Response to the Beyond Einstein Program Assessment Committee (BEPAC) Request for Information

Einstein Inflation Probe

Experimental Probe of Inflationary Cosmology (EPIC) Mission Study

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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.

Science and Instrumentation

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

The scientific objectives for the Experimental Probe of Inflationary Cosmology (EPIC), and measurements required to fulfill them are given in the second and third columns of Table 1 below. The first column puts the scientific objectives in the context of NASA's objectives, and the fourth column gives the instrument criteria that follow from the necessary measurements. The table is split vertically to the primary science objectives (pink) and to secondary science themes (green), which may be achievable by EPIC but do not drive the design of the instrument. We adopt parameters for the instrument based on the NSF/NASA/DOE Weiss committee report (Task Force for Cosmic Microwave Background Research, astro-ph 0604101) where applicable. The scientific objective of detecting the CMB polarization BB power spectrum at a level of r = 0.01 *after foreground removal* are also shown in Fig. 1.

Table 1. EPIC Science Objectives and Measurements

<table>
<tr><th>NASA Objective</th><th>EPIC Objective</th><th>Measurement Criteria</th><th>Instrument Criteria</th></tr>
<tr><td rowspan="5">Discover what powered the Big Bang… search for gravitational waves from the earliest moments of the Big Bang

Discover the origin, structure, evolution, and destiny of the universe
(NASA 2006 Strategic Plan)</td><td rowspan="5">Test Inflationary paradigm at GUT energy scales by probing Inflationary Gravitational Wave B-mode polarization signal to r = 0.01.</td><td rowspan="3">Detect BB signal at r = 0.01* after foreground removal</td><td>$w_p^{-1/2} < 6$ μK-arcmin†</td></tr>
<tr><td>30 – 300 GHz†</td></tr>
<tr><td>Control systematics to negligible levels</td></tr>
<tr><td rowspan="2">Positively detect both the ℓ = 5 and ℓ = 100 BB peaks</td><td>All-sky coverage</td></tr>
<tr><td>Low angular resolution (< 1°)†</td></tr>
<tr><td>Understand how the first stars and galaxies formed</td><td rowspan="2">Distinguish models of reionization history

Extract all available EE cosmology</td><td rowspan="2">Measure EE to cosmic variance</td><td rowspan="5">Parameters above</td></tr>
<tr><td>Determine the size, shape, and matter-energy content of the Universe</td></tr>
<tr><td rowspan="2">Measure the cosmic evolution of the dark energy, which controls the destiny of the universe</td><td>Measure lensing BB to determine neutrino mass and dark energy equation of state</td><td rowspan="2">Measure lensing BB to ~cosmic variance</td></tr>
<tr><td>Remove lensing BB using shear map</td></tr>
<tr><td>…Trace the flows of energy and magnetic fields… between stars, dust, and gas</td><td>Map Galactic magnetic fields</td><td>Measure synchrotron and dust polarization</td></tr>
</table>

Primary Objective (red)

Secondary Objective (green)

†Parameters recommended by Weiss Committee TFCR

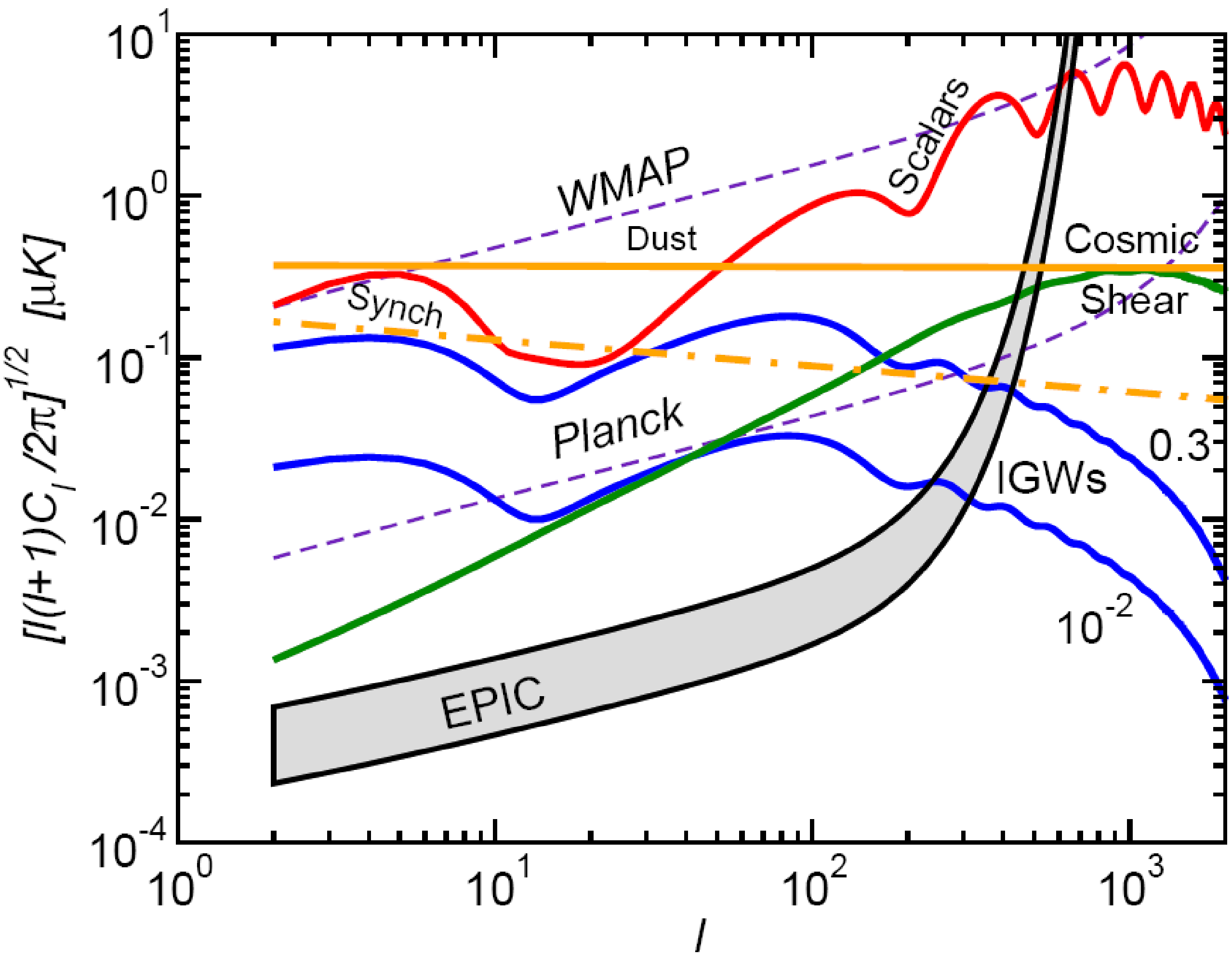

Fig. 1. The sensitivity of EPIC, WMAP and Planck to CMB polarization anisotropies. E-mode polarization anisotropies from scalar perturbations are shown in red, B-mode from tensor perturbations are shown in blue for r = 0.3 and r = 0.01, and B-mode polarization produced by lensing of the E-mode polarization is shown in green. The science goal of EPIC is to reach the level of r = 0.01 for the multipole range ℓ < 100 after foreground subtraction. Expected B-mode foreground power spectra for polarized dust (orange solid) and synchrotron (orange dashed) at 100 GHz are determined by power-law models fits to the foreground power in a combination of WMAP 23 GHz polarization maps (Page et al. 2006), Haslam et al. 1981 low frequency radio maps, and Finkbeiner, Davis, and Schlegel (1999) 100 micron dust map for |b| > 20˚. The sensitivity of EPIC is given over a range from the required baseline sensitivity (top of the gray band) and a 1-year mission to the design TES-option sensitivity and a 2-year mission (bottom of the gray band). Note these curves show raw band-combined sensitivities and do not show sensitivity including foreground removal.

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

EPIC is designed based on the instrument criteria in Table 1. The architecture for the instrument is shown in Figure 2. We have chosen a technical implementation based on high technology readiness level (TRL). The EPIC instrument consists of 6 imaging polarimeters operating at frequencies between 30 and 300 GHz. Each polarimeter consists of a refracting 30-cm telescope assembly with two lenses made from high-density polyethylene, a stepped half wave plate made from sapphire, a focal plane array, and thermal blocking filters. The waveplate is placed in front of the telescope optics. The telescopes and waveplates are cooled to 2 K inside a 450-liter liquid helium cryostat.

The six focal plane arrays are cooled to 100 mK by a single-shot adiabatic demagnetization refrigerator (ADR). The focal planes consist of polarization sensitive antenna-coupled bolometers read out with neutron-transmutation-doped (NTD) Ge thermistors with cooled JFET read outs mount to the 40 K passively-cooled stage. The thermistors and read out electronics are identical to the technologies developed for the ESA/NASA Planck and Herschel satellites. The cryostat is passively cooled by a 3-stage V-groove radiator such that the shell of the cryostat cools to 40 K. The cryostat, radiator, and sunshield are mounted to a commercial 3-axis zero-momentum spacecraft bus.

The radiator consists of 3 rigid sections which provide staged cooling of the bipod supports and wiring. A 3-stage deployed sunshield extends the rigid sections of the radiator to protect the optics and cryostat shell from sunlight and thermal re-radiation. The deployed sunshields are assumed to have zero thermal conductivity and thus not cool the cryostat supports and wiring. A low-gain toroidal-beam antenna is mounted on the back of the spacecraft for downlink.

