Note: Some figures in the original document are omitted , since they no longer apply after EPIC refurbishment

EPIC Instrument Description

Introduction / General Description

This document is intended to bring the overall top -level performance numbers into a single reference document.

The EPIC Instrument consists of 3 major physical components, shown in Figure 1: the Camera/Telescope Assembly (CTA), consisting of all the optics, focal plane and readout electronics; the Main Electronics Box (MEB) containing logic that coordinates focal plane readout electronics and shutter, most health and safety monitor conditioning circuits, and the thermal control electronics; and the EPIC Computer (EC), containing the command interface to the spacecraft, bulk memory, data compression software, and high-level command decomposition / hardware sequencing functions. (Several sides of the EC are covered by ESD protective material in the photo shown.) The EC is a copy of the DSCOVR CompHub flight control computer with an interface board specifically designed to support the EPIC hardware interfaces. There is some minor functionality overlap between the EC and MEB, as described later in this document (see electronics overview).

A high level description of the principal characteristics of the system: EPIC contains a 12", f/ 9.37, Cassegrain telescope with approximately 0.61°full angle FOV; a 2 wheel filter set consisting of 10 interference filters ranging from 317 nm to 905 nm; a shutter with adjustable exposures ranging from 2 ms to indefinite; a single, -40 °C passively cooled, 2048 x 2048 pixel, back-side illuminated, CCD focal plane; lossy JPEG and several lossless compression capabilities; burst 10 image cadence with less than 20 seconds between each image; a focus mechanism for contingency use; and an aperture cover which cannot be re-closed once opened on orbit. To minimize thermal effects on the optical system, the telescope is actively controlled via solid state thermostats to maintain the optical elements temperatures near 20 °C. A functional block diagram is shown in Figure 2.

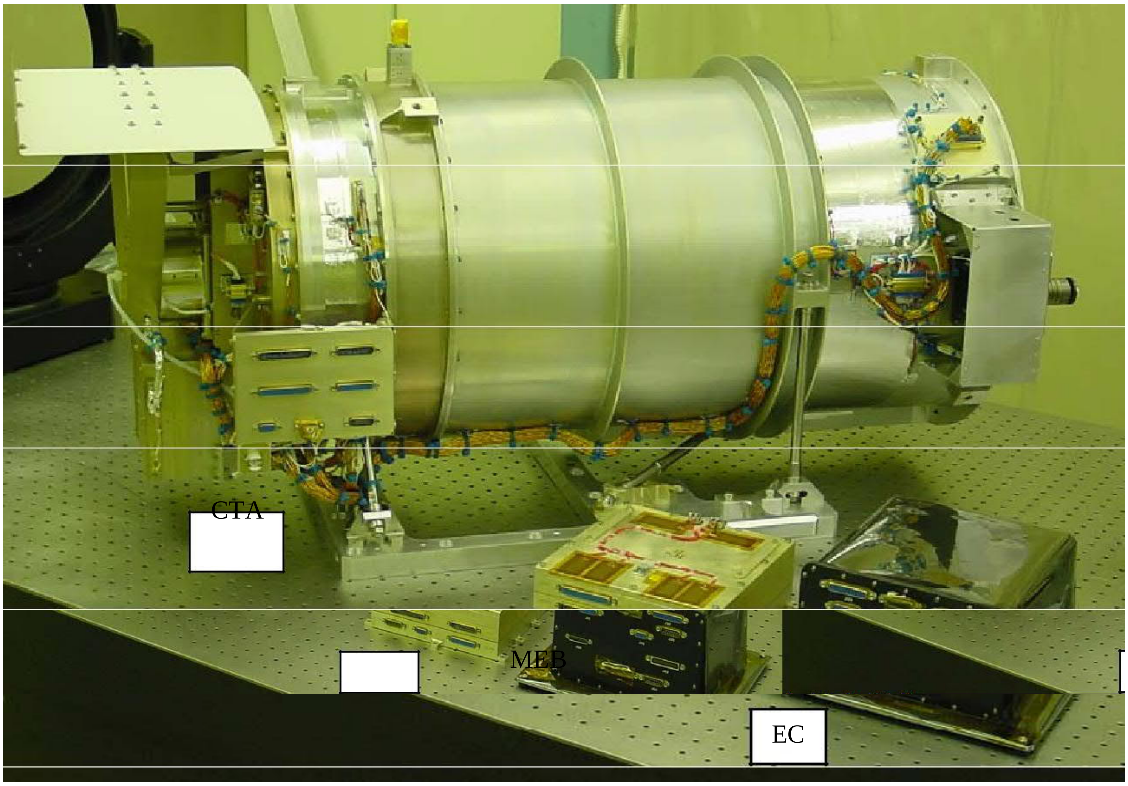


Figure 1: System Components, less blankets

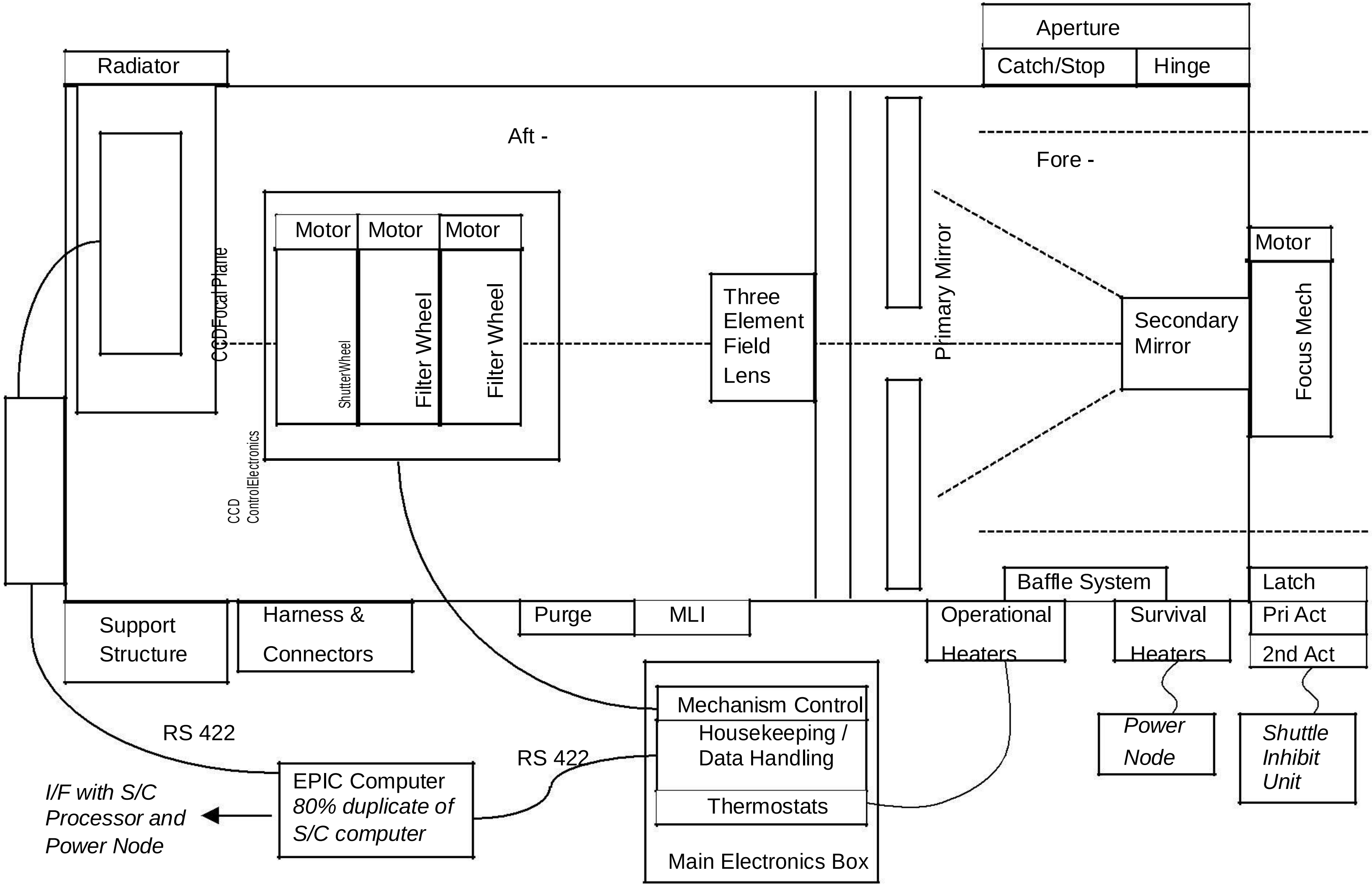


Figure 2: Functional Block Diagram

Optical Performance

The Camera / Telescope Assembly contains all of the optical components, the focal plane, and the focal plane readout electronics. An annotated graphic of the CTA is shown in Figure 3 and a cross section is shown in Figure 4.

