SD-74000-100

Stardust

Navigation Camera

Instrument Description Document

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Jet Propulsion Laboratory

Pasadena, CA 91109

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1.0 Scope

This document is a description of the Stardust Navigation Camera (NC). It breaks down the NC into several functional elements, describes each, gives an overview of how the camera operates and lists the requirements that apply to the Navigation Camera.

2.0 Applicable Documents

The four following Stardust Project documents are the primary documents who's requirements drove the NC design.

Doc. No.	Doc. Name
SD-40000-200	Science Requirements Document
SD-30000-200	Project Requirements Document
SD-76000-100	Navigation Plan
SD-60000-200	Flight System Requirements Document
SD-62200-220	Nav Cam Interface Control Document

3.0 Camera Description

3.1 Navigation Camera Overview

The NC, an engineering subsystem, will be used to optically navigate the spacecraft during approach to Wild 2. This will allow the spacecraft to achieve the proper flyby distance, near enough to the nucleus, to assure adequate dust collection. The camera will also serve as an imaging camera to collect science data. The data will include high-resolution color images of the comet nucleus, on approach and on departure, and broadband images at various phase angles while nearby. These images will be used to construct a 3-D map of the nucleus in order to better understand its origin, morphology, and mechanisms, to search for mineralogical inhomogeneities on the nucleus, and potentially to supply information on the nucleus rotation state. The camera will provide images, taken through different filters, that will give information on the gas and dust coma during approach and departure phases of the mission. These images will provide information on gas composition, gas and dust dynamics, and jet phenomena, if they exist.

In order to meet these science and optical navigation objectives the NC design was developed utilizing a Voyager Wide Angle Optical Assembly. Additionally; the NC has a newly developed scan mirror mechanism to vary the camera viewing angle and a periscope to protect the scanning mirror while the spacecraft flies through the comet coma. The NC is a framing charge coupled device (CCD) imager with a focal length of 200 mm. The NC has a focal plane shutter and filter changing mechanism of the Voyager/Galileo type. The detector is a charge coupled device (CCD), cooled to suppress dark current and shielded from protons and electrons. The electronics contain the signal chain and CCD drivers (located in the sensor head), command and control logic, power supplies, mechanism drivers, a digital data compressor and two UARTs that interface with the spacecraft Command and Data Handling

(C&DH). NC command and telemetry functions will also be handled by the electronics including storage of science commands, collection of science imaging data and telemetry, transmission of imaging data and telemetry to C&DH and receipt of commands from C&DH. The NC uses a data rate of 300 kpixels/s for transferring data to the C&DH. There are also options for data reduction with 12 bit to 8 bit square root compression, windowing and error free compression within windows.