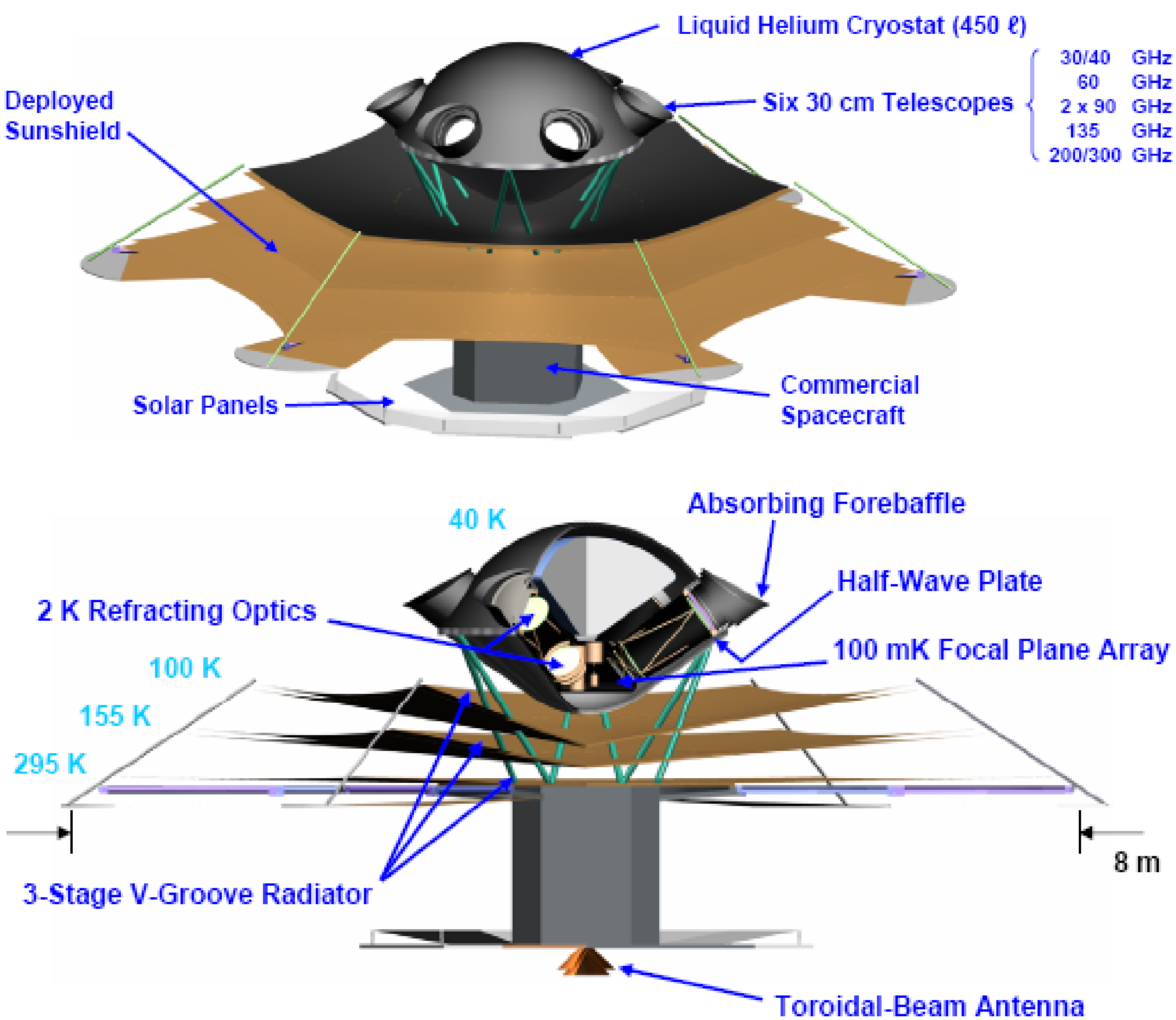

Fig. 2. The EPIC instrument consists of 6 imaging polarimeters. The detailed design for one of the polarimeters is shown in Fig. 5. The telescopes are cooled to 2 K inside a liquid helium cryostat. Bolometric detectors at the focal plane are maintained at a temperature of 100 mK. The cryostat and radiators are mounted to a commercial spacecraft bus through bipods.

The instrument performs the measurements with a single spinning and precessing scan strategy throughout the entire mission life. We optimized the scan strategy for discrimination against polarimetric systematic errors by ensuring that the instrument viewing angle completely rotates relative to each patch of the sky; see Figure 4. The scan strategy also produces redundant daily maps covering more than 50 % of the sky for systematic error mitigation. Finally the same pattern makes maximum use of passive cooling, so that the cryostat shell operates at ~40 K, without ever changing the solar power input to the back of the spacecraft, for maximum thermal stability.

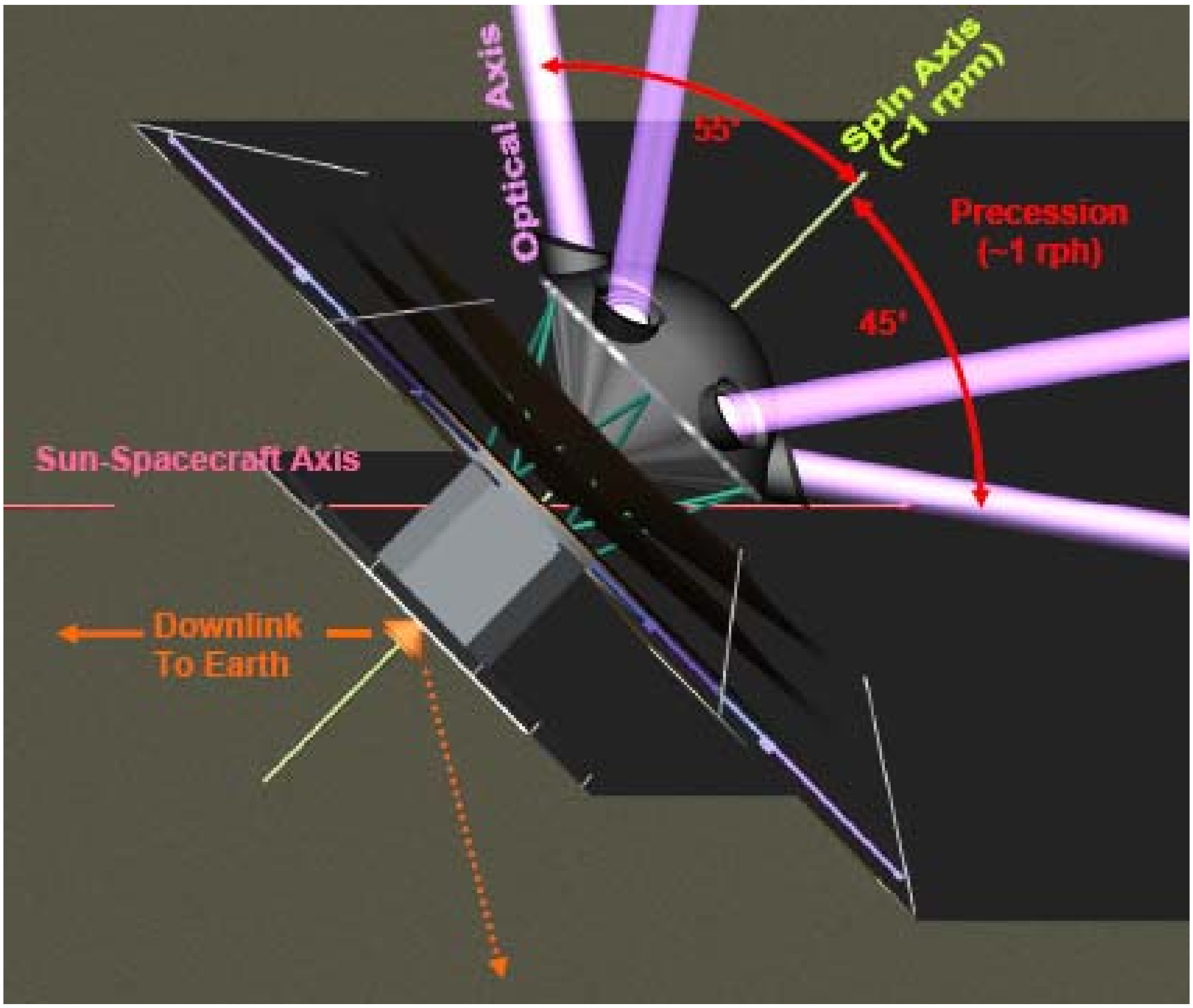

Fig. 3. Schematic of the observing strategy at L2. The instrument rotates about the spin axis at 1 rpm to scan each of the 6 telescope beams on circles on the sky. The optical axis of each telescope is offset from the spin axis by 55˚. The spin axis is set at 45˚ from the sun-spacecraft axis and precesses about the sun-spacecraft axis at 1 rph. This strategy keeps fixed the thermal input power from the sun onto the back of the spacecraft, to maintain high thermal stability. The observation strategy produces a complete map of half the sky in several precession cycles, depending on the exact choice of angles and rates chosen. Over the course of 6 months, as the spacecraft orbits the sun, a complete sky map is produced which has nearly ideal properties for polarimetry, rotating the view of each telescope through a large range of angles on each region of the sky with uniform coverage in angle and integration time. A fixed antenna with a low-gain toroidal beam pattern allows for data downlink to Earth without interrupting the scan pattern. The deployed sunshield and baffles are designed to keep radiation from the sun and moon from viewing the instrument.

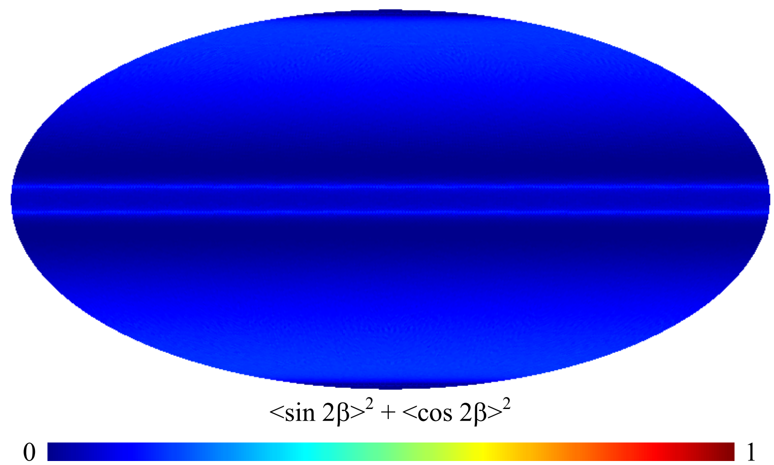

Fig. 4. EPIC 6 month sky map. The uniformity in the crossing angle on the sky, $\langle \sin 2\beta \rangle^2 + \langle \cos 2\beta \rangle^2$, where β is the crossing angle on each pixel of sky, after six months of observing. An ideal polarization experiment would obtain $\langle \sin 2\beta \rangle^2 + \langle \cos 2\beta \rangle^2 = 0$. The EPIC scan strategy provides nearly perfect angular uniformity. Further information on the scan pattern is shown in Figs. 6 and 7 below.