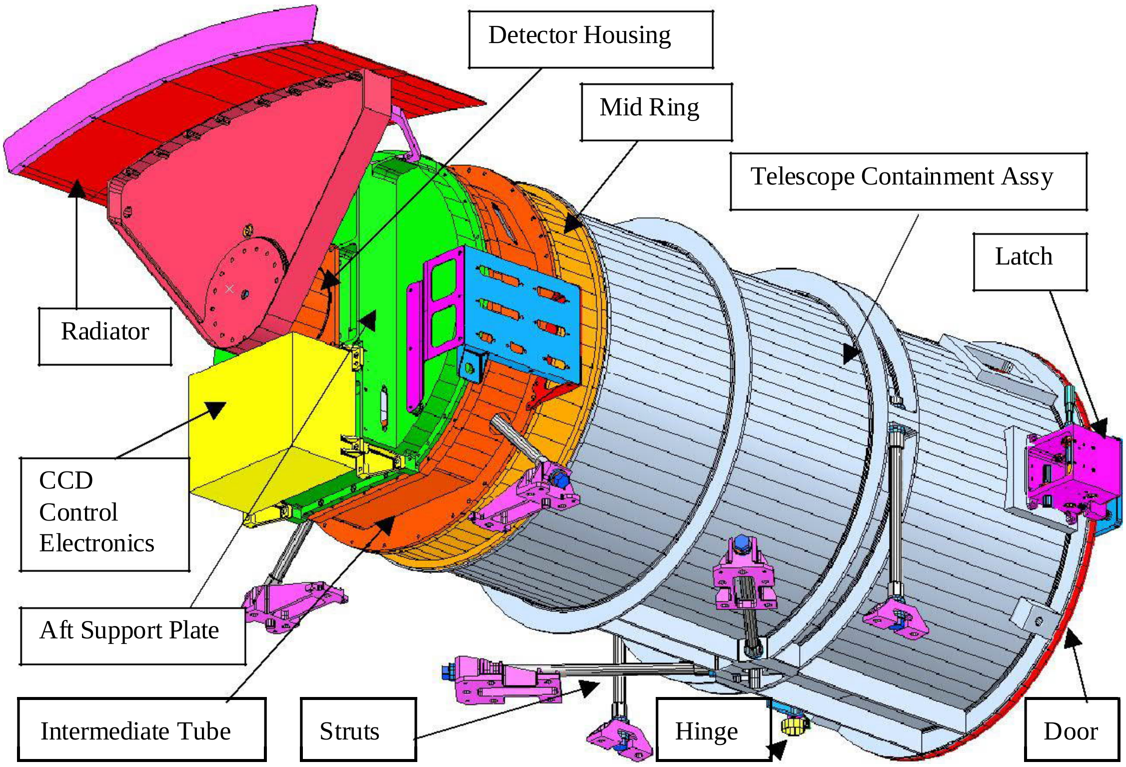


Figure 3: Camera / Telescope Assembly

EPIC Instrument Description

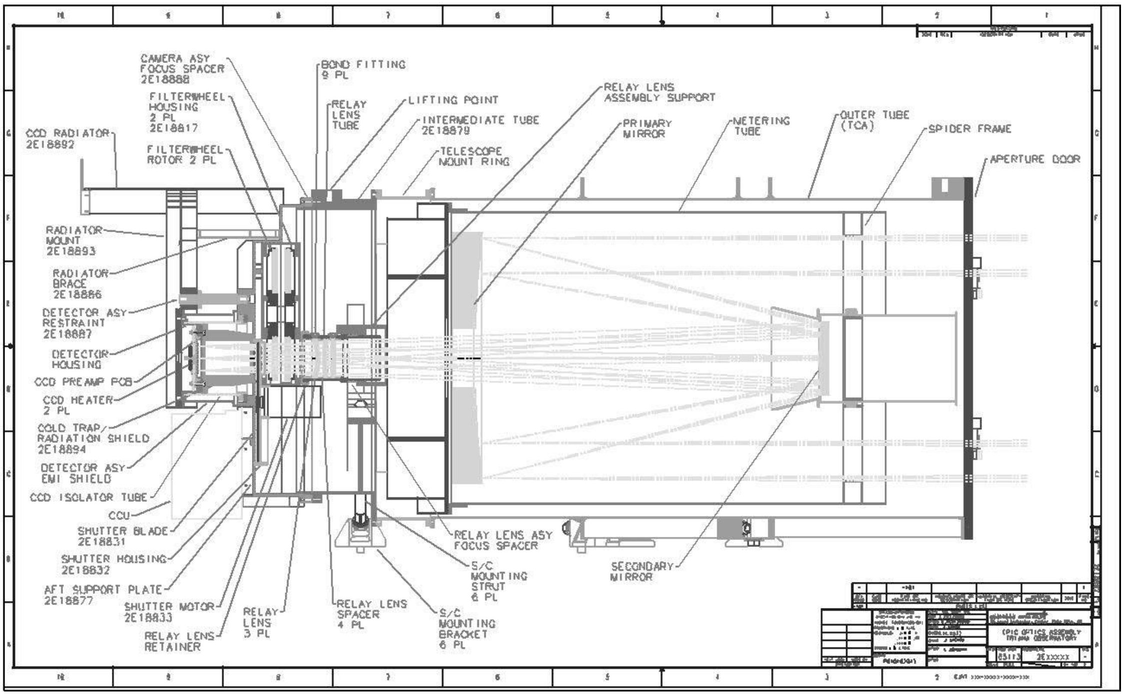


Figure 4: Camera / Telescope Assembly Cross-section

Mirrors and associated structure

The forward end of the telescope beginning with the mid-ring, including the door and latch, focus mechanism, primary and secondary mirrors and associated structures was procured through a subcontract with SSG, Inc. (The door and latch in turn were sub-contracted to Starsys Research Corp. by SSG, Inc.) The relevant optical characteristics for the system level shown below were taken from the "DSCOVR Telescope Final Report".

Entrance aperture: 12.002" (defined by a ring placed just in front of the surface of the primary mirror)
Obscuration of the secondary mirror: 5.172" (outer diameter of the baffle mounted to the secondary mirror)
21.25% of the aperture is obscured by the secondary mirror assembly and support structure.
Focal length prior to the FLG affect: 110.2" (112.4" including the field lens group and a filter)
Transmission: See Figure 5 below.

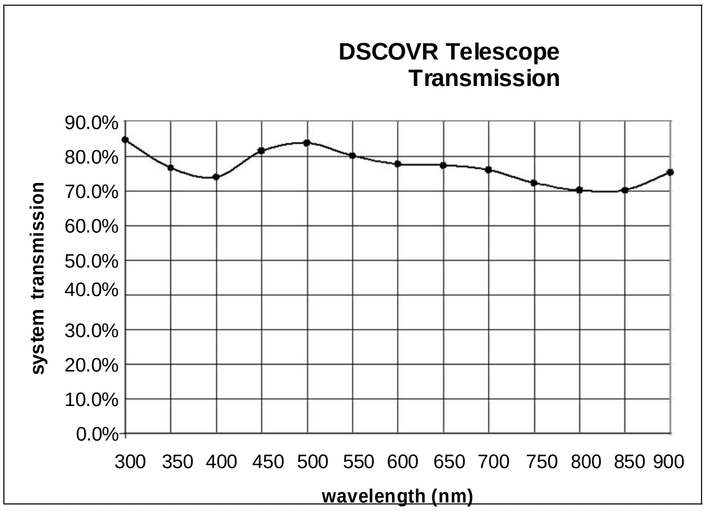


Figure 5: Telescope Transmission

Materials:

The mirrors are made from Zerodur with an aluminum coating and a SiO_2 coating on the primary mirror and aluminum overcoated with MgF_2 coating on the secondary mirror. The structure maintaining the optical separation between the primary and secondary mirrors (metering tube) is a graphite composite cylinder designed to exhibit 0 CTE. (Humidity effects are expected to be equivalent to several focus steps, which is less than a depth of focus.) The mechanical structure supporting the primary and secondary mirrors (between the mirrors and the metering tube) is Invar 36. The non -optical mechanical structure is primarily 6061-T6 aluminum with some Titanium 6Al-4V. Fasteners are either A286 high strength steel, 300 series stainless steel, or 416 stainless steel.

Field Lens group

The purpose of the FLG is to reduce the aberrations inherent in a Cassegrain design. An exploded view of the FLG assembly is shown in Figure 6. In the EPIC system, the FLG is physically located between the primary mirror and the filter wheels.

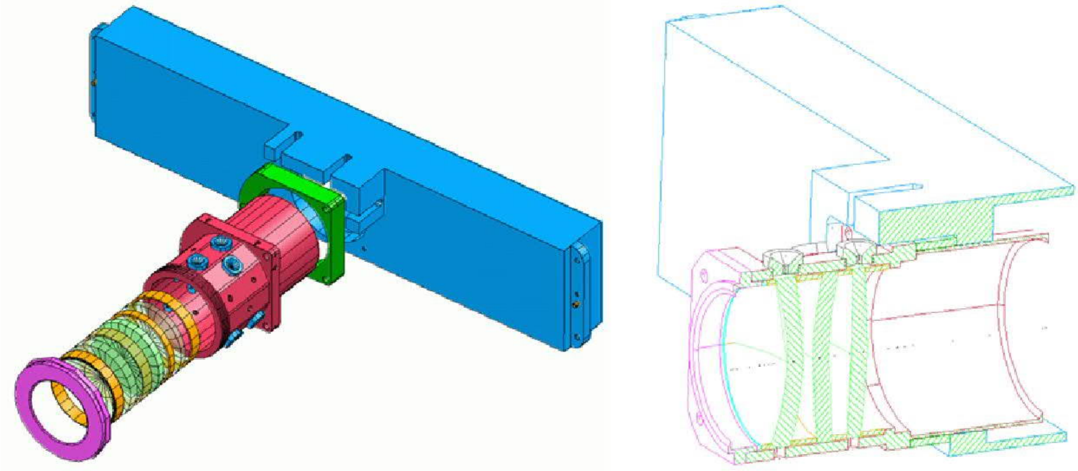


Figure 6: Field Lens Group Assembly

The FLG was assembled, aligned and installed after receipt of the mirror system, resulting in the system Wave Front Error (less filters and CCD), at that level of assembly, shown in Figure 7 below. The outer 8 field points are at 15.3 mm radius, the inner 4 field points are at 5.1 mm radius. Such close agreement between the measured and calculated values lends credibility to the model. The phase diversity test performed just after thermal vacuum/balance indicates comparable performance for the entire system.

