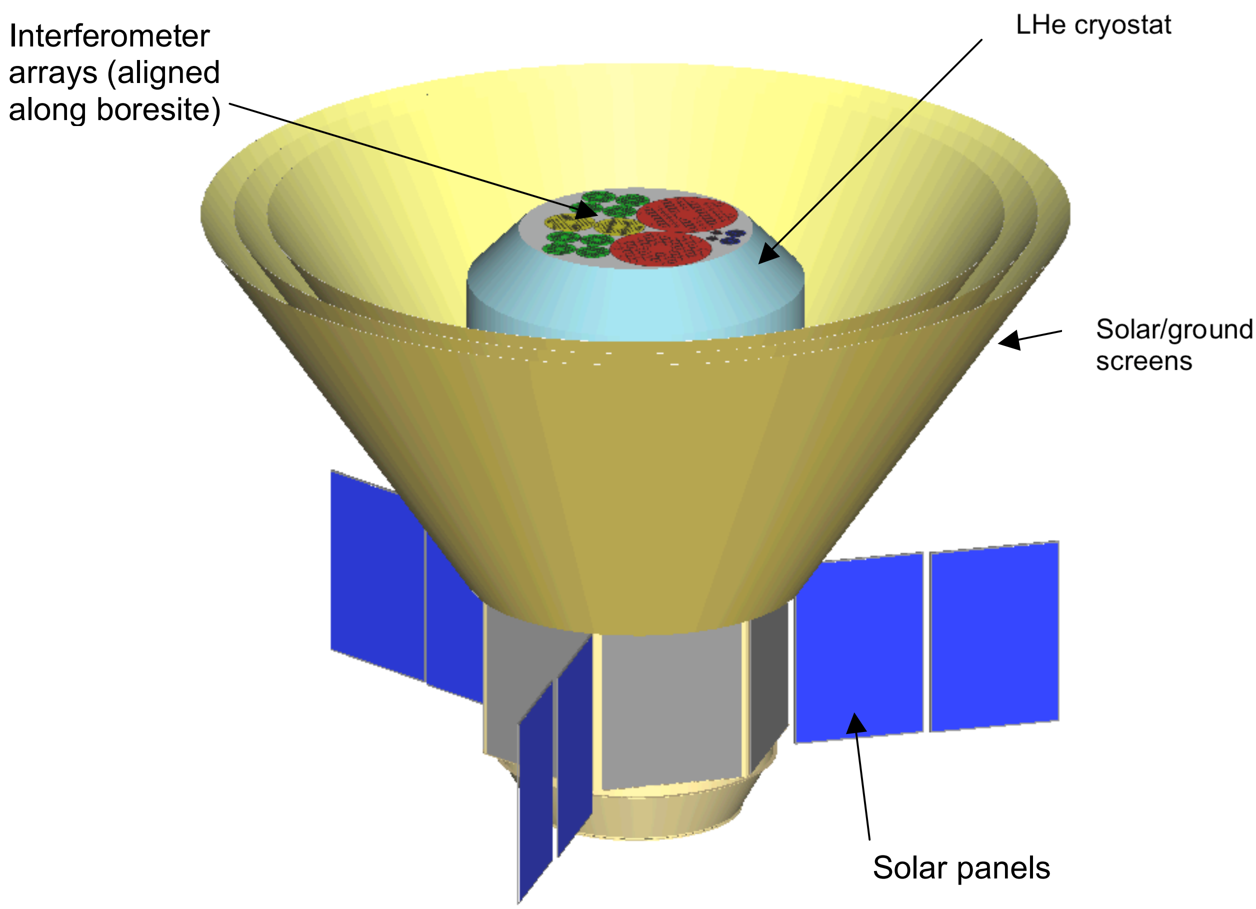

Fig. 3-1. EPIC Observatory.