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

The prime goal of detecting gravitational-wave polarization shown in Table 1 is the most demanding, and sets all the instrument requirements. A space mission is essential to accomplish this objective by providing 1) all-sky coverage to access the required multipole range, 2) suppression of systematic errors, 3) frequency coverage from 30 - 300 GHz necessary to model and remove foreground emission, and 4) sufficient sensitivity. The secondary science goals describe other themes the instrument will address, but do not set requirements.

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

The performance requirements are given in Table 2 below (middle column). They are related to the instrument criteria (first column), which originate from Table 1. In the third column we give the design goals of the instrument which provide margins of safety relative to the requirements.

Table 2. EPIC Performance Requirements

Instrument Criteria	Requirements	Design Goals
High sensitivity	$w_p^{-1/2} < 6$ μK-arcmin	$w_p^{-1/2} < 2$ μK-arcmin
Subtract foreground signals to negligible levels	Remove foregrounds to below r = 0.01 science goal	Optimize bands for foreground removal based on best knowledge
Control systematic errors to negligible levels	Suppress systematic errors to < 10 % of r = 0.01 signal, after correction	Suppress raw systematic effects to less than 10 % of statistical noise level
Maintain sensitivity on large angular scales	All-sky coverage with redundant interleaved scan strategy	
Angular resolution	< 1° at 100 GHz	

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

EPIC is based on a drift-scanned wide-field imaging refracting telescope, from a design that has been fielded and tested by the BICEP CMB polarization experiment. There are 6 such telescopes on the spacecraft. One EPIC telescope is shown in Figure 5. This telescope provides a wide (~20˚) unabberated field of view with excellent polarization properties. CMB polarization measurements with large degree beams place strict requirements on the symmetry and polarization of the main beams. Measurements of the BICEP telescope indicate that main beam effects are small, but not negligible for a space mission with high sensitivity. For additional systematic error control of these effects, we therefore place a wave plate in front of the telescope optics. The wave plate is stepped once every 24 hours. Because the wave plate rotates the polarization direction without changing the illumination on the pupil, and thus without changing the beam shapes on the sky, it allows us to separate a true polarization signal from any polarization induced by the refracting optics. A half wave plate was already used successfully by the CMB balloon borne experiment MAXIPOL in a continuous rotation mode, which is more technically demanding than the stepped mode we are baselining here.

Each telescope is designed for monochromatic operation (except the two extreme bands) so that the lens anti-reflection coatings are optimized for each band. We use an absorbing stop at the primary aperture at 2 K and an absorbing baffle at 40 K to control the edge illumination from the detector antennas. Based on measurements of a similar forebaffle with BICEP, we have determined that coupling to the baffle is small (0.3 %), and that the far-sidelobe response is already controlled to a level that meets EPIC's systematic error requirements.

An array of polarization sensitive antenna-coupled bolometers is placed at the focus of the telescope and cooled to 0.1 K by an adiabatic demagnetization refrigerator. The detectors are sized with 2fλ separations. Use of 2 K optics minimizes the instrumental emission and thus maximizes sensitivity. In the primary science bands, 70 - 200 GHz, emission from the 2.75 K CMB is the dominant source of power loading on the detectors.

Parameters for the instrument are summarized in Table 3 for two options, the baseline system using developed high-TRL NTD Ge bolometers (Table 3a), and a more capable option using larger arrays of TES bolometers (Table 3b). The TES detector arrays have very similar sensitivities to the NTD Ge detectors per pixel, but provide an overall systems advantage due to larger array formats. Our sensitivity estimates are based on values (optical efficiency, bandwidth, coupling efficiency) that have all been achieved. Required sensitivities contain a factor of $\sqrt{2}$ sensitivity margin. For our scientific capabilities we assume the baseline required sensitivities. However our system requirements are specified to accommodate the more-capable TES option so that this technology can be utilized when it becomes mature. We compare the parameters of EPIC to those of Planck in Table 5.

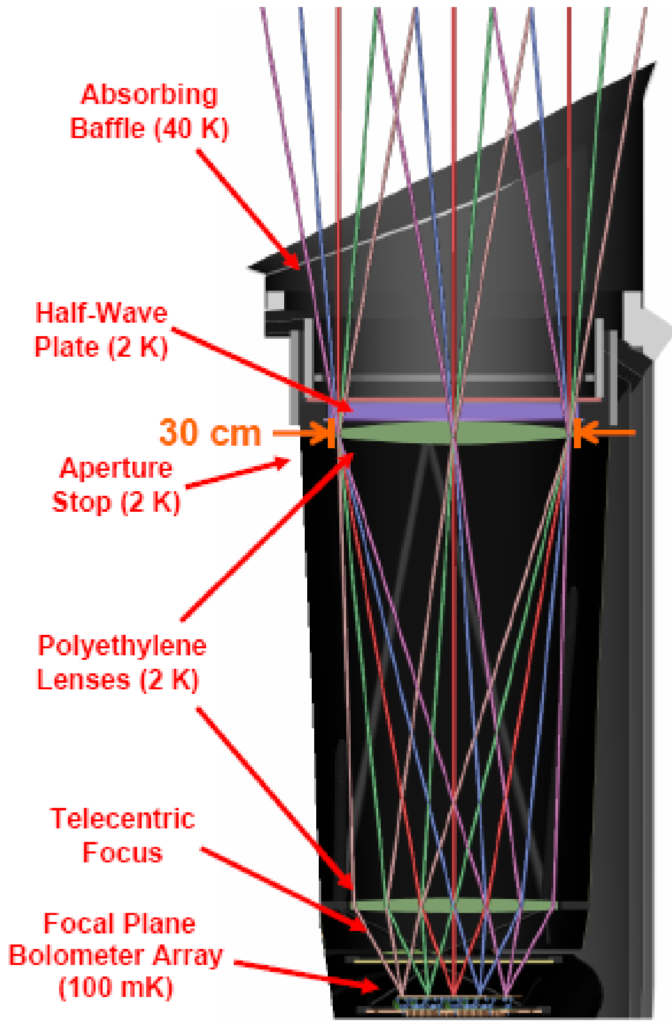

Fig. 5. Refracting telescope design (1 of 6 such telescopes) using 30 cm optics and a half wave plate cooled to 2 K. The wave plate is placed in front of the telescope, and eliminates any polarization produced by the telescope. We step the wave plate by 22.5° every 24 hours. An absorbing aperture stop at 2 K and an absorbing baffle at 40 K are used to control far-sidelobe response. Arrays of polarization-sensitive antenna-coupled bolometric detectors cooled to 100 mK are located at the telecentric focal plane of the telescope.

Table 3a. Detailed Baseline Bands and Sensitivities

Baseline: NTD Ge Bolometers										
Freq [GHz]	**θ_{FWHM} [′]**	**N_{bol}[3] [#]**	**Required Sensitivity[1]**				**Design Sensitivity[2]**			
			NET[4] [μK√s]		**$w_p^{-1/2}$ [μK-′][5]**	**δTpix[6] [nK]**	**NET[4] [μK√s]**		**$w_p^{-1/2}$ [μK-′][5]**	**δTpix[6] [nK]**
			bolo	**band**			**bolo**	**band**		
30	155	8	83	29	90	530	59	21	45	270
40	116	54	73	9.9	30	180	51	7.0	15	90
60	77	128	61	5.4	17	100	43	3.8	8.2	49
90	52	256	53	3.3	10	60	37	2.3	5.0	30
135	34	256	49	3.1	10	56	35	2.2	4.7	28
200	23	64	59	7.3	22	130	41	5.2	11	67
300	16	64	120	15	44	260	82	10	22	130
Total[7]		**830**		**1.9**	**5.9**	**35**		**1.4**	**3.0**	**18**

Table 3b. Detailed Bands and Sensitivities for TES Option

TES Bolometer Option										
Freq [GHz]	θ_{FWHM} [′]	N_{bol}[3] [#]	Required Sensitivity[1]				Design Sensitivity[2]			
			NET[4] [μK√s]		$w_p^{-1/2}$ [μK-′][5]	δTpix[6] [nK]	NET[4] [μK√s]		$w_p^{-1/2}$ [μK-′][5]	δTpix[6] [nK]
			bolo	band			bolo	band		
30	155	8	80	28	87	520	57	20	44	260
40	116	54	71	9.6	29	180	50	6.8	15	88
60	77	128	60	5.3	16	97	42	3.7	8.1	48
90	52	512	52	2.3	7.0	42	37	1.6	3.5	21
135	34	512	49	2.2	6.6	39	35	1.5	3.3	20
200	23	576	54	2.3	6.9	41	38	1.6	3.5	21
300	16	576	92	3.8	12	70	65	2.7	5.9	35
Total[7]		**2366**		**1.2**	**3.6**	**22**		**0.8**	**1.8**	**11**

Notes:

[1]Sensitivity with √2 noise margin in a 1-year mission
[2]Calculated sensitivity with 2-year mission life
[3]Two bolometers per focal plane pixel
[4]Sensitivity of one bolometer in a focal plane pixel
[5]$[8\pi\, NET_{bolo}^2/(T_{mis}\, N_{bol})]^{1/2}(10800/\pi)$
[6]Sensitivity δT in a 120′ x 120′ pixel
[7]Combining all bands together

Table 4. Sensitivity Model Input Assumptions

Optics temperature	T_{opt}	2 K	Focal plane temperature	T_0	100 mK
Optics coupling*	ε_{opt}	10 %	Optical efficiency*	η	40 %
Wave plate temperature	T_{wp}	2 K	Fractional bandwidth*	$\Delta\nu/\nu$	30 %
Wave plate coupling*	ε_{wp}	2 %	NTD Ge heat capacity*	C_0	0.25 pW/K
Baffle temperature	T_{baf}	40 K	NTD time constant†	$\tau(d\theta/dt)/\theta_F$	≤ 1/2π
Baffle coupling*	ε_{baf}	0.3 %	TES safety factor†	P_{sat}/Q	5

*Parameter based on experimental measurement
†Selectable design parameter, θ_F is FWHM

Table 5. Comparison of EPIC and Planck Sensitivity $w_p^{-1/2}$

Freq	EPIC Baseline		EPIC TES Option		Planck[1]
[GHz]	Req'd	Design	Req'd	Design	Goal
30	90	45	87	44	350
40	30	15	29	15	350
60	17	8.2	16	8.1	350
90	10	5.0	7.0	3.5	100
135	10	4.7	6.6	3.3	80
200	22	11	6.9	3.5	130
300	44	22	12	5.9	400
Total[2]	**5.9**	**3.0**	**3.6**	**1.8**	**54**

[1]Planck combined sensitivities in polarization for 1.2 year mission lifetime. Planck bands are shifted slightly to match the closest EPIC band.
[2]Total $w_p^{-1/2}$ is combined $w_p^{-1/2}$ from all bands in μK-arcmin

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?