		0.146 ***0.146***		
	0.135 ***0.130***		0.111 ***0.115***	
		0.093 ***0.088***		
0.119 ***0.120***	0.097 ***0.079***	0.098 ***0.096***	0.094 ***0.109***	0.114 ***0.092***
		0.097 ***0.088***		
	0.155 ***0.174***		0.168 ***0.196***	
		0.191 ***0.191***		

Average 0.126 Calculated
Average 0.126 Measured (average of 5 interferograms)

Figure 7: System Wave Front Error (waves at 632.8 nm) prior to filters and focal plane

Final focal length: 112.4"

Materials:
The lenses are all made from Suprasil fused silica, with no coatings. They are mounted in an aluminum structure.

Filters

The interference filters were manufactured by Barr Associates, Inc.. Each filter consists of a set of 2 filters, a narrow passband band and a wide passband (blocker). Detailed transmission characteristics of all filters are available in the procurement paperwork, with some plots given in an Excel spreadsheet.

Figure 9: Flight Filter Wheels

Wavelength (nm)	Full Width (nm)	Primary Application
317.5 ± 0.1	1 ± 0.2	Ozone, SO 2
325 ± 0.1	2 ± 0.2	Ozone
340 ± 0.3	3 ± 0.6	Ozone, Aerosols
388 ± 0.3	3 ± 0.6	Aerosols, Clouds
443 ± 1	3 ± 0.6	Aerosols
551 ± 1	3 ± 0.6	Aerosols, Vegetation
680 ± 0.2	2 ± 0.4	Aerosols, Vegetation, Clouds
687.75 ± 0.2	0.8 ± 0.2	Cloud Height
764 ± 0.2	1 ± 0.2	Cloud Height
779.5 ± 0.3	2 ± 0.4	Clouds, Vegetation

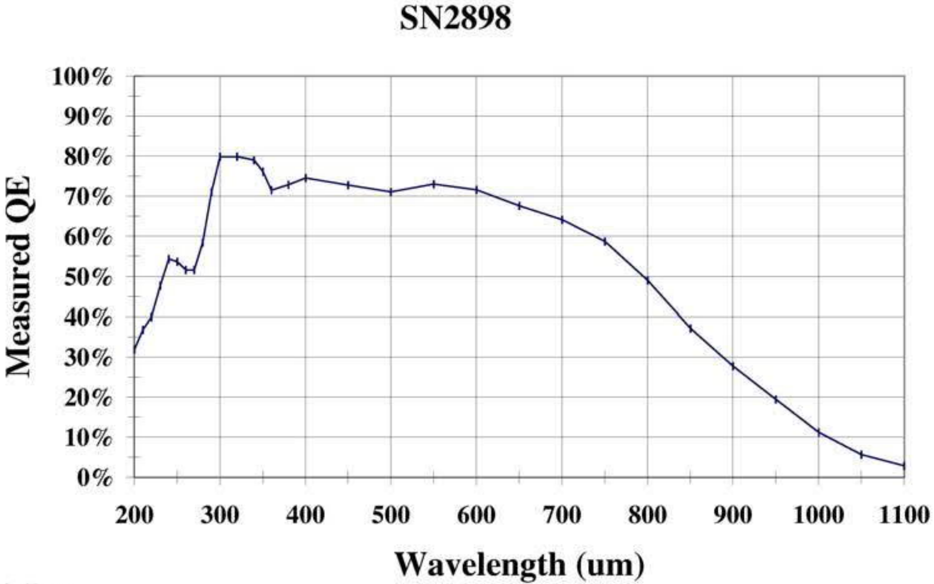
Focal Plane

The focal plane is a 2048 x 2048 pixel CCD, backside-thinned, backside-illuminated and anti-reflection coated to optimize quantum efficiency down to 300 nm (modified LMFS-type CCD 442A). The CCD is passively cooled to approximately -40°C on orbit to reduce dark current and other noise effects. Other characteristics of the focal plane are listed in Figure 10. In normal operation the CCD will be read out from opposite corners at 500 kHz, but the entire array can be read out from either side, thus providing some measure of redundancy. The dark current listed in the figure was measured at the component level. See the electronics section for system level performance specifics.

CCD format	2048 x 2048 pixels (3.072 x 3.072 cm square)
Pixel size	15 μm x 15 μm, 100% fill factor
	1.078 arc-sec
CCD type	Thinned, backside illuminated
Spectral range	200 - 950 nm (QE > 25%)
Pixel full well depth	> 95,000 electrons
Readout	Single or dual (diagonal corners)
Pixel readout rate	500 kHz
CCD operating temperature	-40°C, by passive cooling
System Noise: top analog train	sigma = 1.6 DN
System Noise: bottom analog train	sigma = 3 DN
Dark current	*<5 electrons per second per pixel*

Figure 10: CCD Characteristics

The quantum efficiency of the flight device, measured by the Steward Observatory (who performed the thinning and coating) is shown in Figure 11.



Michael Lesser
University of Arizona

Figure 11: CCD Quantum Efficiency

Flat field images in the top 2 IR channels taken to calibrate the instrument contain an interference fringe pattern attributed to the transparency of Silicon to IR wavelengths. See the radiometric calibration section for details.

Optical Performance

Of particular note, are out-of-field stray light tests described in EPIC-0203 “EPIC Stray Light Test Results” and focus tests described in 2E19318 “Focus Data Report”. Regarding stray light, several tests were performed with a specific goal to determine whether or not out-of-field earth-shine stray light would adversely affect images of the moon acquired for calibration purposes. The test results show that the ratio of stray light power per pixel from the earth, to signal power per pixel when imaging the moon is adequate to allow use of EPIC moon imagery for absolute radiometric calibration.

The estimated horizontal and vertical distortions, based upon a correlated optical model, are shown in Figure 12 and Figure 13, respectively. Note that the distortions are accurately fit by a pure cubic. On-orbit calibration will be required to find the actual center of the field, using a known star field. The focal plane is 0.6047 inches from the center to each edge (0.00059055 in/pixel).