EPIC Top-Level Spacecraft Requirements		Spacecraft Design Feature
1.	Mechanically support 1590 kg (including 25% contingency) instrument	Robust aluminum bus structure with diameter sufficient to provide direct load paths to launch vehicle
2.	250 W (including 25% contingency) instrument power in sun synchronous orbit with 1 RPM Observatory spin	Three solar array wings deployed 120 degrees apart
3.	Zenith pointing instrument, with 3 arcmin pointing control and 1 arcmin knowledge; 1 RPM spin about instrument bore sight	Zero momentum bias design using momentum wheel to compensate for spinning spacecraft angular momentum; stellar attitude determination using high star-rate tracker and high quality gyro.
4.	>4 Gbit on-board data storage	Solid state memory board
5.	8 Mbps science downlink	X-band science data communications systems using existing polar ground stations
6.	2-yr mission life; high reliability (limited life cryogen dewar cannot tolerate significant delays to analyze anomalies)	Full redundancy, except for few graceful degradation components
7.	Precise terminator orbit, maintenance at 900 km altitude, and end-of-life disposal capability	Propulsion subsystem to compensate for launch vehicle orbit insertion error, provide infrequent orbit maintenance, and perform disposal maneuver

Table 3.1-1 The EPIC Observatory bus design is driven by seven mission requirements.

The spacecraft mechanical design for EPIC is based on the flight-proven frame and panel design used on Coriolis (50-months on orbit to date) and Swift, (28-months on orbit to date), and employed on the Gamma-ray Large Area Telescope (GLAST) and GeoEye-1, both scheduled to launch in 2007. The overall EPIC Observatory configuration, including the three solar array wings, is very similar to the GSFC COBE mission because of the very similar payload geometries and spinning, zenith pointing on-orbit orientation. The spacecraft avionics architecture derives from the GLAST design, with additional heritage to the GeoEye-1 spacecraft. The EPIC subsystems, with the exception of the mission-unique structure, are nearly identical to those of GLAST, with a few minor modifications or component substitutions to better match EPIC mission requirements. Generally, the EPIC modifications reduce the complexity of the GLAST design and/or require less demanding performance.

The spacecraft bus comprises seven major subsystems: (1) Structures and Mechanisms (Structures); (2) Command and Data Handling subsystem (C&DH); (3) Electrical power subsystem (EPS); (4) Attitude determination and control subsystem (ADCS); (5) Communications subsystem (Comm); (6) Propulsion subsystem (Prop), (7) Thermal control subsystem (TCS). A brief description of each follows.

The Structures subsystem consists of two major mechanical assemblies, the main bus module (BM) and the propulsion & launch vehicle interface module (PLVM). The BM is a hexagonal aluminum frame and panel assembly. A load ring mounts to the "top" end of the frame to provide stiffness and load transition to a plate to which the instrument mounts. Bus avionics components are mounted to both external and internal surfaces of the BM panels. External placement, used on most previous spacecraft manufactured by General Dynamics, has been shown to adequately meet space environments while simplifying I&T. The “aft” end of the frame attaches to the solid aluminum PLVM that provides the transition from the hexagonal BM to the cylindrical launch vehicle interface. The prop subsystem tanks and components are attached directly to the PLVM; the use of a separate module allows the prop subsystem to be manufactured and tested in parallel with the BM and its avionics components, thereby mitigating schedule conflicts.

The C&DH controls the overall Observatory using a RAD 750 processor (CPU) operating on a cPCI backplane. Flight software images are stored on a companion Multipurpose Memory (MPM) board. The MPM also contains the 16 Gb memory for storing science and housekeeping data. The flight software memory is physically separate from and shares no inputs with the science data memory to ensure the integrity of the spacecraft software. Five, function-specific boards interface to the subsystems and instruments. The Propulsion Drive Electronics (PDE) board sends control-level signals to the thruster valves. A General Purpose Input/Output (GPIO) board issues discrete commands and receives direct discrete, digital, and analog housekeeping data for all bus and some instrument components. An Attitude Control Electronics (ACE) board receives data from ADCS sensors and transmits control signals to ADCS actuators. An Uplink/Downlink (UDL) board receives ground commands and sends telemetry via the S-band Comm subsystem transceivers. Science data at 660 kbps is received by the Payload Interface Electronics (PIE) board and stored on the 16-Gbit MPM science data memory. The UDL also transfers data from the MPM to the X-band transmitters for downlink at 8 Mbps. The C&DH is block redundant. Subsystem components are cross-strapped so that a subsystem failure does not require the C&DH to failover to the stand-by block. A single Autonomous Redundancy Management (ARM) board monitors both sides of the C&DH and initiates failover, if an anomaly is detected. The ARM also has a selectable ground control mode where failover must be commanded. The ARM contains the system watchdog timers, as well as launch vehicle interface (separation) circuits. Although part of the power system, the C&DH chassis houses Integrated Power Converter Unit (IPCU) boards that convert the unregulated primary 28V power to regulated 3V, 5V, and $\pm$ 15V levels.