Below in Table 6a we describe the risks to the scientific requirements and the approaches we have taken to mitigate risks to the principal instrument criteria, derived from science requirements in Table 1 above. More detailed mitigations that are associated with the fundamental architecture of the instrument are compiled in Table 6b.

Table 6a. Scientific Risk Assessment

Instrument Criteria	Requirement	Impact of Not Meeting Requirement	Mitigations
Sensitivity	$w_p^{-1/2} < 6$ μK-arcmin	Sensitivity to r decreases	- NET has 1.4x margin - Lifetime has 2x margin
Foreground subtraction	Remove foregrounds to below r = 0.01 science goal		- Limited subtraction needed in clean regions - Wide band coverage, flexible band weighting
Systematic error control	Suppress systematic errors to < 10 % of r = 0.01 signal, after correction		- Multiple levels of polarization signal modulation - Wave plate in front of telescope - Temperature control - High mapping redundancy to assess systematic error contributions
Mapping large angular scales	All-sky coverage with redundant interleaved scan strategy	Sensitivity at low ℓ reduced	- Similar scanning technique already demonstrated for WMAP
Angular resolution	< 1° at 100 GHz	Sensitivity at high ℓ reduced	- Chosen by design

Table 6b. Detailed Risk Reduction Strategy

Instrument Requirement Risk	Approach	Risk Mitigations
Sensitivity	NTD Ge detectors	Heritage from Planck & Herschel Requirement includes √2 noise margin Up scope to TES bolometers when mature
Subtract foreground signals below r = 0.01	Antenna-coupled bolometers	Single technology covers 30 – 300 GHz
Suppress systematic errors to < 10 % of r = 0.01 signal, after correction	Spinning/precessing scans	Uniform angular coverage on the entire sky
	Highly redundant scans	Redundant daily maps cover > 50 % of sky to allow comprehensive jackknife tests. Immunity to data interruptions, bad pixels, bad arrays Two full maps in 1-year for systematic error testing
	Dual-polarization detector	Suppresses common-mode temperature signals, thermal drifts

	Wave plate modulator in front of telescope	Suppresses main beam systematics by modulating polarization without altering beam shapes Suppresses 1/f noise, gain and temperature drifts by signal modulation if continuous
	Monochromatic refracting telescope	Low instrument- and cross- polarization Low main beam asymmetries Optimized low-reflection coatings Low far-sidelobe response
All-sky coverage	1-year required lifetime	Cryostat lifetime at L2 has > 100 % margin
Technical simplicity and cost	30 cm refracting telescope	Polyethylene lenses, simple AR coatings Demonstrated technology in BICEP
	LHe cryostat	Low technology risk Low integration risk: no microphonics, EMI or B-field disturbances Readily allows systems-level testing
	Commercial spacecraft	Modest requirements on spacecraft
	Fixed downlink antenna	Eliminates risk of counter-rotating antenna

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).

Table 7 gives the technology readiness levels (TRL) of a selected, critical set of components in the baseline option of the instrument. In the baseline option the focal plane arrays consist of NTD Ge bolometers that are coupled to radiation with antennas. NTD Ge bolometers and read out electronics are identical to the flight detector systems developed at JPL for Planck and Herschel. Antenna-coupled bolometers have been measured to meet EPIC's optical specifications on beam symmetry, efficiency, bandwidth, and polarization leakage in the laboratory at 100 and 150 GHz. An identical refracting telescope has been tested and fielded by the BICEP experiment at the South Pole.

Half wave plates have been fielded on several ground-based experiments. The wave plate is stepped every 24 hours using a cryogenic stepper motor that has been flight tested on Spitzer. The long-duration LHe cryostat is based on the flight-proven Spitzer cryostat design. The 100 mK ADR cooler for the focal plane arrays has been demonstrated on Astro-E2. The sunshield and downlink antenna are based on flight-proven components and designs. We plan to develop a qualification model of each of these units in our program.

Table 7. EPIC Technology Readiness

Technology	TRL	Heritage
Focal Plane Arrays (NTD Ge bolometers)		
NTD thermistors and JFET read outs	8	Planck & Herschel
Antennas	4	Demonstrated at 100/150 GHz
Wide-Field Refractor	6	BICEP
Wave plate (stepped every 24 hours)		
Wave plate optics	6	SCUBA, HERTZ, MAXIPOL, etc.
Cryogenic stepper drive	9	Spitzer
LHe Cryostat	9	Spitzer, ISO, Herschel
Sub-K Cooler: Single-shot ADR	9	ASTRO-E2
Deployable Sunshield	4-5	All components TRL = 9
Toroidal-Beam Downlink Antenna	4-5	All components TRL = 9

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

Scientific operations consist of a single observing mode, with a continuous spinning and precessing scan strategy. For the baseline, the spin rate is 1 rpm and the precession rate is 1 rph. The data are downlinked once per day without interrupting observations. The waveplate is stepped every 24 hours to allow cross-comparison of adjacent maps. The single-shot ADR is cycled every 48 hours. A summary of these parameters is given In Table 8. Table 9 gives design parameters for the telemetry and down link. The torroidal-beam antenna and 100 W transmitter are designed with sufficient margin to accommodate the requirements of the more demanding options of using TES arrays with either a continuously rotating wave plate (middle row), or with a stepped wave plate but with a faster spin rate of the spacecraft (last row).

Table 8. Science Observations Operations

Mission Operation	Rate
Spin Spacecraft	Continuous, 0.1 - 3 rpm
Precess Spin Axis	Continuous, 1 rph
Step Wave plate	Once every 24 hours
Cycle ADR	Once every 48 hours
Downlink	Once every 24 hours
Maintain Orbit	Small maneuvers ~4 times per year

Table 9. Telemetry and Downlink Requirements

Option	Spin rate [rpm]	Wave plate spin rate	Input rate[1] [kbps]	Downlink time per day [hrs]	
				12-m DSN	34-m DSN
Baseline Scan-modulated NTD bolos[2]	1.0	step 22.5° per day	87	4.2	0.5
Option Wave plate-modulated TES bolos[3]	0.1	40 – 300 rpm	480	-	2.8
Option Scan-modulated TES bolos[4]	3.0	step 22.5° per day	1260	-	7.4

Notes:
[1]Assumes 4 bits per sample per detector (Planck compression ratio) with Nyquist sampling, plus 100 % contingency.
[2]Requires a 1/f knee < 16 mHz (already demonstrated for NTD bolometers).
[3]Assumes 10 polarization cycles per beam crossing for each band. Requires 1/f knee < 2.5 Hz.
[4]Requires a 1/f knee < 50 mHz (near state-of-the-art for TES bolometers).

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.

The mission design contains resource margin in order to accommodate options as follows: 1) the downlink antenna and X-band transmitter are sized to the maximum data rate with TES bolometers; 2) the propulsion capacity is sized for 4-years of observations at L2, and assumes a conservative trajectory correction scenario; 3) we allocate mass for continuous wave plate drives; 4) we assume an Atlas V 401 launch vehicle based on the expected lack of future availability of Delta-II launches. Descoping these resources would result in some cost savings.

The instrument could be descoped by reducing the number of telescopes and/or decreasing the aperture size. A detailed tradeoff on the number and size of the telescopes was beyond the scope of our mission concept study. Such a study may flag options for cost savings, but we feel they are unlikely to be significant since the current instrument satisfies the requirements of the Weiss committee report without large factors of margin in sensitivity, band coverage, or angular resolution.

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

We give the three primary technical risks, their impact, probability, and mitigations we are taking to reduce the probability in Table 10.

Table 10. Summary of Primary Technical Risks

Risk	Impact	Probability	Mitigations
Single-point failure in cryogenic chain	Mission fails	Low	Design heritage
Detector array fails	Loss of 25 % of one band	Moderate	Redundant wiring and read out
Wave plate mechanism fails	Main beam systematic errors increase in one band	Moderate	Errors are partially correctable with scan strategy

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).

Table 11. Baseline Instrument Parameters Summary Table

Instruments	Six telescopes (30 cm diameter x 95 cm long)
Bands	30, 40, 60, 90, 135, 200 & 300 GHz
Detectors	830 (baseline NTD)
Sensitivity	$w_p^{-1/2}$ = 5.9 μK-arcmin (required), 3.0 μK-arcmin (design)
Resolution	16 – 155 arcmin (FWHM)
FOV	20 deg
Pointing Knowledge	30"
Focal Plane	Antenna-coupled NTD bolometers (baseline)
Read Out	Si JFETs mounted at 40 K with warm AC bias and demodulation
Pol. Modulation	Half-wave plate before telescope
Optics	Six 30-cm wide-field refractors
Cryogenics	Passive to 40 K / LHe cryostat to 2 K / ADR to 0.1 K
Payload Mass	898 kg including 43 % contingency (see Table 12)
Payload Power	272 W including 43 % contingency (see Table 13)
Average Data Rate	88 kbps including 100 % contingency (see Table 9)