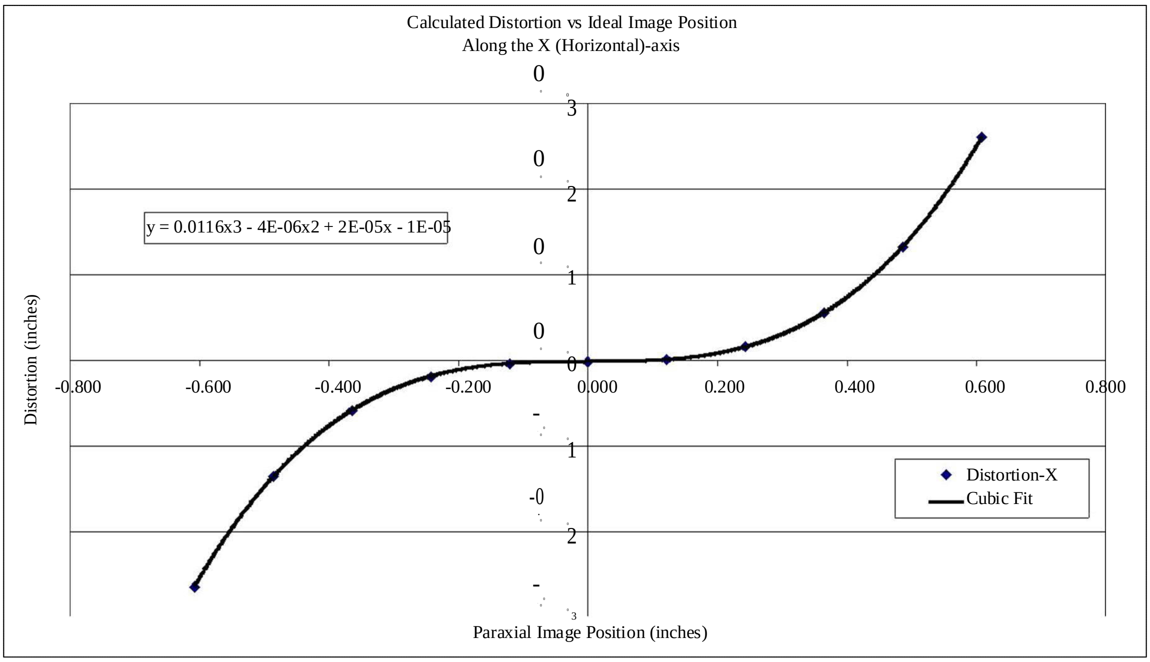


Figure 12: Estimated horizontal optical distortions

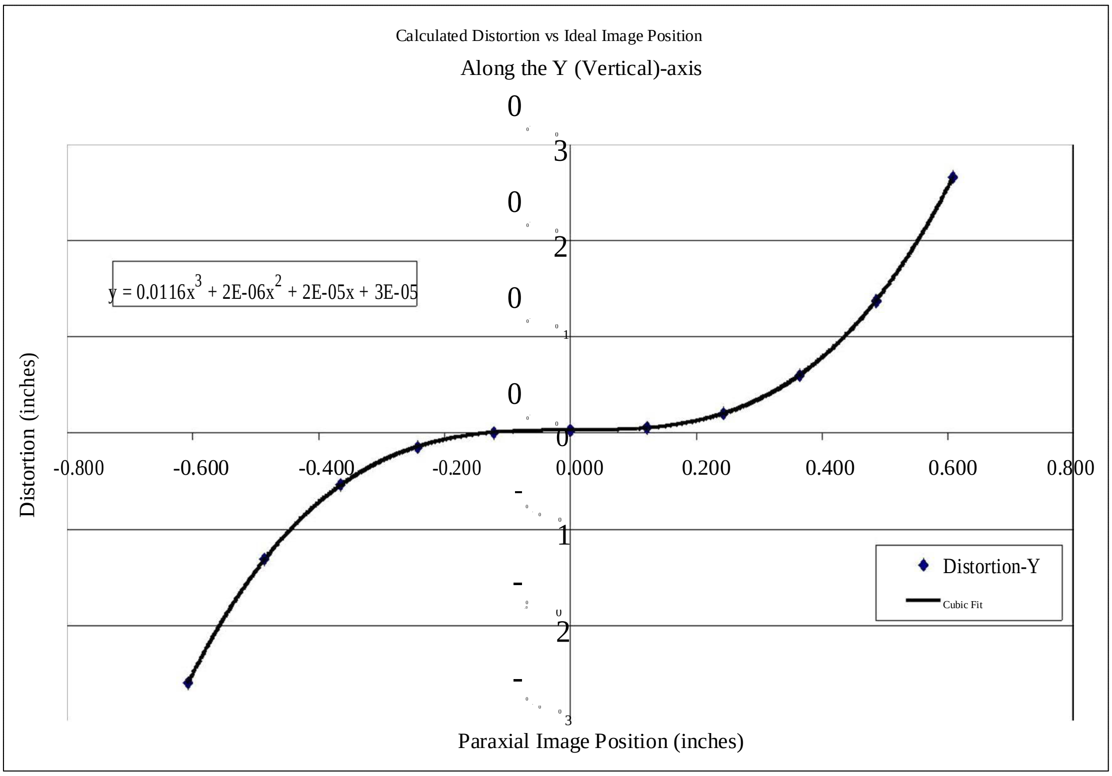


Figure 13: Estimated vertical optical distortions

Field of View

The FOV defined by the baffling system and entrance stops is 0.665 degrees, with the diameter slightly larger than the horizontal and vertical dimensions of the CCD. This makes it impossible to illuminate the corners of the CCD, allowing them to be used as a good measure of stray light and dark current. Since the edge of the FOV is defined by the CCD in the vertical and horizontal directions, the typical full width is 0.607 degrees, but is slightly dependent on the CCD read mode, because of the over-scanned pixels (±8 arc-sec). See 2E19281 “Optical Performance Evaluation” for details. (See the CCU description below for details about over-scanned pixels.)

Several interesting features can be seen in the full field illumination image shown in Figure 14. The over-scanned pixels are apparent along the top and bottom edges, as well as the lower half of the left edge and upper half of the right edge. Along any given edge, the CCD is the field limiting device for the center 1000 pixels. This image was acquired at LMMS at room temperature during the consistency check just prior to thermal vacuum pump-down. (Large vertical bands in the image, if seen, are a result of the print/reproduction process, not actually in the image.) Note the “spot” located slightly right of the left-right center, near the bottom of the image.

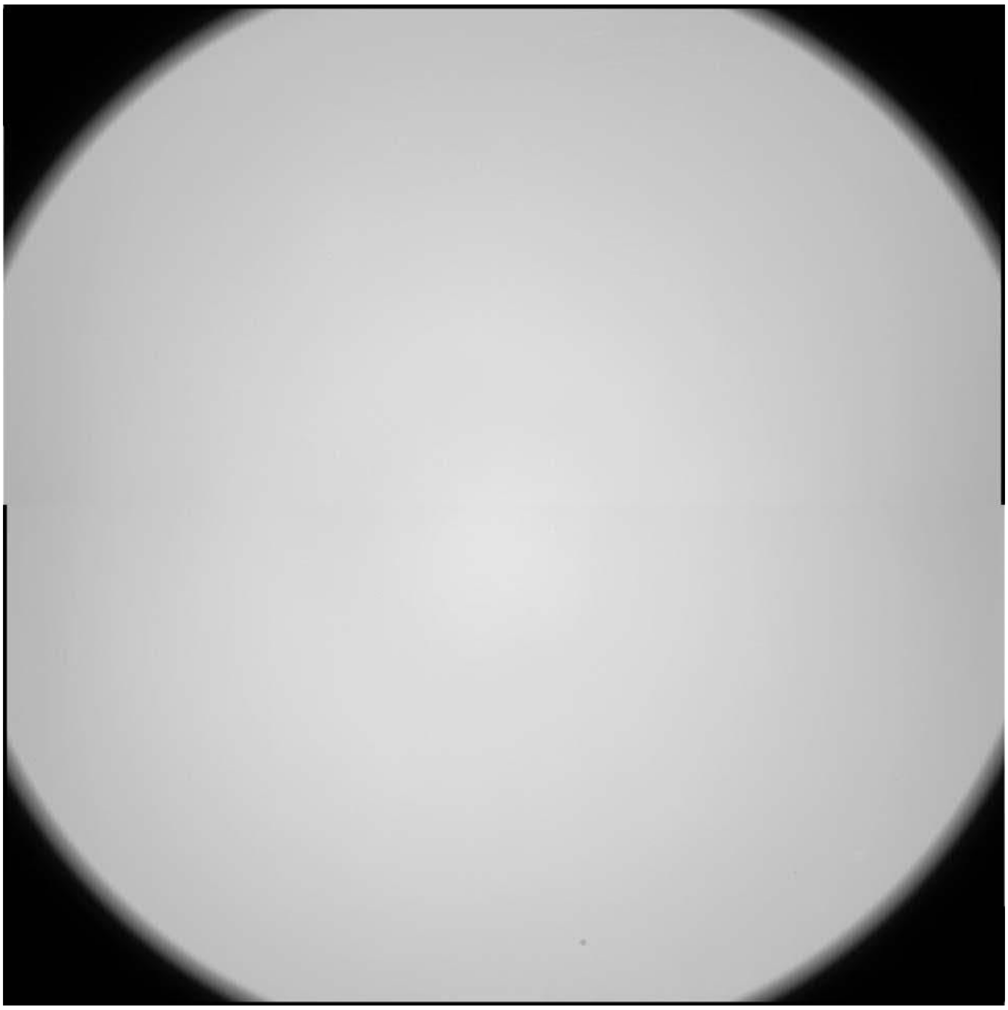


Figure 14: Full field illumination

Periodic calibration will be required to maintain optimal quality data. During the instrument level thermal vacuum test, a radiometric calibration was performed with gross behavior shown below Figure 16 indicates the preliminary responsivity determined using the calibration data acquired during the instrument level thermal vacuum test. The responsivity is in DN/L/s, where L is the spectral radiance in mW/(m^2 nm sr). Note also that the numbers are for a 1 second exposure.

Figure 17 shows examples of the shutter-induced non -uniformity for both 2 ms and 10 ms exposures. The source of the non-uniformity is the change in angular rate of the shutter as the slot edges move through the field of view.

These short exposure lengths will not be used because of the induced non-uniformity. Rather exposures no shorter than 30 ms will be used

Figure 17 Shutter-induced Exposure Non-uniformity

Matrices have been developed to correct images for the shutter related non-linearity. See "Calibration Analysis of Scripps-EPIC" for the detailed recipe and associated files. Histograms of the correction factors for the 3 shutter slots are shown in Figure 18. The colored histograms for the medium and narrow slot corrections represent the different algorithms possible for correcting a given image. For instance, correcting any medium slot exposure can occur by relating it to either the C to B or B to C direction of the wide slot exposure. The same is true for the narrow slot exposure. The black histogram represents the average of all equivalent paths used in determining the CCD non-uniformity correction.