The many similarities in hardware between EPIC and GLAST and in operational modes between EPIC and Coriolis, including the management of angular momentum, GLAST, enable substantial software reuse. Software development tasks for EPIC are considered minor and relate to interfacing the specific data stream from the instrument and to working the details for the safehold mode which requires the instrument boresight to remain zenith pointed (performed using earth sensors).

The EPS comprises the three solar array wings, a battery, a charge control unit (CCU), a SC Load Control Unit (LCU), and the IPCUs. It is a direct energy transfer, battery-clamped system providing main bus voltage of 28 $\pm$ 6 VDC and supporting an Observatory normal mode orbit average power of 533W, including contingency. The three solar array wings have cells mounted on both front and rear surfaces to enable most effective power generation for the spacecraft’s spinning mode. The arrays are fabricated with 28% efficient cells (BOL), with each wing having an active cell area of 2.65 m^2 per face (6 faces). The total array output power at the 2-yr mission EOL for the 900 km terminator sun synchronous orbit is 660 W, including 24% margin above contingency. The

CCU allows solar array power to be transferred directly to the bus or directed to charging the 16 A-hr, LiIon battery. The battery is required for the seasonal eclipse period which has duration of 15 minutes. The short eclipse seasons and two-year mission life pose no issue with number of cycles for the LiIon battery. The battery is sized to limit depth of discharge to 30% under normal observatory operating mode conditions. The LCU switches power to SC components and the payloads. Critical SC components, such as the communications receivers, are on an essential power bus that cannot be disconnected.

The ADCS includes four reaction/momentum wheels arranged to provide 3-axis Observatory control and momentum compensation for the spinning mode, an internally redundant 3-axis gyro, a multi-head star tracker with redundant electronics, two magnetometers, three magnetic torquers, eight coarse sun sensors, and three earth sensors. The zero momentum bias, three-axis design uses stellar reference for attitude determination with rates provided by the gyro to achieve attitude knowledge of <0.5 arcmin. The four star tracker heads are positioned azimuthally around the bus and zenith canted so that except f or a few brief periods where the moon and sun are in a specific alignment at least three heads are providing data. The tracker heads are capable of acquiring data at rates exceeding the 6^{o}/sec Observatory spin rate. The high quality gyro quality is capable of propagating attitude for long periods, if an outage occurs. Attitude control is maintained by the wheels to less than 0.25 arcmin. Wheel momentum is managed using the magnetic torquers with the local magnetic field vector determined by a magnetometer. The earth sensors provide a broad coverage to ensure the earth direction can be well defined for safehold mode. The coarse sun sensors augment the earth sensor data by indicating the sun line direction.

The communications subsystem has both S-band and X-band capabilities. Commands are received by the observatory at S-band at 2 kbps. Housekeeping telemetry is transmitted at S-band to the ground at 32 kbps. Science data is downlinked at X-band at 8 Mbps. Per NASA directives, decryption hardware is used to receive encrypted commands. S-band hardware consists of two GN/SN compatible transceivers, two filters, one splitter, one RF switch, and four broad beam antennas that provide near 4-pi steradian coverage. X-band hardware consists of two X-band transmitters, a transfer switch, and two fixed medium gain antennas.