Table 12. Detailed Mass Summary

Sub-Assembly		**Mass (CBE) [kg]**	**Contingency [%]**	**Allocated Mass [kg]**
Focal Planes	Mass at 0.1 K per unit	0.9	43	1.3
	Mass at 0.4 K per unit	1.0	43	1.4
	Mass at 2 K per unit	0.5	43	0.7
	Total Focal Plane Assemblies (6)	**14.2**	**43**	**20.3**
Tele-scopes	Lenses at 2 K per unit	2.1	43	3.0
	Supports per unit	1.6	43	2.3
	Shields per unit	0.9	43	1.3
	Total Telescope Assemblies (6)	**27.8**	**43**	**39.8**
Wave Plates	Wave plate 3-stack ave per unit	3.0	43	4.3
	Suspended bearing/motor per unit	1.5	43	2.1
	Non-suspended mass	2.5	43	3.6
	Total Wave plates (6)	**41.7**	**43**	**59.6**
Adiabatic Demagnetization Refrigerator		**5.7**	**43**	**8.2**
Ejectable Telescope Covers (6)		**6.0**	**43**	**8.6**
Cryostat and Shell	Liquid Helium	62.9	0	62.9
	Helium Tank	29.5	43	42.2
	Vapor-Cooled Shields	57.5	43	82.2
	Vacuum shell	185.0	43	264.6
	MLI	12.7	43	18.2
	Fill/vent lines, valves, ports	16.0	43	22.9
	Total Cryostat and Shell	**363.6**		**493.0**
Cabling		7.0	43	10.0
Warm Electronics		40.0	43	57.2
V-groove Radiators		51.3	43	73.4
Deployed Sunshield		74.1	43	106.0
Struts from S/C to Instrument		15.5	43	22.2

Subtotal for Wet Payload	**646.9**		**898.3**
Attitude Control System	81.9	43	117.1
C&DH	24.1	43	34.5
Power	52.6	43	75.2
Propulsion (dry)	22.1	43	31.6
Structures and mechanisms	212.9	43	304.4
Launch adapter	14.3	43	20.4
Cabling	46.4	43	66.4
Telecom + X-band Antenna	18.7	43	26.7
Thermal	25.5	43	36.5
Propellant [ΔV = 215 m/s]	172.0	0	172.0
Subtotal for Wet Spacecraft	**670.5**		**884.8**
Total Launch Mass	**1318**		**1783**
Launch Vehicle Maximum Payload Mass to L2 (C3 = -0.6)			
Vehicle	**Pld Mass [kg]**	**Margin [%]**	**Margin [kg]**
Atlas V 401	**3485**	**95**	**1702**
Delta IV 4040	**2773**	**56**	**990**

Table 13. Power Summary

Item	Power (CBE) [W]	Contingency [%]	Allocated [W]
Bolometer Electronics	150	43	215
ADR Electronics	40	43	57
Subtotal Payload	**190**	**43**	**272**
Attitude Control	264	43	378
C&DH	69	43	99
Power	106	43	152
Propulsion	25	43	36
Telecom (transmit mode)	191	43	273
Thermal	31	43	44
Subtotal Spacecraft	**686**	**43**	**981**
Total Power	**876**	**43**	**1253**
GaAs Triple Junction Solar Panels			
Panel Area	**Power [W]**	**Margin [%]**	**Margin [W]**
4.0 m^2 Fixed at 45° Incidence	710		
3.8 m^2 Deployed at 45° Incidence	670		
Total	**1380**	**10**	**127**

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).

Task Force for Cosmic Microwave Background Research (Weiss committee) defined the parameters for a space-borne CMB polarization mission. This report is available online, astro-ph 0604101. Engineering reports on the design of the sunshield and the study of the L2 orbit are available upon request. We are in the process of preparing a final report summarizing the results of our mission study of the Einstein Inflation Probe to NASA, which will also be made available upon request.

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

A functional description of the single science mode, the scanning/precessing scan strategy, is described in Table 8 above. On-orbit the instrument will be absolutely calibrated to high accuracy from the annual modulation by the CMB dipole by the earth's velocity around the sun. The daily CMB dipole serves as a transfer standard, and also allows an accurate instantaneous measurement of the relative gain between polarized channel pairs. Main beam parameters will be measured on bright astrophysical point sources.

Because the instrument is contained in a cryostat, we are planning to carry out a system-level calibration prior to integration with the spacecraft. Efficiency of polarization modulation will be measured on the ground. Cross-polarization and instrumental polarization will be calibrated using flight data and will be verified against measurements on the ground.

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

Analysis of the EPIC data requires the statistical detection of CMB polarization anisotropies and their separation from foreground components. Both of these functions will be carried out by Planck, with higher angular resolution but lower sensitivity. Thus the complexity of the analysis is best assessed by comparison with Planck.

Factors that increase complexity:
-- EPIC's noise level is an order of magnitude lower than Planck's, which requires control of systematic errors to an order of magnitude lower as well.
-- EPIC has an order of magnitude more detectors, each of which must be treated separately.

Factors that decrease complexity:
-- EPIC beam sizes are an order of magnitude greater. The data rate per detector is ten times lower, leading to an overall data rate comparable to Planck, but with 100 times fewer pixels in the maps. Given the very steep scaling of computing time with number of pixels and pixel size, this is a large simplification.
-- EPIC has only one type of detector, and covers a smaller frequency range.
-- Systematic polarization errors are removed to negligible levels in hardware in EPIC, using a scan strategy that gives much greater uniformity of effective beam sizes and shapes on the sky, and with much greater uniformity of polarization angle coverage. These place less stringent demands on the assessment and removal of these errors in software. Furthermore, systematic errors are more easily assessed than in Planck due to the highly redundant daily maps.

The factors decreasing complexity outweigh those increasing complexity. On balance, Planck data analysis provides an upper bound to EPIC analysis. Especially given that in addition to Planck, several suborbital experiments with great sensitivity over smaller parts of the sky will provide a rigorous test of polarization analysis methods at noise levels approaching EPIC, we expect EPIC data analysis to be a straightforward extension of that for prior experiments.

Provide an instrument development schedule if available.

Our development schedule for the instrument is 18 months for phase A, 12 months for phase B, and 48 months for phase C/D. The phase C/D duration may seem longer than typical, but we feel 48 months is appropriate due to the cryogenic nature of the instrumentation. Note the spacecraft phase C/D is assumed to be 37 months, and decoupled from the instrument phase C/D.

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

The technology developments required for the baseline mission are modest. Specific items for development are antenna-coupled bolometers, the deployed sunshield, and the toroidal-beam antenna.

Antenna-coupled bolometers have been demonstrated at 100 and 150 GHz in laboratory testing. In particular, the optical properties of the antennas have been measured to the specifications of EPIC, including polarized beam patterns, spectral passbands, and optical efficiency. The antenna designs need to be scaled in frequency to the other EPIC spectral bands. In terms of risk mitigation, we note that antennas are only necessary for the 30 and 40 GHz bands in the baseline. The bands above 90 GHz can use the feed-coupled PSBs developed for Planck. The Planck PSBs are suitable for 75 GHz, so some modest development would be needed to operate feed-coupled PSBs at 60 GHz.

The deployed sunshield is a high-TRL hinged design. Our mission planning assumes the sunshield is fabricated by an industrial partner who provides a qualification model that is tested at JPL prior to the delivery of the flight unit. Likewise, the toroidal-beam antenna will be developed as qualification model for testing and characterization at JPL. As a fallback, the antenna can be replaced by a gimbaled, continuously rotating conventional antenna. We believe that both of these developments are modest in scope as the sunshield and antenna are well within state-of-the-art for similar flight-proven systems.

The TES option is based on new detectors and read outs, and would only be considered if these technologies were mature at the time of the AO for a mission opportunity. TES detectors and read outs are currently being developed under R&A funding from NASA, and are being fielded in a variety of sub-orbital instruments (EBEX, SPIDER, South Pole Telescope, Atacama Cosmology Telescope, SCUBA 2) funded by NASA and NSF. TES bolometer arrays are emerging rapidly, with first-light planned in 2007 for SCUBA 2, SPT, and ACT. Successful demonstration in a balloon environment by EBEX and SPIDER will bring these technologies to TRL 6.

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

The flight software complexity for this mission is low. Flight software supports a single continuous science mode: EPIC has one instrument, one observing mode used for the whole science mission, one moving part (the rotating half-wave plate), one scan strategy, modest requirements on pointing accuracy and knowledge, routine station keeping at L2, and modest downlink data rates. By comparison to observatory-class missions, these demands on flight software are simple.

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

EPIC provides approximately 10 times higher sensitivity than Planck, as shown in Table 5, and 300 times higher than WMAP, as shown in Fig. 1. The EPIC scan strategy is ideal for polarimetry, and a significant improvement over that of WMAP and Planck as shown in Fig. 7. Finally, unlike WMAP and Planck which were originally conceived to measure temperature anisotropies, EPIC is designed specifically to suppress systematic errors in polarization, and includes low-polarization optics and a polarization modulator placed in front of the telescope as shown in Fig. 5.

Mission Design

Please answer the following as completely as possible:

- 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?).

EPIC carries out scientific observations from an L2 halo orbit. We reach L2 approximately 170 days after launch by means of a transfer orbit using lunar assist. The delta-V budget of 215 km/s includes 72 +/- 45 km/s for injection errors, a conservative trajectory correction strategy, and 4 years of orbit correction at L2. We take 95 % probability on all maneuver errors add then include an additional 10 % overall margin. The sunshield is deployed and the aperture lids are ejected early in the mission in order to reduce the heat load on the cryostat en route to L2.

Once at L2, the instrument executes a single observing mode which consists of a spinning/precessing scan strategy. This strategy provides uniform and redundant coverage of the sky and efficiently rotates the telescope direction on all regions of the sky. Data are transmitted to earth once per day via a toroidal-beam antenna, which enables downlink during observations without the use of a counter-rotating antenna. The single-shot adiabatic demagnetization refrigerator is cycled at regular intervals of 48 hours. The half wave plates in front of each telescope are stepped every 24 hours to remove the systematic effects of main beam asymmetries.

Table 14. Summary of EPIC Delta-V Budget

Event / Function	Very Conservative	
	Mean	Sigma
Injection Cleanup	64	45
Post-Injection up to Lissajous Insertion (L + 200 days)	7	3
Sub Total	72	45
Lissajous per Rev	4	1
4-Years Sub Total	31	10
Grand Total	103	46
Total 95% Probability	195	
Margin	10	
Total Budget	215	

Note: Units are m/s. Less conservative correction strategies, such as used on Genesis, would reduce the total budget by 40-80 m/s. Reducing the design lifetime at L2 to 2 years would save a further 62 m/s.