3.2 Major Functional Elements

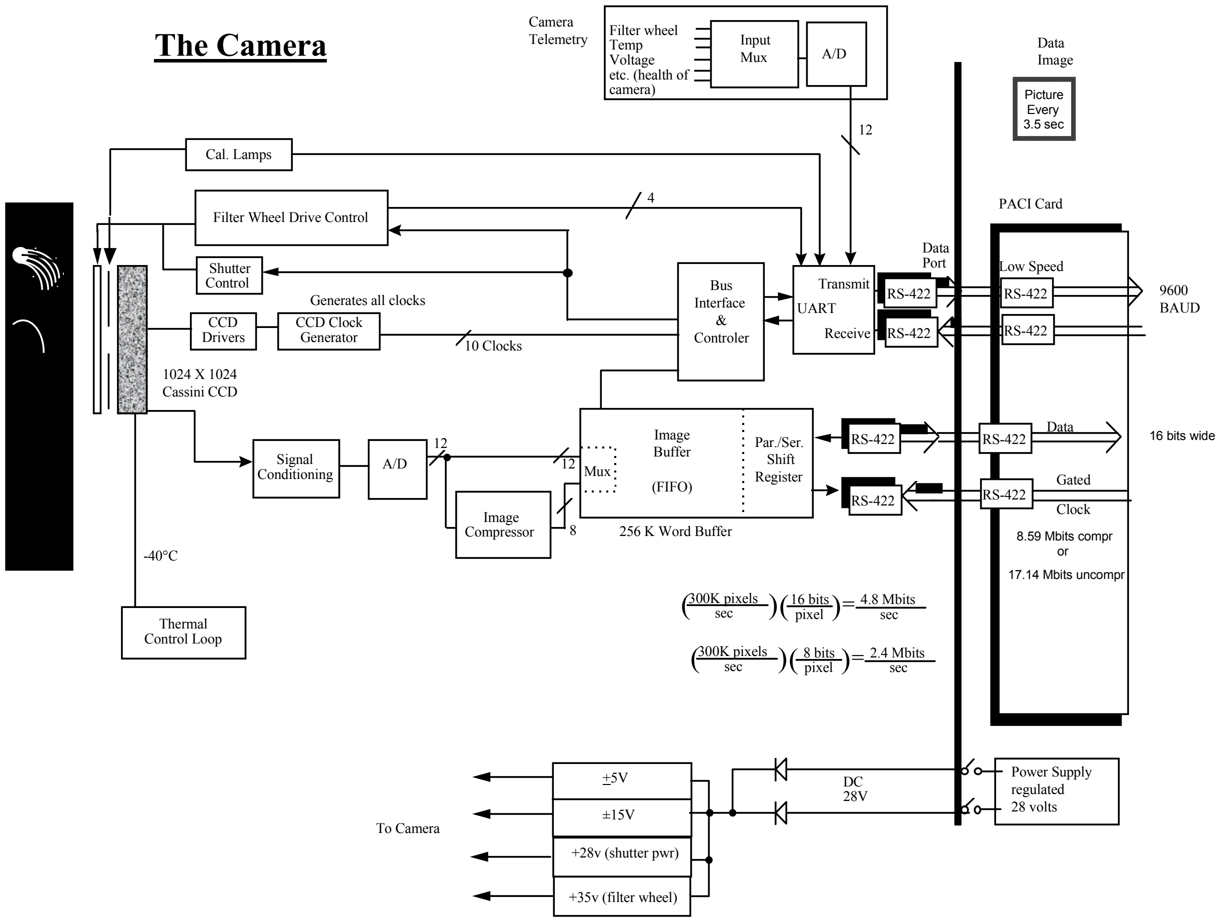
The NC consists of the following major functional elements. A functional block diagram is shown in Figure 1.

(a) Optics
(b) Filter Wheel and Shutter Mechanisms
(c) Sensor Head/Detector
(d) Scan Mirror Mechanism
(e) Periscope
(f) Platform
(g) Electronics

3.2.1 Optics

The optics subassembly is inherited hardware designed, build and tested for the Voyager Project. It is a Petzval-type refractor lens with a 200 mm focal length, f/3.5 and a spectral range 380 nm - 1000 nm. A schematic diagram of the optical design is presented in Figure TBD and the optical characteristics listed in Table 1. The optical components, with the exception of the filters, are manufactured from LF5G15 and BK7G14 materials which are radiation resistant. A new field flattener element, located in front of the CCD window, was designed for Stardust to reduce field curvature and to provide additional CCD radiation shielding. The optics are supported on three invar rods that athermalize the system to keep the camera in focus over the operating temperature range. The optical barrel assembly mounts to the filter wheel and shutter assembly utilizing an aluminum truss structure. The housing and truss are also inherited hardware from Voyager. There is a small incandescent lamp, spider mounted in front of the first lens element, that can be used for in-flight calibrations.

Because radiation resistant optical materials were used to harden the optics, the lens has a poor broad band MTF performance (axial color). The theoretical MTF for the spectral range 380 nm to 1100 nm is 30% at 32 lp/mm. The thickness of individual filters will be optimized to improve the MTF over the filters passband.