The 283 m/s (2-yr service with 21% margin) hydrazine monopropellant propulsion system enables maneuvers for orbit insertion error, orbit altitude maintenance, and controlled de-orbit. The blow down system configuration has twelve 22N thrusters arranged in four groups of three. Three hundred twenty-four kilograms of propellant are contained in a single tank. The tank has greater than a 10% fill margin above the 21% propellant load margin. The tank is isolated from the thrusters with latch valves until orbit is achieved. Filters in the gas and propellant tank outlet lines capture any particulates to ensure no failures are caused by particulate contamination. Pressure gauges monitor pressure at component inlets and outlets.

Bus thermal control is performed passively using the lateral bus surfaces, appropriately coated or taped to adjust thermal and optical properties, as radiators. Thermostatically-controlled heaters augment the system to limit low temperatures excursions. Temperature sensors are distributed throughout the bus to monitor performance.

The bus is essentially fully redundant, except for those items where reliability is high and failure modes have graceful degradation. The components that are not implemented with full redundancy include wheels, magnetic torquers (redundant excitation windings on a common core), battery (extra cell and bypass switches), propellant tanks (high reliability), thrusters (functional redundancy using other thrusters), solar array wings (extra strings), antennas (high reliability), and RF network hardware (high reliability).

Key observatory performance parameters are presented in the responses to items 3.5 and 3.10. ITAR and proprietary considerations preclude including a detailed block diagram in this document.

3.2 Provide an overall assessment of the technical maturity of the subsystems and critical components. In particular, identify any required new technologies or developments or open implementation issues.

The spacecraft subsystems and critical components are technically mature and no new developments are required. Almost all components have already been qualifed and most have significant flight heritage. The ability to use designs/hardware employed on GLAST and similarities to GeoEye-1 and Coriois result in a low risk approach for EPIC. Since GLAST, GeoEye-1, and Coriolis also avoided new developments as much as possible, much of the EPIC design has multiple mission heritage. Other than the bus structure, which is a straightforward adaptation of the structure used on Swift, GLAST, GeoEye-1, and Coriolis, and for which a flight quality test structure will be built to verify strength and modal responses, qualification/re-qualification is limited to board modifications to accommodate EPIC-unique requirements.

3.3 What are the three greatest risks with the S/C?

Since EPIC subsystem designs have a significant heritage base, technical development risk is low. The three most significant technical design challenges are associated with thermal control and the spinning normal operations mode of the Observatory:

1. Thermal design: Provide low thermal conductivity between the bus and the instrument to minimize heat transfer and thereby maximize cryogen lifetime.
2. Attitude control: Ensure the Observatory is always oriented to point slightly away from the normal to the sun line to ensure the instrument sun shade admits no sunlight. Provide a robust attitude control subsystem to ensure safehold mode always maintains the instrument zenith pointing and that anomaly situations (e.g., changes in momentum compensation wheel speed) can be handled with no or minimal violations of nominal zenith pointing.
3. Component layout: Arrange system components and balance masses to provide the most favorable mass distribution (moments of inertia) to minimize perturbations to the spin mode that might degrade pointing control or accuracy.

Optional detail (provide if you have selected a specific S/C implementation):

3.4 If you have required new S/C technologies, developments or open issues and you have identified plans to address them, please describe (to answer you may provide technology implementation plan reports or concept study reports).

No new S/C technologies are required for the EPIC mission. Most tasks for implementation can be categorized as "routine" tasks typical of detailed design. The items requiring particular attention relate directly to the spacecraft risks listed above in paragraph 3.3:

1. Optimal performance of the EPIC instrument with its He-II cryogenic dewar is dependent on maintaining a good thermal environment. This means good thermal isolation of the instrument from the spacecraft and good attitude control by the spacecraft to constantly point the instrument slightly away from the sun at all points in the orbit (ensures shade performance). Thermal isolation is achieved through proper selection of interface materials and interface configuration to provide low thermal conductivity, while simultaneously offering structural integrity to support launch loads. This task will require iterative analysis of the integrated thermal/mechanical Observatory model. Maintaining the instrument zenith off-point throughout the orbit is a standard attitude control function. Orbit simulations during ADCS code development will provide confidence that the desired orientation is achieved.
2. The 1 RPM spin rate of the Observatory requires careful layout of components and balance masses to minimize moment of inertia cross products and thereby minimize demands on the attitude control subsystem. The attitude control subsystem must be designed with robust sensors, actuators, and algorithms to sense perturbations and maintain required pointing.