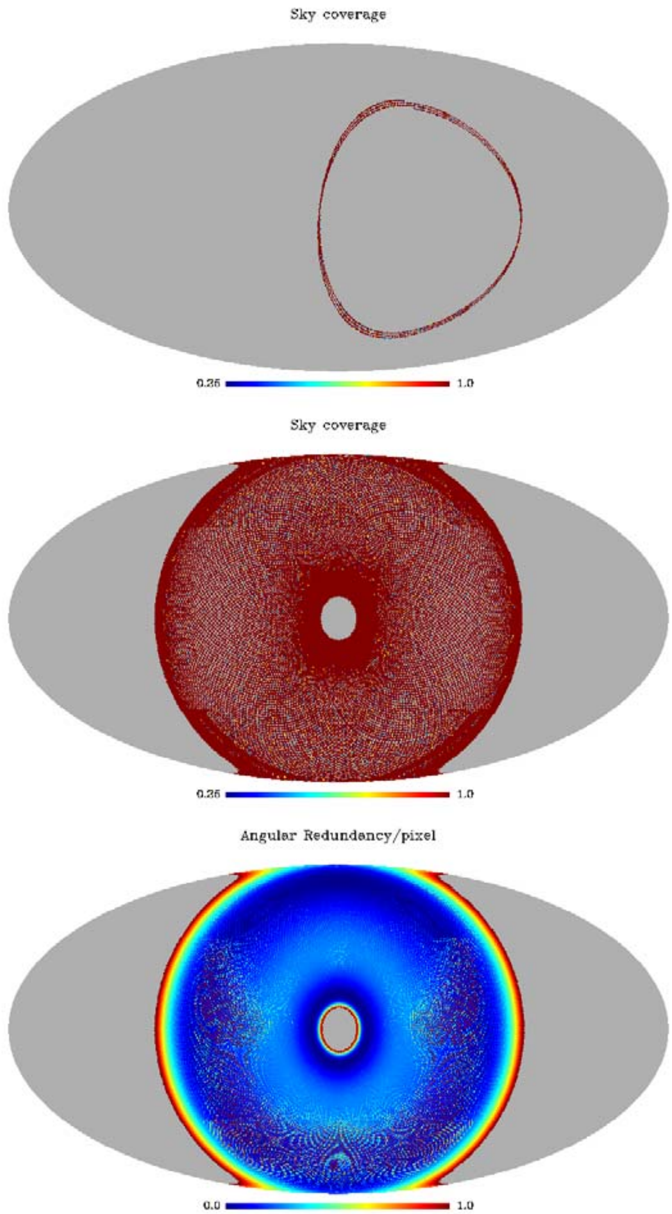

Fig. 6. Coverage of the sky for a single pixel in the focal plane for (top) three spin cycles in 3 minutes, and (middle) one precession cycle in 1 hour. Coverage in one precession cycle is a bit larger than 50 % of the sky. Note that wide range of crossing angles in the middle figure. At bottom, we show the uniformity in the crossing angle on the sky, $\langle \sin 2\beta \rangle^2 + \langle \cos 2\beta \rangle^2$, where β is the crossing angle on each pixel of sky, after a single day of observing. An ideal polarization experiment would obtain $\langle \sin 2\beta \rangle^2 + \langle \cos 2\beta \rangle^2 = 0$, very nearly achieved over the majority of this daily map.

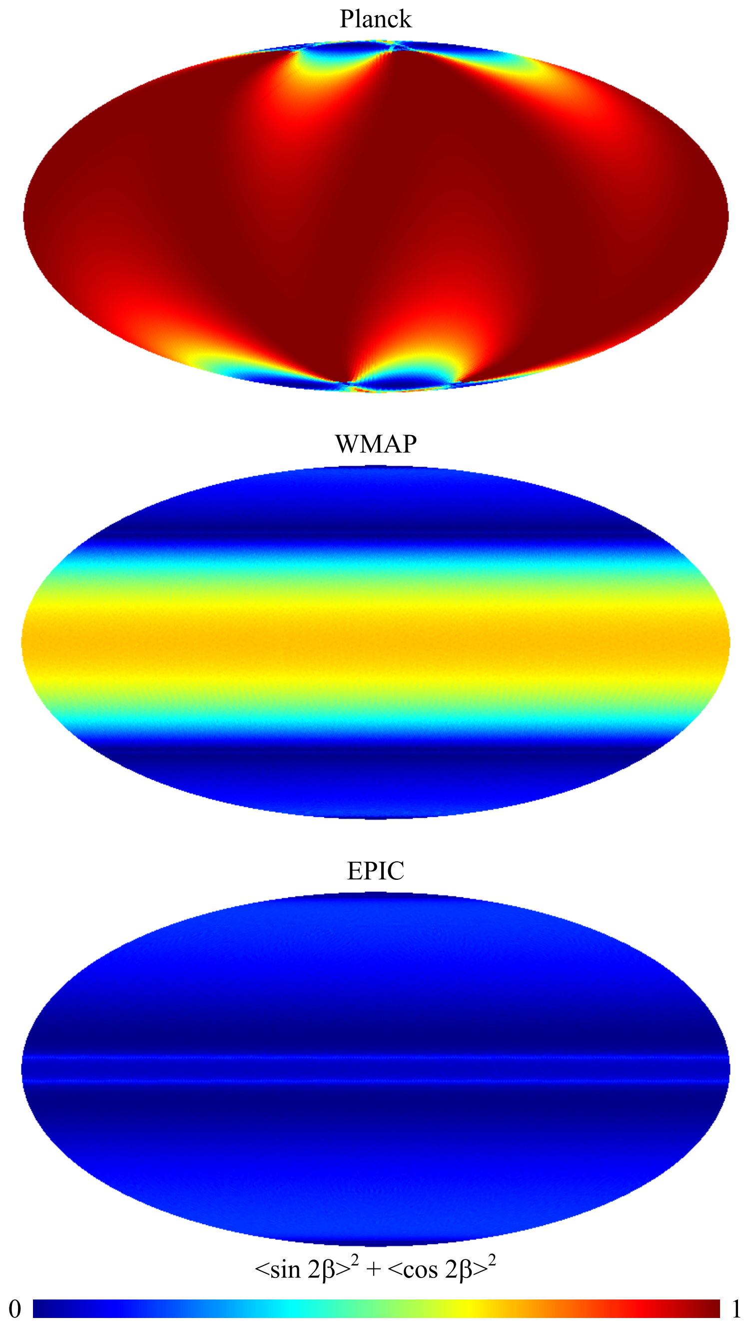

Fig. 7. The uniformity in the crossing angle on the sky, $\langle \sin 2\beta \rangle^2 + \langle \cos 2\beta \rangle^2$, where β is the crossing angle on each pixel of sky, after six months of observing for Planck, WMAP, and EPIC. An ideal polarization experiment would obtain $\langle \sin 2\beta \rangle^2 + \langle \cos 2\beta \rangle^2 = 0$. The EPIC scan strategy provides nearly perfect angular uniformity, and is significantly improved compared to Planck and WMAP.

- 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).

Table 15. Mission Design Summary

Orbit	L2 Halo
Mission Life	1 year at L2 (required), 2 years at L2 (design)
Maximum Eclipse Period	0
Spacecraft dry bus mass and contingency	713 kg, includes 43 % contingency
Spacecraft propellant mass and contingency	172 kg (ΔV budget, contingency, and margin shown in Table 14)
Launch vehicle	Atlas V 401, Delta IV 4040, option for Delta 2925H-9.5 Star 48
Launch vehicle mass margin	1702 kg (95 %), 990 kg (56 %)
Spacecraft bus power and contingency by subsystem	See Table 18
Mass weighted reuse percentage of payload and spacecraft subsystem components	We define reuse as commercial hardware at TRL = 9. Spacecraft components have 90 % reuse by mass, calculated excluding structure and cable mass. The payload has 5 % reuse by mass.
Mass weighted redundancy of payload and spacecraft subsystem components	Spacecraft components have 20 % redundancy by mass, calculated excluding structure and cable mass. The payload has 0 % redundancy by mass.

- 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.

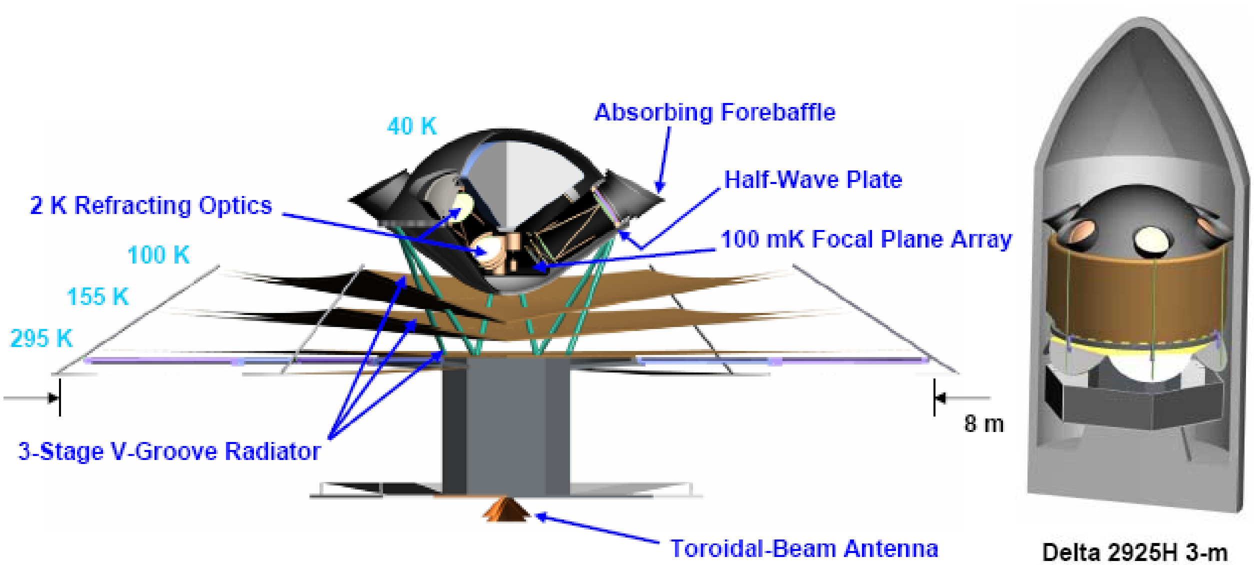

Fig. 8. Overview of the EPIC payload in deployed and stowed configurations. The instrument consists of a 450 liter liquid helium cryostat enclosing six 30-cm telescopes, each with an array of 100 mK bolometers. The cryostat is mounted on bipod supports with a 3-stage V-groove radiator to the spacecraft. Power is provided by body mounted and hinged solar panels at the bottom of the spacecraft. A deployed 3-stage sunshield keeps solar and re-radiated thermal power from reaching the cryostat vacuum shell. The sunshield stows to fit inside a 3-m launch fairing. Each telescope is sealed with a fly-away lid that deploys prior to observations. While we have sized the experiment to fit within the parameters of a Delta-II 2925H, we have baselined an Atlas V 401 launch based on best current information on future Delta-II availability and cost.