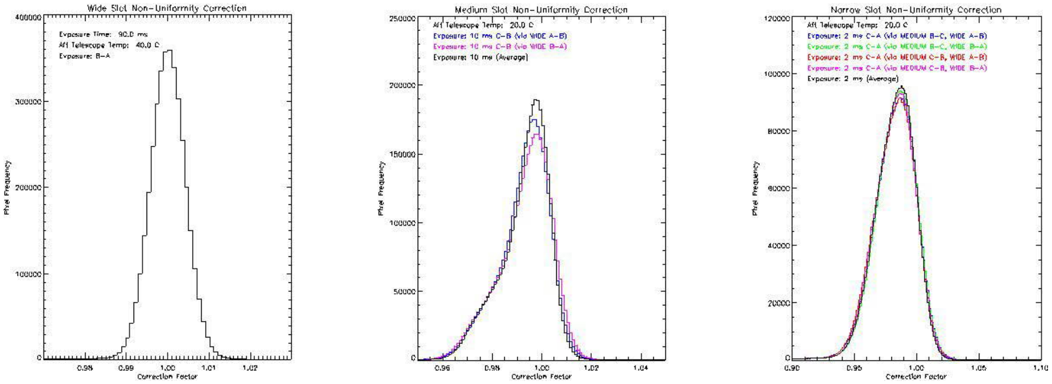


Figure 18 Histogram of Shutter Non-linearity Correction Coefficients

There is an area approximately 15 pixels in diameter, centered at (1185, 1919) that exhibits behavior uncharacteristic of the rest of the focal plane, see Figure 15 above. At room temperature, this area has a high dark current. At normal operating temperatures, it is apparent that the responsivity in the area is a strong function of wavelength.

The linearity of the EPIC system was characterized by a series of measurements made during the instrument level thermal vacuum test. The plot presented in Figure 21 is a summary of the data taken on 3 different days, each day using a different wavelength. The maximum non-linearity is near 0.5% at full scale.

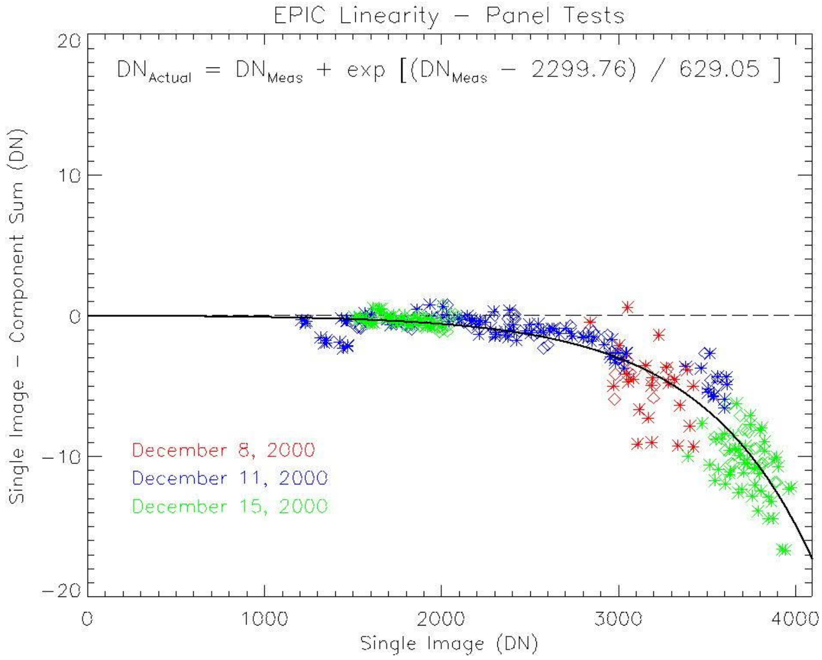


Figure 21 Response Linearity

Alignment

A 5-faced 1/2" polished aluminum alignment cube is located on the structure supporting the primary mirror. The direction defined by the forward-facing cube face is 46 ± 6 arc-sec from the center of the EPIC FOV. A spot aligned to the cube appears near pixel (981, 1018) where (0,0) is the upper left corner of the image.

The CCD is rotated 0.80 ±0.05 degrees counterclockwise relative to the EPIC +Z cube face. This causes the image to be rotated clockwise when rows and columns define horizontal and vertical.

Focus Mechanism

The focus mechanism should not be needed. It is available for contingency, with enough range to allow acquisition of a focused image with no filter in place. The moon and earth are too bright for this to be useful using the shortest available exposure of about 2 ms. Optimal focus is located near the center of travel. The focus mechanism will not be used in-orbit at L-1

Shutter Performance

The measured behavior is a result of the radiometric calibration analysis. The shutter stopping behavior changes with temperature, enough that changes to the delay parameter are needed for correct functioning of the shutter when operated significantly outside the normal temperature range. See 2E18808 “Hardware – Software ICD” for more details.

For ease of reading, the exposure times stated in the following text are rounded to the nearest millisecond. The narrow medium and wide slots producing a 2 ms, 10 ms and 46 ms or longer exposure, respectively. The normal positions for the shutter to be stopped are shown in Figure 22.

Label	Position
A	Between narrow and wide
B	Between medium and wide
C	Between narrow and medium
Dwell	Wide slot is Open

Figure 22 Shutter Positions

Basic limitations

The shutter blade contains 3 slots: the narrow and medium width slots are used to produce 2 and 10 ms exposures, respectively; the wide slot is used for exposures > 46 ms. For 2, 10 and 46 ms exposures, the shutter blade is moved so that the appropriate slot crosses the light path in a single motion. For exposures longer than 46 ms, the wide slot is used. While in the open position, the blade slows down, then speeds up to complete the exposure. For an exposure longer than about 60 ms, the blade comes to a complete stop in the open position, prior to closing. Photos of the flight shutter assembly are shown in Figure 23. In the photo on the right, you can see part of the edge of the fixed opening (between the wide and narrow slots).

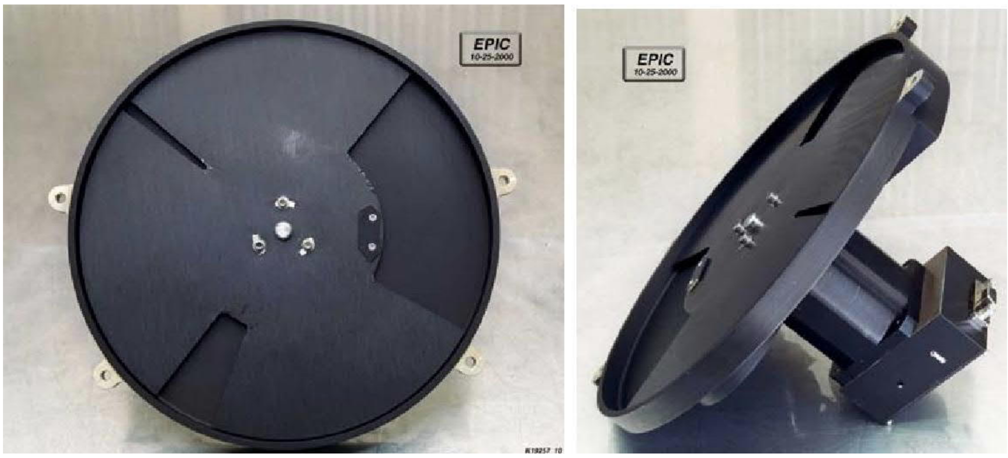


Figure 23: Shutter Assembly

In order to perform exposures between 2 ms and 46 ms in 2 ms increments, the shutter can be commanded to perform a sequence of up to 8 exposures in rapid succession, called a multiple exposure sequence. A single exposure requires approximately 200 ms for the start/stop sequence, resulting in a sequence where snapshots are spaced at 200 ms. From 2 ms to 46 ms, the exposure is any combination of the 3 slots. Over 46 ms, the commanded exposure has 1 ms resolution.

The shutter blade's angular velocity is not constant as the edges of the slot cross the optical path. Since the shutter blade is not located at a pupil (it is several inches from the CCD), this causes different areas of the CCD to have different exposures. For wide exposures greater than about 60 ms, this affect is less than 0.1%. Shutter related effects on the radiometric performance can be seen in the "Radiometric Performance" section above. Predicted non- uniformity for various shutter motions (calculated at the plane of the shutter blade) is shown in Figure 24

Slot	Exposure (ms)	Non-uniformity (%)
Narrow	2 **NOT USED**	10.6
Medium	10	8.3
Wide	46	3.1
Wide	70	0.090
Wide	100	0.071

Figure 24 Predicted Exposure Non-uniformity vs. Shutter Motion

Measured exposure times / shutter linearity

Thermal sensitivities of the shutter encoder system cause shutter acceleration, and therefore speed to be a slight function of temperature. Figure 25 indicates the actual exposure time at several temperatures and both directions, for the narrow and medium slots. Since the overall behavior of the wide slot is dependent on the desired exposure, it's behavior is a little more complicated. Figure 26 shows the actual exposure time that resulted from the commanded exposure for several temperature and exposure combinations. The SHUTTER_DELAY parameter in the shutter controller needs to be changed for correct operation of the shutter if the shutter's temperature is much different from 20 °C. At 20 ±5 °C the default power-on value for the SHUTTER_DELAY parameter of 128 is appropriate. At –15 °C, a value closer to 155 is needed.