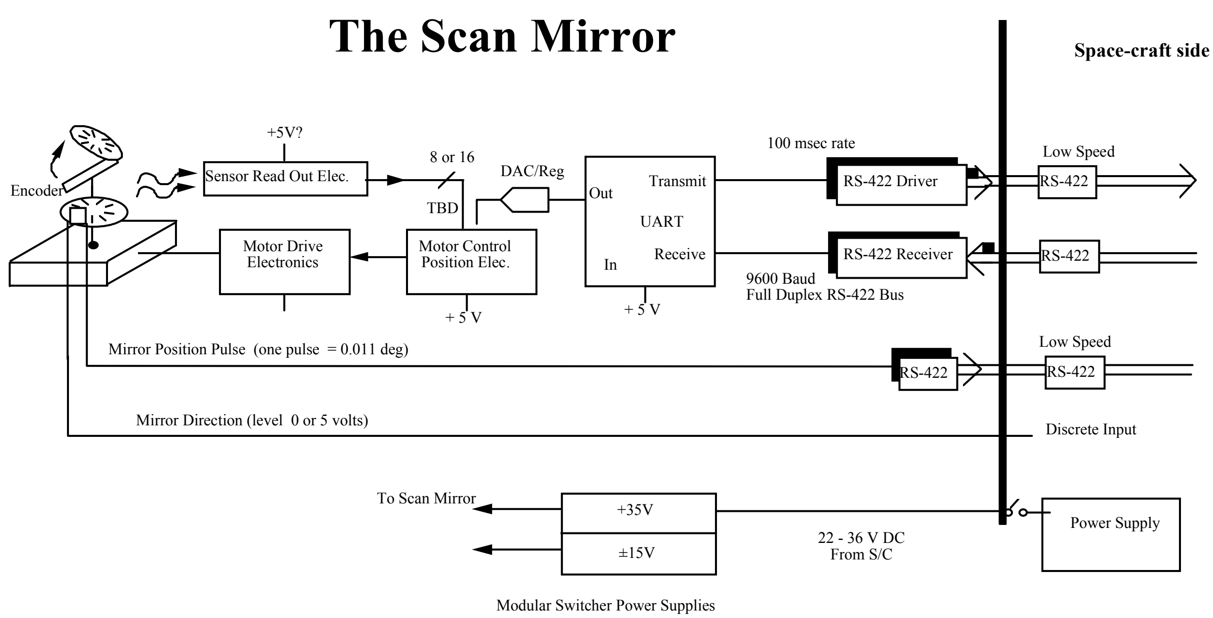


Figure 1 NC Functional Block Diagram

Table 1 Optics Characteristics

Focal length	200 mm
Relative aperture	f/3.5
Spectral Range	380 - 1100 nm
Resolution	60 microradian/pixel
Field of view	3.5 x 3.5 deg^2

3.2.2 Filter Wheel Subassembly

The NC filter wheel assembly is inherited Flight Spare hardware from the Voyager Project. The assembly contains an eight position filter wheel and a driving mechanism as can be seen in Figure 3. To actuate the mechanism a pulse is sent that energizes the linear solenoid, thereby rotating the rocker arm by means of the connector rod. The pawl, pivoted on the rocker arm, is driven toward the next wheel cog. At this point the pawl releases latch A from the cog wheel, extends the drive spring and then engages the next cog on the wheel. This puts the mechanism in the cocked position. When the solenoid is de-energized, the rocker arm and pawl are returned to there original position by the drive spring, which advances the filter wheel one filter position. During this travel the A latch follows the pawl inward and is in position to stop the filter wheel at the end of the stroke. The back latch B ratchets over the cogs, preventing the wheel from back lashing. A series of photo-diodes are uncovered by a pattern of small apertures in the filter wheel which are unique for each filter position. Thus the filter that is in the optical path is known for each image taken and is included as part of the engineering telemetry.