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

We give the three primary overall risks, their impact, probability, and mitigations we are taking to reduce the probability in Table 16.

Table 16. Three Primary Mission Risks

Risk	Impact	Probability	Mitigations
Single-point failure in cryogenic chain	Mission fails	Low	Design heritage
Single-point failure in deployed sunshield	Mission fails	Low	Design heritage, ground testing
Detector array fails	Loss of 25 % of one band	Moderate	Redundant wiring and read out

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.

EPIC is sized for a Delta-II 2925-H-9.5 launch vehicle with a 3-m shroud, as shown in Fig. 8. It now appears unlikely that this vehicle will still be available at the time of a launch opportunity, and even if it is available the future cost of a Delta-II appears to be comparable to an Atlas V 401 or Delta-IV 4040. Therefore we have based our masses, contingencies, and costs assuming an Atlas V 401 launch. We are equally compatible with a Delta-IV 4040. If a Delta-II 2925-H-9.5 is indeed a viable alternative, we can study a mission implementation for this vehicle. Our mass and volume requirements allow us to consider the possibilities of co-launch options or foreign launch vehicles.

- If you have identified key mission tradeoffs and options to be investigated describe them.

The most significant mission tradeoff is the TES bolometer option. We are holding a sufficient margin in telemetry rate and spin capability to accommodate the TES option. We have allocated mass for continuous wave plate drives to allow for rapid polarization modulation. We have also studied the implementation of a mechanical cooler to 4 K to replace the liquid helium dewar, to reduce mass and extend the mission life. The solar panels can be easily resized to accommodate the power needed for the 4 K cooler option, and in fact the panels for this can be entirely body-mounted for an Atlas V 401 shroud. Finally we have sized the propellant tanks for a 4-year mission at L2 anticipating the likely possibility of a significantly longer cryogenic life.

Spacecraft Implementation

Please answer the following as completely as possible:

- 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.

Table 17. Spacecraft Requirements and Capabilities

	RSDO Summary Capability	Units	Spectrum Astro SA-200HP	EPIC Requirement
Compatibility	Payload Power (OAV) (EOL)	W	650	272 (includes 43 % contingency)
	Payload Mass Limit of Bus	kg	666	898 (includes 43 % contingency)
	Bus Dry Mass (w/o Payload)	kg	354	
	Science Data Downlink Capability	kbps	50,000 (X-band)	500 (baseline) 4,000 (TES option)
	Science Data Storage Capability	Gbit	100	16 (baseline) 215 (TES option)
	Pointing Knowledge	arcsec	0.5	30
	Pointing Control	arcsec	16	3600
	Pointing stability (jitter)	arcsec/s	0.1	20
	Slewrate	deg/min	120	360 (baseline) 1080 (TES option)
	Mission Design Life	yrs	4	2
	Compatible LVs		Taurus, Athena I, Athena II, Delta II, Titan II, Atlas	Atlas V 401, Delta IV 4040, Delta II
	Types of Orbit Available		LEO circular (nominal), many other orbits available	Earth-Sun L2
	Internal Volume Available for Payload		100 cm dia. x 75 cm tall	Sufficient for warm electronics
Description	Attitude Control System		3-axis zero momentum bias/thruster based management	3-axis momentum compensated
	Batteries	type/Ah	Two NiH_2 50 Ah each	Two at 24 Ah each
	Arrays	Type/ area	Triple junction GaInP/GaAs/Ge 10.32 m^2	Triple junction GaAs 4.0 m^2 body mounted 3.8 m^2 deployed
	Nominal Voltage	V	28	28
	C&CH Bus Architecture		VME-based 32-bit RISC	422 or 1553
	Downlink Formats		CCSDS: STDN/DSN	CCSDS
	Downlink Band		X-band and S-band	X-band
	Structure		Octagonal, Al space frame construction with honeycomb	Al or composite
	Propulsion		Blowdown hydrazine system	Hydrazine
	Propellant Capacity	kg	67	172
	Mass Delta-V	m/s	131	215
Programmatic	Heritage Missions		New Millennium Deep Space 1	
	Nominal Schedule	months	36	36
	Contract Options		Full Redundancy	Replace S/C telecom with toroidal antenna
			Deep Space Configuration	Body mounted and deployed solar panels
			Ground Segment Integration Support	Add momentum wheel in spin axis
				Modify propulsion tanks
				Modify mechanical support

The requirements on the spacecraft are described in Table 17 above. We assume EPIC will operate with a custom-built commercial spacecraft bus. However, we note that the requirements are close to the capabilities of a modified 'off-the-shelf' commercial bus. As an example, we show below the specifications of the Spectrum Astro-200HP spacecraft, the capabilities of which (from the RSDO catalog), are close to our specifications. For specificity, we compare our requirements to a modified SA-200HP, but at this stage in the project we have not selected an industrial partner and many options for a spacecraft are available.

- 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 itself requires no new technology. A custom-designed X-band antenna producing a toroidal beam is baselined. This item would be provided equipment to the spacecraft vendor. However, the downlink requirements could be satisfied by a gimbaled conventional antenna that continuously counter spins at 1 rpm. Furthermore, the toroidal antenna is over specified for the low data rate of the baseline and could be descoped to a simpler design in this scenario. EPIC requires a bus-mounted solar panel plus 4 hinged deployed panels on the sun-facing side of the bus. The deployable sunshield would be a provided payload element and is not part of the spacecraft.

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

We give the three primary risks for the spacecraft, their impact, probability, and mitigations we are taking to reduce the probability in Table 18.

Table 18. Three Primary Spacecraft Risks

Risk	Impact	Probability	Mitigations
Sun avoidance	Possible loss of mission through cryogen boil off	Low	Spitzer, WMAP sun-avoidance heritage
Navigation at L2	Eclipsing by the earth	Low	WMAP, Planck heritage
Dynamic stability with flexible sunshield	Pointing jitter	Low	Modest 30" requirement on pointing knowledge, post reconstruction

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

- 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).

The design of the toroidal-beam antenna is shown below. The antenna would be developed by JPL and provided to the spacecraft vendor. The antenna is based on space-qualified components and has low technical risk. We plan to qualify this unit at component level. A fallback is to replace this antenna with a continuously counter-rotating gimbaled antenna.

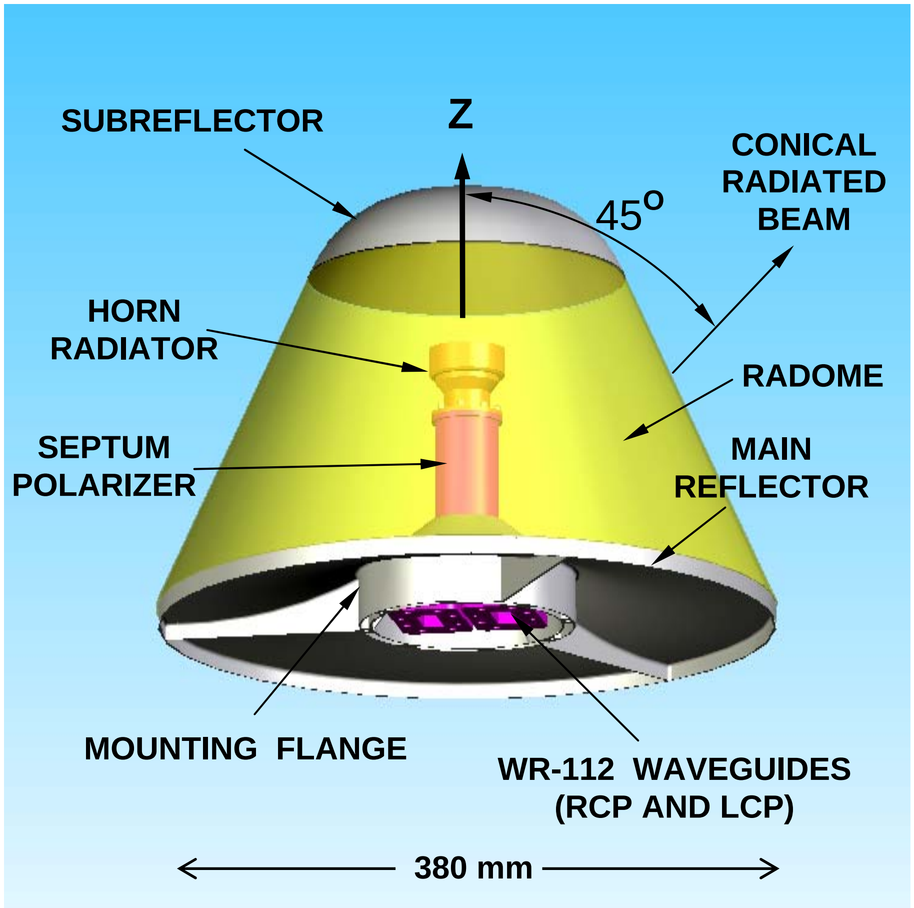

Fig. 9. Design of the toroidal-beam antenna used for data downlink. The antenna produces a low-gain toroidal beam pattern with an opening half angle of 45 degrees. The opening angle of the beam pattern is large enough to account for all variations to the sun-spacecraft-earth angle over the life of the mission. This antenna eliminates the associated risks of a continuously counter-rotating gimbaled antenna (reliability, microphonics). The antenna would be developed and qualified at JPL and provided to the spacecraft vendor.

- 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.