Exposure (ms)				
	Narrow Slot		Medium Slot	
Temperature	A -> C	C -> A	C -> B	B -> C
Cold (-10 C)	2.08	2.06	10.16	10.12
Nominal (20 C)	2.03	2.02	9.93	9.89
Hot (40 C)	1.99	1.98	9.76	9.73

Figure 25 Exposure Time vs. Camera Assembly Temperature

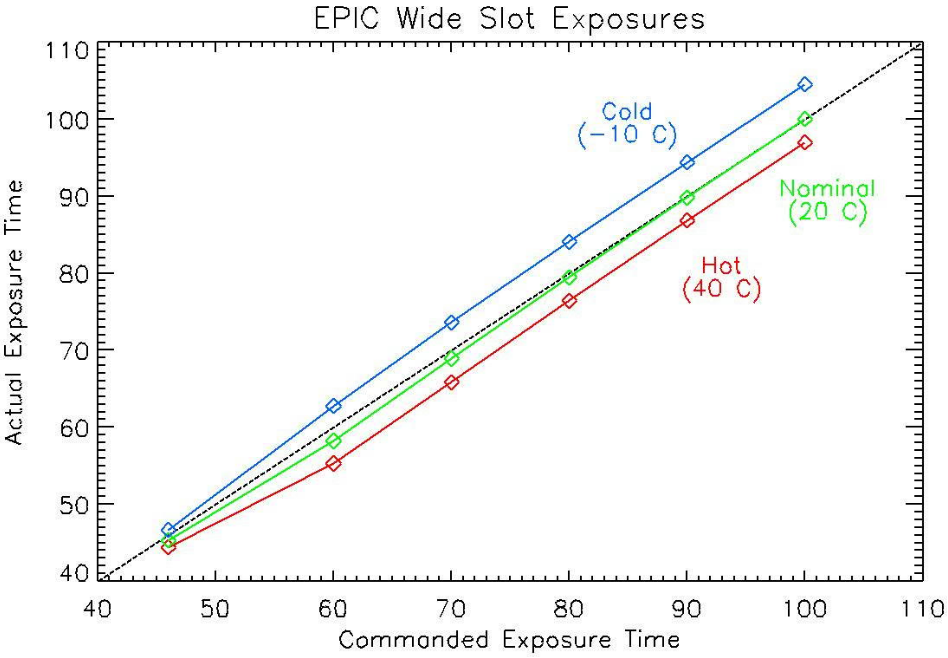


Figure 26 Commanded vs. Actual Exposure for the Wide Slot

The “design” correction for the shutter telemetry is approximately as follows:

Wide: Actual exposure = (close-open) * 4.000000 μsec * 1.0000
Medium: Actual exposure = (close-open) * 4.000000 μsec * 0.8750
Narrow: Actual exposure = (close-open) * 4.000000 μsec * 0.1750

Electrical Performance

The electronic system for EPIC consists of 2 electronics boxes mounted to the S/C: the EC and MEB; and the CCU, which is mounted to the aft end of the CTA. See Figure 27 for a block diagram of the electrical system. DC/DC converters required for each box are contained in each box. The power path is from the S/C to the EC, which contains switches to power the MEB and operational heater busses. The MEB, in turn, contains the switches to feed power to the CCU and the thermostats to control power to the operational heaters. The mechanism motors are also controlled (and powered) by the MEB. Survival heater and door latch power are CTA connections directly to the S/C.

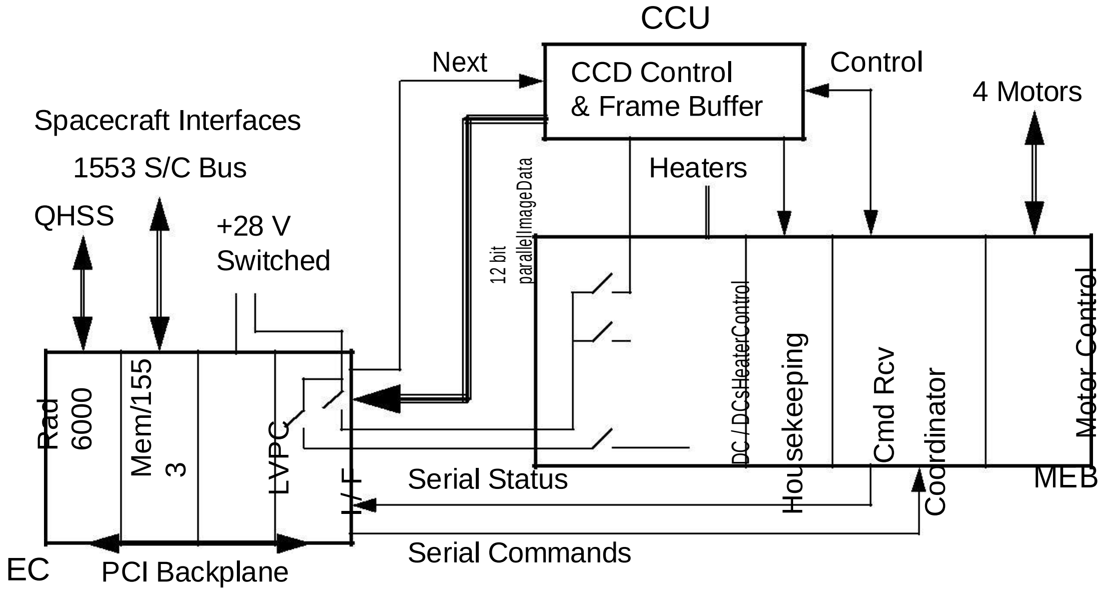


Figure 27: Electronics Block Diagram.

Total Power Consumption

The nominal total power consumption stated is at 25 V. As the bus voltage increases, the power will increase until there is more than enough power to maintain the thermostat set-points. The DC/DC converters also are about 5-10% less efficient at 40 V input than at 21 V input.

Nominal power: 67.9 W

Latch actuator: Redundant actuators, the primary actuator heater is 110 Ω, the secondary is 108 Ω. Duration for latch operations vary from 1 to 5 minutes depending on bus voltage and the temperature of the TCA.

Electronics Power Consumption

At room temperature and 28 V:

EC:	15.3 W (supplied by GSFC)
MEB:	8.6 W
CCU:	6.8 W standby, 8.4 W while acquiring an image

The theoretical maximum power drawn by the focus, filter wheel and shutter motors is 5.7, 0.4 and 2.8 W, respectively. However, to draw that much power beyond a short peak, requires that a motor be “stuck”.

Approximately 0.08 W is dissipated in the sense head when idle, and approximately 0.2 W during clearing and readout.

Thermal Power Consumption

Average power is in a nominal operations configuration, i.e. the door is open and the telescope is pointed at the earth, and at minimum voltage (21 V for survival heaters, 25 V for operational heaters). The operational heaters are all located in/on the TCA, and are intended to maintain the entire optical system near 20 °C to minimize thermal effects. Thermistor in the TCA are used as controlling signals for thermostats located in the MEB.

Survival Heater	Circuit Name	Measured Resistance (Ω)	BOL Average Power (W)
1	Aft Support Plate	74.7	< 4.5
2	TCA	14.2	< 25
3	M2 Structure	134.6	< 2.3
4	MEB	64.6	< 6
5	EC	95.8	< 6
Total			< 44

Operational Heater	Circuit Name	Measured Resistance (Ω)	BOL Average Power (W)
1	M1 Star 1A	25.7	5.7
2	TCA Fore 1A	26.5	22.7
3	M2 Hub A	201.	3.1
4	M1 Bezel A	97.7	1.6
5	M1 Star 2A	45.3	1.5
6	M1 Star 1B	26.4	
7	TCA Fore 2B	50.6	
8	M2 Hub B	198.	
9	Camera Assy B	62.0	2.6
10	M1 Star 2B	45.3	
Total			37.2

CCD Heaters: 150 Ω and 250 Ω

Possibly used to maintain CCD temperatures above freezing to mitigate condensing contaminants during early mission operations. May be useful for annealing radiation damage. These heaters do NOT have thermostats, simply commanded on or off by operators.

EPIC Computer (EC)

The EC is a copy of the S/C CompHub computer with the up/downlink card replaced by an EPIC specific hardware interface card. The common parts in the EC include: Low Voltage Power Converter (LVPC); PCI backplane; 256 Mbyte, after EDAC, bulk memory card also containing the 1553 bus interface; and a Rad 6000 processor card including the QHSS interface.

The EPIC specific interface card detailed design and manufacture was performed by GSFC. It contains a GSFC heritage PCI interface FPGA chip set; housekeeping signal conditioning circuitry for 8 analog status signals; 4 power switches; and the RS-422 command and data interfaces to the MEB and CCU.

Power: 15.3 W

Main Electronic Box (MEB)

The MEB consists of 3 circuit boards. One contains only mechanism control electronics: the FPGA; switches; encoder interpretation; and ballast resistors used to control the motors. Another contains the solid state thermostats for the CTA thermal control and the power supplies needed to power the MEB logic and all of the motors. The third board contains the command/data interface between the EC and MEB as well as the command interface between the MEB and CCU; housekeeping signal conditioning circuitry for the majority of the EPIC system status monitors; and the FPGA that coordinates the CCU and shutter operations during an exposure.

Power: 8.6 watts

CCD Control Unit (CCU)

The CCU controls the CCD, feeding status information to the MEB for mechanism coordination and transferring image data to the EC. It contains all of the power conditioning and switches required to drive the CCD, CCD output signal conditioning circuitry, single frame of memory, and RS-422 interfaces to the EC and MEB.