Solutions for both design problems are expected to use proven techniques and mature, flight qualified hardware.

3.5 Describe subsystem characteristics and requirements to the extent possible. Such characteristics include: mass, volume, and power; pointing knowledge and accuracy; data rates; and a summary of margins.

Subsystem characteristics are summarized in the following table. Because of the difficulty in assigning volumes to the subsystems, that parameter is not presented. Mass and power contingencies are calculated based on maturity of components, with values ranging from 2% of the estimated mass for the most mature components with well demonstrated properties to 30% of the estimated mass for those items that are new. Additional data are provided in 3.10.

Subsystem Parameter	Mass	Power	Requirement	Capability	Margin
Overall Observatory	2261 kg dry (21.6% Contingency) 2585 kg wet	533 W OAP (16.5% Contingency)	Mass < 6600 kg for sun sync using Atlas 401	2585 kg; 660 WOAP	184 % Mass; 24% Power
Bus	674 kg dry (12.6% Contingency)	270 WOAP (9.5% Contingency)	N/A	N/A	N/A
Structures & Mechanisms	305 kg (19.6 % Contingency)	N/A	N/A	N/A	N/A
Power	147 kg (9.8 % Contingency)	12.6 WOAP	N/A	N/A	N/A
Attitude Control	64 kg (5.0 % Contingency)	62 WOAP	N/A	N/A	N/A
Control	N/A	N/A	3 arcmin	< 1 arcmin	> 200%
Knowledge	N/A	N/A	1 arcmin	< 0.5 arcmin	> 100%
Spin Rate	N/A	N/A	1 RPM	1 RPM	N/A
C&DH	28.7 kg (7.9 % Contingency)	74.7 WOAP	N/A	N/A	N/A
Science Memory	N/A	N/A	4.1 Gbit/Contact	16 Gbit	290%
Instrument Data Rate	N/A	N/A	660 kbps	> 5 Mbps	> 650%
Communications	19.9 kg (15.6 % Contingency)	39.3 WOAP	N/A	N/A	N/A
Downlink S-band TLM 32 kbps	N/A	N/A	3 dB Margin	14.3 dB	11.3 dB
Uplink S-band CMD 2 kbps	N/A	N/A	3 dB Margin	>20.0 dB	> 17.0 dB
Downlink X-Band 8 Mbps	N/A	N/A	3 dB Margin	5.9 dB	2.9 dB
Propulsion (Note line heaters in thermal budget)	46.7 kg (9.1 % Contingency)	11.3 WOAP	N/A	N/A	N/A
Delta V	N/A	N/A	233 m/s (2 yrs + de-orbit)	283 m/s (2 yrs + de-orbit)	21.4%

Thermal Control	11.1 kg (19.4 % Contingency)	23.7 WOAP	N/A	N/A	N/A
Harness	52.0 kg (20% Contingency)	25.0 W (Loss)	N/A	N/A	N/A

3.6 Describe the flight heritage of the spacecraft and its subsystems. Indicate items that are to be developed, as well as any existing instrumentation or design/flight heritage. Discuss the steps needed for space qualification.

The spacecraft avionics architecture for EPIC is based on the Gamma-ray Large Area Telescope (GLAST) spacecraft currently in Observatory I&T leading to a 2007 launch, with additional heritage to the GeoEye-1 spacecraft scheduled to launch in 2007. EPIC subsystems are nearly identical to those of GLAST, with a few minor modifications or component substitutions to better match EPIC mission requirements. The re-use of previous subsystem designs employing flight-proven hardware, in general, eliminates the need for qualification. Modifications to electronics boards are not expected to be major, since EPIC operational parameters are in general less demanding than those of GLAST and GeoEye-1. Modifications will be assessed for impact to the heritage design. All modifications will be fully tested and, if of significant scope, those specific boards will be re-qualified using established ISO-approved procedures.