EPIC requirements on the spacecraft bus are summarized in the Spacecraft Characteristics Table 19. An estimate of subsystem masses and power requirements based on a team-X study (which assumes a custom-built spacecraft bus) as follows:

Table 19. Spacecraft Sub-System Characteristics

S/C Subsystem	Mass [kg, CBE]	Mass Ctgcy. [%]	Power [W, CBE]	Power Ctgcy. [%]
Attitude Control System	81.9	43	264	43
C&DH	24.1	43	69	43
Power	52.6	43	106	43
Propulsion (dry)	22.1	43	25	43
Structures and mechanisms	212.9	43		
Launch adapter	14.3	43		
Cabling	46.4	43		
Telecom + X-band Antenna	18.7	43	191	43
Thermal	25.5	43	31	43
Propellant [ΔV = 215 m/s]	172.0	43		

- 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.

All required spacecraft hardware is existing (previously flown) technology, with the exception of the JPL-provided antenna.

- 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).

Basic requirements to the spacecraft are as follows:

Payload Mass: The total mass of the payload, including the deployable sunshield, support struts, X-band antenna, and LHe is 898 kg, which includes 43 % contingency on all masses except LHe.
Payload Power: The total payload power required is 272 W, including 43 % contingency.
Instrument Output Data Rate: 87 kbps (baseline). 1260 kbps (TES option).
Instrument Pointing/Scanning: Continuous 1 rpm spin; continuous 1 rph coning/precession (baseline). 3 rpm spin; 3 rph precession (TES option).

These requirements do not present challenges to the spacecraft design.

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

The spacecraft itself requires no new technologies -- all technologies are at a TRL of 9, having been previously flown. The X-band antenna is provided equipment. Its TRL is estimated between 4 and 5 but is composed entirely of TRL = 9 space-proven components.

- Provide a preliminary schedule for the spacecraft development.

A 37-month spacecraft delivery schedule is assumed, consistent with a standard commercial bus. The schedule impact of utilizing body-mounted solar panels and a customer-provided X-band antenna is not significant. We assume that the spacecraft phase C/D is decoupled from the 48-

month instrument C/D.

Table 19. Spacecraft Characteristics

	Spacecraft bus	Value/ Summary, units
Structure	Structures material	Aluminium or composite
	Number of articulated structures	None
	Number of deployed structures	4 deployed solar panels
T/C	Type of thermal control used	Passive
Propulsion	Estimated delta-V budget	215 m/s
	Propulsion type(s) and associated propellant(s)/oxidizer(s)	Hydrazine
	Number of thrusters and tanks	One 25 N Main Thruster Twelve 0.9 N RCS Thrusters One tank
	Specific impulse of each propulsion mode	220 s
Attitude Control	Control method	3-axis, momentum compensated
	Control reference	Inertial
	Attitude control capability	1.0 deg
	Attitude knowledge limit	30 arcsec
	Agility requirements	None
	Articulation/#–axes	None
	SENSORS: Sun Sensors (8) Star Trackers (2) IMU (1) ACTUATORS: Reaction Wheels (4) Momentum Wheels (4)	 1 arcsec accuracy 0.003 deg/hr stability 20 Nms momentum, 0.1 Nm torque 60 Nms momentum, 0.14 Nm torque
C & DH	Spacecraft housekeeping data rate	10 kbps
	Data storage capacity	16 Gbits (baseline) 215 Gbits (TES option)
	Maximum storage record rate	98 kbps (baseline) 1270 kbps (TES option)
	Maximum storage playback rate	500 kbps (baseline) 4000 kbps (TES option)
Power	Type of array structure	4.0 m^2 body-mounted solar panels 3.8 m^2 hinged solar panels
	Array size, meters x meters	7.8 m^2
	Solar cell type	Triple-junction Ga-As
	Expected power generation	1511 W BOL; 1380 W EOL
	On-orbit average power consumption	981 W (incl. 43% contingency)
	Battery type	Li-Ion (two)
	Battery storage capacity	50 Ah

NOTE: the values supplied in this table are the EPIC requirements -- not the specifications for any particular implementation. The vendor for the spacecraft bus for this mission has not yet been selected.

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.

Spacecraft continuously executes spinning and precessing scan strategy. The data downlink is once per day to a 12-m ground station antenna in the baseline configuration. The TES focal plane option has a higher incoming data rate and would require 2 passes to a 34-m ground station (max). Data collection is continuous even during downlinks. The spacecraft requires occasional (every several months) small maneuvers to maintain orbit at L2.

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

None. We design enough storage to allow the spacecraft to miss 2 days worth of downlinks.

- Identify any unusual or especially challenging operational constraints.

None. Operational parameters well within state of the art and demonstrated in WMAP, Spitzer, etc.

Table 20. Mission Operations and Ground Data Systems

Down link Information	Value, units
Number of Data Dumps per Day	1 (baseline) 2 (TES option)
Downlink Frequency Band	8.425 GHz (Near-Earth X-Band)
Telemetry Data Rate	500 kbps (baseline) 4000 kbps (TES option)
S/C Transmitting Antenna Type(s) and Gain(s)	Toroidal-beam antenna, 9.0 dBi
Spacecraft transmitter peak power	191 W (total power)
Downlink Receiving Antenna Gain	58.7 dBi (baseline, 12-m DSN) 68.3 dBi (TES option, 34-m DSN)
Transmitting Power Amplifier Output	100 W (RF power)
Uplink Information	**Value, units**
Number of Uplinks per Day	1
Uplink Frequency Band	7.17 GHz
Telecommand Data Rate	1 kbps at 45°
S/C Receiving Antenna Type(s) and Gain(s)	Low-gain omnis, 7.7 dBi boresight

TOTAL MISSION COST FUNDING PROFILE TEMPLATE

(FY costs[1] in Real Year Dollars, Totals in Real Year and 2007 Dollars)

Item	FY09	FY10	FY11	FY12	FY13	FY14	FY15	FY16	Total (RY)	Total (FY07)
Phase	A	A-B	B-C/D	C/D	C/D	C/D	C/D-E	E		
Concept Study	0.1	2.7	1.3	-	-	-	-	-	4.1	3.7
Science	0.0	0.1	0.6	2.4	3.5	3.6	6.0	8.4	24.7	19.6
Instrument	0.1	1.2	9.4	37.2	55.3	57.1	31.1	-	191.4	157.9
Spacecraft	0.1	1.0	8.1	31.9	47.4	48.9	26.6	-	164.0	135.3
Ground Data System Dev	0.0	0.1	1.2	4.6	6.8	7.0	3.8	-	23.4	19.3
MSI&T [2]	0.0	0.1	0.4	0.3	0.4	3.9	4.1	-	9.2	7.4
Launch services	-	-	-	28.4	52.6	54.2	29.5	-	164.7	135.0
MO&DA[3]	-	-	-	-	-	-	5.8	12.0	17.8	13.7
Education/Outreach	0.0	0.0	0.0	0.1	0.2	0.2	0.7	1.3	2.6	2.0
Reserves	0.0	0.9	7.0	27.8	41.4	42.6	24.9	3.5	148.3	122.1
Project Management	0.0	0.1	0.6	2.4	3.5	3.7	2.3	0.7	13.1	10.7
Project System Engineering	0.0	0.1	0.9	3.4	5.1	5.2	2.8	-	17.5	14.4
Safety Mission Assurance	0.0	0.1	1.0	3.8	5.6	5.8	3.2	0.1	19.5	16.1
Total Cost	**0.3**	**6.3**	**30.4**	**142.3**	**221.7**	**232.0**	**146.9**	**26.1**	**800.2**	**657.4**
Total Contributions	-	-	-	-	-	-	-	-	-	-
							Total Mission Cost			**657.4**

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

Note on cost estimate: Costs were generated by JPL's Advanced Concurrent Engineering Design Team (Team X), which includes experts in science, mission design, instruments, programmatics, ground system, and every spacecraft subsystem. Team members synthesize their own expertise and discipline-specific models to generate complete mission studies including cost details. JPL has used Team X to generate well over 600 project studies.

The Parametric Mission Cost Model (PMCM) is widely used for estimating project costs. It is comprised of a series of cost estimating relationships (CERs) that represent the cost of each project WBS element. The CERs were derived by multiple regression techniques from about 150 (Team X) studies. CERs take into account the key engineering technical drivers that affect mission cost. PMCM has been validated against the costs of actual missions flown by JPL.

Prior to the team-x session, the instrument costs for the deployable sunshade, antenna, cryostat, telescopes, focal plane detector arrays, and warm and cold readout electronics were calculated based on a grassroots basis by the team members involved in their design. These costs were scaled from actual costs on similar hardware delivered for Planck and Herschel where applicable. The grassroots cost for the instrument was $145M (FY07), so we instead used the larger team-X model-based instrument cost of $158M (FY07) in the above table.

NAFCOM In order to validate the costs for the EPIC Mission, the costs were cross checked using NAFCOM v.2006, build date 4/18/2006. The NAFCOM costs for this mission were estimated to be

$706M (FY07) after applying a 30% reserve, in good agreement with the above cost table. The inputs to NAFCOM were based on the mass and power summaries shown in Tables 12 and 13 assuming an unmanned, earth-orbiting, scientific mission category.

Analogy to Spitzer. In order to further cross-check our cost estimate, we carried out a comparison to the actual costs of a similar cryogenic mission. The best example available was Spitzer, an infrared great observatory with a suite of 3 science instruments launched in 2003 with a cost of $1075M (FY07) for phases A-E without extended operations. We applied the following reductions to the Spitzer actual costs: 1) change phase E from 30 to 18 months; 2) scale the instrument development for a 48 month phase C/D from a 66 month phase C/D; 3) reduce the instrument requirements (3 instruments with a near-infrared diffraction-limited Be telescope to a single 100 mK instrument with mm-wave optics); 4) scale the spacecraft based on the less demanding pointing, control and data rate requirements for EPIC; 5) reduce the flight software for a single operating mode; 6) reduce the science management costs from that of a great observatory. Then we made the following additions: 1) add deployable sunshade cost; 2) add custom antenna; and 3) add higher launch vehicle cost. The estimate based on these adjustments agrees within 10 % of the above cost estimate, although we must emphasize that the adjustments are significant due to the dissimilarity of the two missions.

Disclaimer: The total estimated mission cost provided here are for budgetary and planning purposes only and does not constitute a commitment on the part of Caltech/JPL.