The manufacturer of the CCD labeled pins associated with the words left, right, upper and lower. These connections are appropriately labeled for discussions about the front-side illuminated device, as an operator would view the CCD. However, when optical system effects and back-illumination is taken into account, the part of the CCD labeled "Upper" is actually the bottom of the EPIC image. Correspondingly, the "Lower" section of the CCD is actually the top of the EPIC image. The commands that affect the operation of the hardware use the electronic signal names, not the name relative to the EPIC image. Hence, the "Upper Offset" adjusts the offset in the electronics that reads through the bottom of the image.

The CCU can be commanded to perform image reads through either 1 corner, the opposite corner, or both corners. The CCD is cleared through identical clocking sequence as the image read, maintaining consistent dark current in columns. Since the read rate is always 500 kHz, the clear and read sequences required either 4.5 or 9.0 seconds, depending on how many corners are used (CCU mode). A test mode also exists, where the pixel value is set to the row + column of the pixel, producing a diagonal gradient across the image.

Mode	Behavior
1	Nominal mode. Uses both amplifiers.
3	Reads out through the bottom left corner of the image.
4	Reads out through the top right corner of the image.
7	Test pattern.

There are no barriers between the edge columns and the bulk silicon outside the image area of the CCD. This allows charge to migrate from the bulk silicon into the edge columns. Given enough excess charge, the barriers between columns is crossed and several edge columns can be corrupted. This is most often seen as saturated pixels of an edge when illumination extends outside the FOV (full field illumination).

Resolution: 12 bits (4095 DN is approximately 90000 e-)
Read rate: 500 kHz
System Noise:
    Top analog train σ= 3 DN
    Bottom analog train σ= 1.6 DN
Gain: For CCD temperatures -55 °C – -20 °C: (No CCU temperature dependance.)
    Top analog train 21.4 – 21.8 e-/DN
    Bottom analog train 21.5 – 22.0 e-/DN
Offset command: -4.85 DN / bit
Offset vs. CCU temperature: Top (Lower) offset is 137.6 + 0.0976 T (where T is °C)
    Bottom (Upper) offset is 132.4 + 0.120 T (where T is °C)

Over-scanned image

While reading the CCD, the CCU throws away the first 8 pixels from every row and the first 8 (only 7 when reading through the bottom of the image) pixels of every column. The same number of pixels thrown away are then read at the end of each row and column, presenting the user with a 2048 x 2048 image. These over-scanned pixels theoretically have only dark current in them, and are therefore useful during image analysis. In actual practice, the over-scanned pixels in each row have some minor edge effects which are not fully characterized. The EPIC software compensates for the over-scanned pixel collection so that the transformation from pixel to position-in-scene in the processed image files is the same for all CCU read modes. It does this by placing the over-scanned pixels into the area of the pixels that were thrown away

Mechanical Properties

Refer to 2E18851 “EPIC/GSFC Mechanical Interface Drawing” for details such as envelope, mount dimensions etc. The primary frequencies are detailed in 2E19295 “EPIC Instrument Vibration Test Report”, and the mass properties are detailed in 2E19306 “EPIC Mass Properties Report”. As indicated in 2E18851, the instrument coordinate system is such that the telescope look direction, toward earth, is defined as –Y, and the direction from the telescope toward the S/C is +X.

Telescope

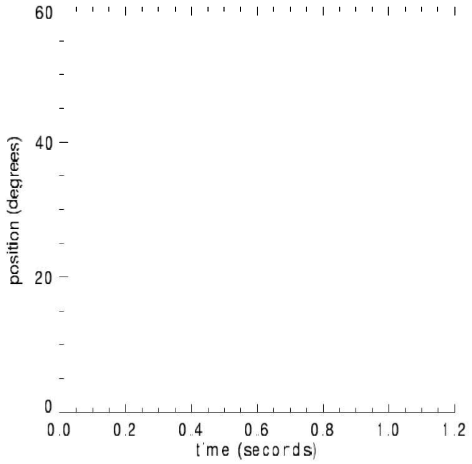
Mass: 118.0 ± 0.1 lb

Center of Gravity by analysis:
- X = -8.8" ± 0.3"
- Z = 8.2" ± 0.3" (Door Open)

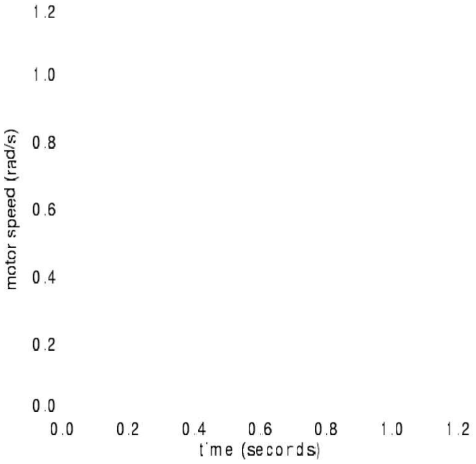
Center of Gravity by measurement:
- Y = -7.24" ± 0.05"
- Z = 7.83" ± 0.05" (Door Closed)

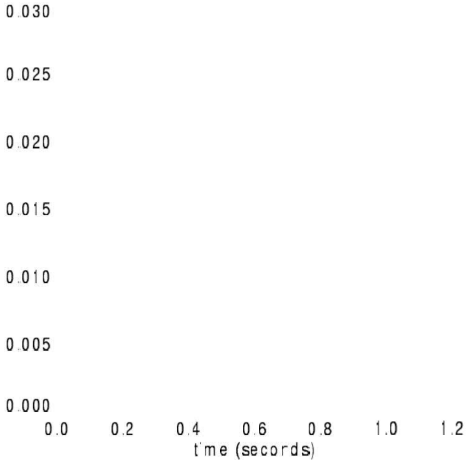
Moments of inertia (calculated, ± 12%):
- Ixx: 43.9 snail–in^2
- Iyy: 11.8 snail–in^2
- Izz: 44.4 snail-in^2
- Ixy: 0.24 snail–in^2
- Ixz: 0.20 snail–in^2
- Iyz: -0.78 snail–in^2

Primary frequency: 72 Hz


position (degrees)
60
40
20
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
time (seconds)


torque (oz-in)
2


motor speed (rad/s)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
time (seconds)


0.030
0.025
0.020
0.015
0.010
0.005
0.000
0.0
0.2
0.4
0.6
0.8
1.0
1.2
time (seconds)

Software Functionality

The 3 tasks coded by LMMS perform the EPIC hardware-specific interface: EH principally communicates with the Interface Card; EC takes high-level command input from the user and orchestrates the hardware (via EH) to perform the requested commands; ED performs the data manipulations such as pixel correction, image compression and centroid calculations.

Error handling

There are three levels of error handling in the LMMS EPIC software: command errors, software limit checking, and hardware checks.

Command errors refer to parameter range checking, inconsistent parameter exclusion, and command sequencing errors where setup and execute commands are sent out of order. These are flagged as errors and the command is ignored.

Software limit checks involve the side effects of commands. These include running out of bulk memory, failure to open files (such as Huffman tables or offset tables), and errors involved with converting between file types (such as JPEG conversions or RAW to IMG translations). Most of these checks cause warnings, and as much of the command as possible is executed before ending the command.

Hardware checks include end of travel indicators for the focus motor, confirmation of movement of the shutter and filter wheels using their encoder readings, and hardware ready bits for subsystems such as the CCU and interface board. For the suite of commands intended for regular use, a hardware error will abort the command with the appropriate reason as the error message. A secondary series of commands are available which either bypass or ignore these checks, but require additional user control of the instrument.

All reasonable conditions for error checks and handling have been included in the LMMS software. However, certain situations may arise in orbit that will require changes in the flight software (such as multiple permanent failures of hardware). All of the software can be rewritten and reloaded after launch into an alternate area of the instrument, and the spacecraft can select if the original or the new code is to be used for operations.

Hardware Control

The hardware is controlled by the EH task, sending the appropriate signals to the MEB, CCU, or interface board as needed. Unless directly commanded by the user, the EH task normally takes its direction from the EC task and the HK (housekeeping) task.

Commands from the EC usually send a sequence of operations through the EH task for complex operations. For a single picture, the shutter is first prepositioned and the filter wheels are moved to the proper location. Once the encoders have confirmed the positions of all mechanisms and the CCU and interface board reports that they are ready, the CCU is commanded to start taking a picture. Once the CCU is ready, the shutter is moved one or more times to take the exposure. Once the shutter movements have completed, the CCU data is read out through the interface board. Each of these steps uses the EC to EH interface to complete the appropriate action.

The housekeeping task periodically (about once every 5 seconds) reads the data required for the housekeeping packet using the EH task. Since the same mechanism is used to gather data for the HK task as is used to receive a periodic hardware status for the EC task, a series of two commands is used to gather this type of data. If both EC and HK require data within 10 ms of each other, only one gathering request is issued, and the same data will be sent to both systems. This avoids interference and does not delay either task.

EPIC Instrument Description

Image compression

A standard implementation of the JPEG algorithm, with 12 bit data, is the lossy compression scheme. It is expected that this will be the primary compression used on orbit, once the appropriate parameters are developed with on-orbit data. Quality factors between 1 (maximum compression, small file) and 100 (minimum compression, big file) are implemented, allowing both science quality and video broadcast quality images to be produced with minimum bandwidth requirements.