The EPIC bus structure employs the same design approach and manufacturing techniques as used on GLAST, GeoEye-1, Swift, and Coriolis. Swift and Coriolis were launched in 2004 and 2003 using Delta II and Titan-II launch vehicles, respectively. These launches provide relevant validation of the design approach. Since, however, a structure of the identical configuration as EPIC with identical loading has not flown, a flight quality development test vehicle (DTV) is used to validate bus strength and stiffness. The type of stress test (push-pull, centrifuge, etc.) to be used is TBD. Stiffness is determined by comparison of resonant frequency measurements to modal analysis models.

3.7 Address to the extent possible the accommodation of the science instruments by the spacecraft. In particular, identify any challenging or non-standard requirements (i.e. Jitter/momentum considerations, thermal environment/temperature limits etc).

The EPIC instrument requires no non-standard considerations in terms of interface or operating parameters, i.e., all of the EPIC requirements can be met using approaches and hardware that have been used on several prior spacecraft. As mentioned and explained above, the key engineering tasks relate to ensuring thermal isolation of the instrument and to careful layout and ADCS design to address the dynamics of a constantly zenith pointed spinning spacecraft that must also remain zenith pointed in safehold mode. Features of the spacecraft design that particularly fulfill EPIC instrument requirements are discussed in the following.

The 2.5 m diameter and 1590 kg mass (including 25% contingency) of the EPIC instrument are accommodated by the tailored bus structure, adaptations of which have been used for instruments with masses to 3000 kg (GLAST). The bus dimensions and elements, as well as the interface to the instrument mounts, were chosen to provide good load paths to the launch vehicle to minimize the effects of launch loads on the instrument. The structural design also offers a full 2-pi steradian unobstructed field of view on the zenith side of the observatory, which is important for easy integration of the dewar/detector unit and the large nested thermal shades. The three-wing solar array configuration maximizes power generation efficiency while spinning, maintains the open field of view for the instrument, and provides a more beneficial moment of inertia distribution for the spin axis. The bus C&DH is designed to receive data from the instrument continuously at 660 kbps and includes a 16 Gbit solid state memory to store science data between downlink events. The baseline mission operations plan calls for downlinking ~4 Git of data once an orbit to a polar ground station. The excess memory allows any missed contact to be recovered by scheduling a contact with a ground station at the opposite pole (usable ground stations include Svalbard, Poker Flats, and McMurdo). The ADCS has a reaction wheel configuration that compensates for the spacecraft spin angular momentum so that the slow slew to maintain zenith pointing throughout the orbit is easily achievable. The multi-head star tracker and gyro enable the bus to meet the EPIC knowledge and control requirements for the spin mode. The earth sensor complement enables zenith pointing safehold. The communications subsystem is designed to downlink the large science data volume by using a X-band link operating at 8 Mbps. The S-band transceiver allows real time transmission of commands to the Observatory and telemetry to the ground. The propulsion subsystem corrects orbit insertion errors to minimize eclipse times and fulfill zenith pointing budgets. The propulsion subsystem also provides end-of-life controlled de-orbt.

3.8 Define the technology readiness level of critical S/C items along with a rationale for the assigned rating.

ITAR and proprietary considerations preclude a detailed listing of spacecraft components and parts in this document. As described earlier, the spacecraft subsystems and critical components are technically mature, with substantial reuse of GLAST, GeoEye-1, Swift, and Coriolis designs. No new developments are required. EPIC will fly in nearly the identical environment as GeoEye-1 and all four spacecraft are designed for lifetimes significantly longer than the 2-year EPIC mission. Coriolis and Swift have already completed their baseline missions, with no failures to date, and both GLAST and GeoEye-1 will have over 2 years of on-orbit flight before EPIC begins Phase-B. GeoEye-1 has a slightly more severe orbital environment than EPIC. Consequently, almost all components have already been qualified and most have significant relevant flight heritage, resulting in TRLs of 8 and 9. As also described above, for the bus structure, which is based on scaling of basic core structural architecture from which GLAST, Swift, and GeoEye-1 are derived, a flight quality test structure will be built to verify strength and modal responses. The completed observatory is also tested in the system-level environmental test sequence. The structure will achieve a TRL of 7-8. The relatively few EPIC-unique modifications in electronics will be assessed to the extent of impact of the modification to the qualified design. All modifications will be retested/requalified in relevant environments to achieve TRL 8.

3.9 Provide a preliminary schedule for the spacecraft development.

3.10 Spacecraft Characteristics Table (Optional – fill out any known entries if you have selected an implementation.)

In the following table, detailed data on attitude control sensors and actuators has not been included because of ITAR and/or proprietary considerations.

Spacecraft bus	**Value/ Summary, units**
Structure	
Structures material (aluminum, exotic, composite, etc.)	Aluminum
Number of articulated structures	None
Number of deployed structures	Three solar array wings
Thermal Control	
Type of thermal control used	Cold bias passive with heaters
Propulsion	
Estimated delta-V budget, m/s	283 m/s including 21% contingency
Propulsion type(s) and associated propellant(s)/oxidizer(s)	Blow down hydrazine monopropellant
Number of thrusters and tanks	12, 5N thrusters; 1 fuel tank;
Specific impulse of each propulsion mode, seconds	220 seconds for both orbit maintenance and de-orbit
Attitude Control	
Control method (3-axis, spinner, grav-gradient, etc.).	3-axis
Control reference (solar, inertial, Earth-nadir, Earth-limb, etc.)	Zenith pointing, stellar reference
Attitude control capability, degrees	< 1 arcmin
Attitude knowledge limit, degrees	< 0.5 arcmin
Agility requirements (maneuvers, scanning, etc.)	1 RPM spin about instrument boresight
Articulation/#–axes (solar arrays, antennas, gimbals, etc.)	None
Sensor and actuator information (precision/errors, torque, momentum storage capabilities, etc.)	
Command & Data Handling	
Spacecraft housekeeping data rate, kbps	2
Data storage capacity, Mbits	16,000

Maximum storage record rate, kbps	660
Maximum storage playback rate, kbps	8,000
Power	
Type of array structure (rigid, flexible, body mounted, deployed, articulated)	Deployed wings (3), stationary
Array size, meters x meters	1.0 m x 2.65 m per wing face (6 faces)
Solar cell type (Si, GaAs, Multi-junction GaAs, concentrators)	Multi-junction GaAs
Expected power generation at Beginning of Life (BOL) and End of Life (EOL), watts	841 W BOL, 807 W EOL (2 years).
On-orbit average power consumption, watts	533 W with 16.5% Contingency
Battery type (NiCd, NiH, Li-ion)	Li-ion
Battery storage capacity, amp-hours	16 A-hr

4. Mission Operations

Provide a brief description of mission operations, aimed at communicating the overall complexity of the ground operations (frequency of contacts, reorientations, complexity of mission planning, etc). Analogies with currently operating or recent missions are helpful.

Identify any unusual constraints or special communications, tracking, or near real-time ground support requirements.

Identify any unusual or especially challenging operational constraints (i.e. viewing or pointing requirements).