There are 2 lossless implementations that can be used. The first is to pack the 12-bit data into the 16-bit data system, reducing the data by 3/4. The second method is a lossless JPEG compression, which performs a difference on each successive data item, then uses the Huffman encoding to reduce the size of the resulting file. In addition to the methods above, the data can be averaged or decimated from 2x2, 4x4, or 8x8 grids into a single point, reducing the file size by a factor of 4, 16, or 64. Also, a reduced region-of-interest can be selected to remove excess background, further reducing the file size. EPIC will use the 2x2 averaging except for 443 nm, which will be given at full resolution.

Performance and Resource Utilization

Using the IECEPICIMGS command, the total time required to take 10 images (each using a different filter), with a one-second exposure and compress them using the lossless JPEG compression to prepare the images for transmission, is about 12 minutes. The images are taken approximately 22 seconds apart. Note that the transmission time to transfer the files from the instrument to the spacecraft, or from the spacecraft to the ground, are not part of the 12 minutes, but these activities can proceed in the background while future images are being processed.

A lossless JPEG vs a Q=100 lossy JPEG take about the same time to complete (within 1 sec, 44 sec avg.) for an Earth-type picture. A Q=1 vs Q=100 will save about 12 seconds for an Earth-type picture. Most of the time is required for reading and writing files, not the actual conversion. Reduced ROI and/or averaging/decimation is proportional to the output image size minus ~20% overhead.

The processor memory is 7 MB. Image files and related data processing files are generally stored in bulk memory, which is approximately 249 MB after the EDAC and file system overhead is accounted for. The flight code at launch does not use the bulk memory, but uses the "boot" area instead (1 MB). The uploadable "norm" (1 MB) currently only contains the EEPROM focus file (8 bytes), the Q table file (~4K), huffman tables (each ~4K), and any uploaded code (currently 1K for the "load" file which will get updated if any code is uploaded).

Images take 8.2MB+ (RAW or IMG). Converting files takes an extra 8.2MB for RAW2IMG (which is recovered immediately after the conversion when the RAW file is deleted) and another 8.2 MB (maximum) for compressing the file. RAW and IMG file creation are forced to leave about 12 MB free so this conversion can occur. Scale and/or offset files take about 8.1 MB each. Pixel correction files are 16 bytes + 9 bytes per defect. 10 images (without using the PURGE option) must have ~97 MB free to work properly.

Concept of Operations

Constraints

Instrument configuration/status constraints for individual commands are described in 2E18808 "EPIC Hardware - Software ICD". Not adhering to those constraints may cause unexpected instrument behavior, generally no more damaging than causing an image or image set from being acquired in the way the user expected.

Given required survival heater power, the EPIC instrument as a whole is generally difficult to damage in orbit. The major issues for operations personnel to keep in mind are:
1) Contamination of the optical system, forcing the door opening operation to be delayed until after major insertion burns are completed
2) Heating of the secondary mirror, the focus mechanism and its support structure when a solar load is allowed to impinge on the mechanism cover, forcing a hemisphere keep-out zone for the sun
3) Overheating the CCD caused by leaving the CCD heaters turned on
4) Enabling too many heaters too quickly when warming from a survival condition (is a spacecraft power issue, EPIC will not be damaged). In particular, the primary mirror support structure redundant heaters are applied over the top of the primary heaters, so they should not be operated simultaneously (power density issue for the foil/kapton heaters).

The focus mechanism contains fiducial switches, which are located near the end of travel. In the aft direction (increment), the focus mechanism drives into a hard stop, which is allowed. In the forward direction (decrement), the mirror's motion limit occurs when the motor drive screw backs away from the mirror leaving the flexure in its relaxed state. Eventually (100s of steps), the drive screw will also hit a hard stop. This behavior has not been tested and should be avoided.

Initial Operations

After launch, several instrument configuration changes must be made to prepare the instrument for normal operations.

At any time:
- Power up the EC and monitor status. At this point, CCD and MEB temperatures can be monitored.
- Power up the MEB and monitor status. All thermal telemetry is available, except the CCU Bias Board temperature, which is only visible when the CCU is powered.
- Power up the CCU. Images can be acquired at any time. Mode 7 images are useful for verifying command and data paths. Dark images are useful for verifying CCU/CCD operation.

Readying for imaging:
- Enable the CCD heater as appropriate to maintain approximately +20 °C. This will minimize contamination condensing on the CCD during telescope outgassing.
- Enable operational heaters to warm the telescope. With the door closed, significantly less power (lower heater duty cycle) will be required to maintain operational temperatures. At this time, proper operation of all solid state thermostats should be verified.
- Open the door. When this is done, the heater duty cycles will increase substantially, particularly for the secondary mirror system and the TCA.
- Turn off the CCD heater.
- Once operational temperatures have stabilized, verify/adjust focus as required.

Perform a calibration

Focus verification/adjustment

Prior to launch, the focus mechanism is set to the expected best focus position. It is likely, therefore, that minimal adjustment will be required on orbit. Focus verification can be performed by imaging a star scene and determining that the star spot size is approximately 1 pixel. If the spot size is too large, a series of images taken in the neighborhood of best focus (near best, ±6 steps, ±12 steps) can be used to determine the new best focus. Because of hysteresis effects in the focus mechanism drive, repeatability is optimized by approaching the desired focus mechanism position from a consistent direction (the IECFOCUSLOC command does this).

Calibration

The distortion map can be calibrated using the star field images acquired during the focus verification/adjustment. Since the distortion is radial in nature, at launch the largest expected uncertainty is the location of the center of the distortion pattern. The star field images should contain enough point sources to allow a good numeric fit. Star field images that are slightly out of focus are preferable, since the centroid of the star location can be determined with higher precision.

The radiometric response calibration should be performed periodically. Current expectation is that the lunar calibration will be performed once per month by acquiring many images of the moon and employing algorithms that compare different pixels' responses to the same area of the moon.

Radiation damage may cause pixel defects. When too many defects exist, or the CCD has condensed too many contaminants, the CCD can be warmed with its heaters in an attempt to anneal it and outgas condensed material. A radiometric calibration should be performed after cycling the CCD temperature through these extremes. Depending on past stability of the radiometric response, a calibration should also be done prior to heating the CCD, to capture a calibration baseline for previous images.

Normal operation

Data system stress analysis was performed with an assumed 10 science quality images per 90 minutes:. At least for initial operations, it is likely that at least 1 dark image per hour will be useful for understanding on-orbit instrument behavior. It is hoped that with operational experience, compression will allow more images to be acquired every hour.

There are several aspects of the instrument that are temperature dependant. The halo orbit is expected to produce slow changes in temperature of several parts of the instrument. In particular, the radiometric sensitivity has a slight dependence on CCD temperature, and the shutter has a dependence on the telescope aft end temperatures and the optimal CCU Offsets are dependent on CCU temperature. These effects are detailed in previous sections of this document.

Safe-hold

Although it is preferred to send an IEHEPICSAFE command prior to shutting down the instrument (aborts any image acquisition sequence being performed and closes the shutter), powering off the instrument with no warning does NOT cause any problems for the EPIC instrument. Using the IEHEPICSAFE command places the instrument into a configuration which is least susceptible to direct solar illumination. No relays are used in the instrument, causing all power-ups to proceed with the instrument in a known state except for the position of the filter and shutter motors. (The software maintains the focus mechanism location in EEPROM each time it is moved.) Powering off the electronics boxes and disabling all of the operational heaters will cause the instrument to cool beyond temperatures where the optical system is best characterized. However, survival heaters will maintain all temperatures above damaging limits, when they are enabled.

Recovering from safe-hold should be similar to initial operations, except that the door will already be open. It is probably unnecessary to warm the CCD for contamination issues.

Acronym List

BOL	Beginning of Life
CCD	Charge Couple Device (focal plane)
CCU	CCD Control Unit
CTA	Camera / Telescope Assembly
CTE	Coefficient of Thermal Expansion
DC	Direct Current
DN	Digital Number or Discrete Number, a digitization not yet converted to engineering units
EC	EPIC Computer
EOL	End of Life
EDAC	Error Detection and Correction
EEPROM	Electrically Erasable Programmable Read Only Memory
EPIC	Earth Polychromatic Imaging Camera
ESD	Electro-Static Discharge
FLG	Field Lens Group
FOV	Field of View
FPGA	Field Programmable Gate Array
GFE	Government Furnished Equipment
GSFC	Goddard Space Flight Center
Hz	hertz
ICD	Interface Control Document
IDL	Interactive Display Language
IR	Infra-Red light
ITOS	Integration and Test Operating System
JPEG	Joint Photographic Experts Group
LMMS	Lockheed Martin Missiles & Space
LVPC	Low Voltage Power Converter
MLI	Multi-Layer Insulation
MEB	Main Electronics Box
MTF	Modulation Transfer Function
NASA	National Aeronautics and Space Administration
PCI	a computer interface specification
PSF	Point Spread Function
QHSS	Quad High Speed Serial
RMS	Root-Mean-Squared
ROI	Region of Interest
SMEX	SMall EXplorer program at GSFC
S/C	Spacecraft
S/N	Serial Number
TCA	Telescope Containment Assembly (external metal tube surrounding the metering tube)
UV	Ultra Violet light
WFE	Wave Front E