Mission Operations and Ground Data Systems Table (Optional – provide only if you have selected a S/C and operations implementation)

Down link Information	**Value, units**
Number of Data Dumps per Day	
Downlink Frequency Band, GHz	X-band
Telemetry Data Rate(s), bps	8 Mbps
S/C Transmitting Antenna Type(s) and Gain(s), DBi	
Spacecraft transmitter peak power, watts.	
Downlink Receiving Antenna Gain, DBi	
Transmitting Power Amplifier Output, watts	
Uplink Information	**Value, units**
Number of Uplinks per Day	
Uplink Frequency Band, GHz	S-band
Telecommand Data Rate, bps	2 kbps
S/C Receiving Antenna Type(s) and Gain(s), DBi	

The communications subsystem has both S-band and X-band capabilities. Commands are received by the observatory at S-band at 2 kbps. Housekeeping telemetry is transmitted at S-band to the ground at 32 kbps. Science data is downlinked at X-band at 8 Mbps. Per NASA directives, decryption hardware is used to receive encrypted commands. S-band hardware consists of two GN/SN compatible transceivers, two filters, one splitter, one RF switch, and four broad beam antennas that provide near 4-pi steradian coverage. X-band hardware consists of two X-band transmitters, a transfer switch, and two fixed medium gain antennas.

TOTAL MISSION COST FUNDING PROFILE TEMPLATE

(FY costs[1] in Real Year Dollars, Totals in Real Year and 2007 Dollars.
All figures in millions of dollars.)

Item	FY 09	FY 10	FY 11	FY 12	FY 13	FY 14	FY 15	FY 16	FY 17	FY 18	Total (Real Yr.)	Total (FY 2007)
Cost												
Concept Study	1.6										1.6	1.5
Science		0.6	0.6	0.6	0.7	0.7	1.5	1.6	1.6	1.7	9.6	6.5
Instrument (EPIC)		23.2	36.5	38.3	20.1	14.1	7.4				139.5	110
Spacecraft		15	24.6	42.3	38.6	30.6	14.2	13.4			178.9	135.1
Ground Data System Dev		1.2	1.2	1.3	2.7	4.2	4.4	3.1			18.1	13
MSI&T [2]		1.2	2.4	5.1	6.7	9.9	10.3	7.8			43.3	31
Launch services								233			233	150
MO&DA[3]								9.3	19.5	20.5	49.4	30
Education/Outreach		0.4	0.7	0.9	0.7	0.6	0.4	2.7	0.2	0.2	7.0	5.0
Reserves		8.7	13.1	14.6	10.1	9.7	8.0	7.5	6.4	6.7	84.6	62.1
Other – Management, Safety, Mission Assurance		3.5	3.6	3.8	4.0	4.2	4.4	4.7	1.6	1.7	31.6	23
Total Cost	$1.7	$53.7	$82.8	$106.9	$83.6	$74.	$50.7	$283.	$29.4	$30.9	$796.3	$567.2
Contributions												
Concept Study												
Science												
Instrument A												
Spacecraft												
Ground Data System Dev												
MSI&T[2]												
Launch Services												
MO&DA[3]												
Education/Outreach												
Reserves												
Other (Specify)												
Total Contributions	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0

1 Costs should include all costs including any fee
2 MSI&T - Mission System Integration and Test <u>and</u> preparation for operations
3 MO&DA - Mission Operations and Data Analysis

EPIC instrument costs are based on a comparison with the XRS instrument on the ASTRO-E2 mission (2005 launch). The XRS included a cryostat with a planned lifetime of 2 years and ADR system, We adjusted these cryogenic system costs for inflation and then included additional costs for the microwave hardware and detector systems required for EPIC.

EPIC spacecraft bus costs were estimated by comparing the EPIC block diagram and mission requirements to those of GLAST. The GLAST costs were adjusted for differences in hardware and associated labor to implement those hardware items. The adjusted GLAST price was escalated to reflect cost increases since the award of GLAST in 2003. Inflation factors ranged between 3% and 5% per year. Additional costs for management and technical staff support were added because the EPIC implementation period is seven years as compared to five years for GLAST. Throughout the comparison process, a conservative perspective was maintained, i.e., estimates tended toward higher costs.

The cost estimate for the Mission Operations Center (MOC) is included in MSI&T. The estimate is based on recently priced MOC efforts that are patterned after the GeoEYE-1 MOC, which is currently in test in preparation for Observatory launch later this year. The GeoEye-1 MOC capabilities are beyond what is required for the relatively simple operations concept for EPIC. Consequently, the EPIC MOC costs are also considered to be conservative.