The spectral response of the camera is controlled by bandpass filters. The bandpass filters for Stardust will be new and will be installed into the filter wheel to replace the Voyager filters. In Table 2, the filters are identified along with some of their characteristics and their position location (TBD) in the filter wheel. Note there are 9 filters listed and only eight filter positions. If Op Nav can use the HiRes filter for navigation then the OpNav filter will not have to be flown, this will give science all 8 filter positions. If the OpNav filter needs to be flown science will have to decide which 7 science filters will fly.

3.2.3 Shutter Subassembly

The NC shutter assembly is also inherited Flight Spare hardware from the Voyager Project. As shown in Figure 4, the device is a two-blade focal plane mechanism. Each blade is actuated by its own permanent rotary solenoid. The duration of the exposure is controlled by the time interval between two pulses (an open pulse and a close pulse). The open pulse powers the “leading” blade and the close pulse powers the ”trailing” blade. The exposure sequence starts with the leading blade covering the aperture. An open pulse moves the leading blade, uncovering the aperture, and the close pulse moves the trailing blade, in the same direction, covering the aperture again. The permanent magnets in the rotary solenoid of each blade hold the blades in a detent position when the shutter is not powered. Exposures can be taken with the blades moving in either direction. A total of 4096 exposure times are available that range from 5 ms to 20 s, in 5 ms increments. There is also a bulb command, for longer exposures, that allows the shutter to be held open for any desired length of time.

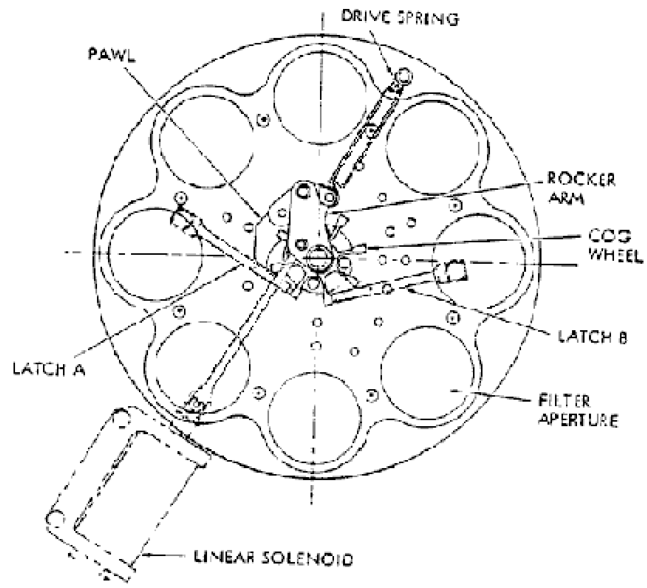


Figure 2 Filter Wheel Assembly

Table 2 Stardust Filter Characteristics

Filter Name	Central λ or Passband	FWHM	Transmission	Blocking	Wheel Position
HiRes	4900-6900	-	85%	10^{-3} : 3000-4800, 10^{-3} : 7000-11000	TBD
NIR Continuum	8800	400	70%	10^{-2} @ 8400 10^{-3} @ 9100	TBD
Yellow Continuum	5800	40	50%	10^{-2} @ 5750 10^{-2} @ 5850	TBD
NH2 Emission	6650	150	70%	10^{-2} @ 6500,6800 10^{-3} @ 6450, 6850	TBD
0[1D] Emission	6340	120	60%	10^{-3} @ 6200, 6500	TBD
Red Continuum	7128	58	70%	10^{-1}: 3000-7082 10^{-1}: 7175-11000	TBD
Blue Continuum	4450	67	55%	10^{-1}: 3000-4398 10^{-1}: 4503-11000	TBD
C2 (C2 delta v=0 band)	5141	118	65% 52%: 5099-5174	10^{-1}: 3000-5051 10^{-1}: 5230-11000	TBD
OpNav	4900-9400	-	90%	10^{-3} : 3000-4800, 10^{-3} : 9500-11000	TBD

Notes: All wavelengths are in Angstroms. There are no requirements for lambda <3000 or >11000.

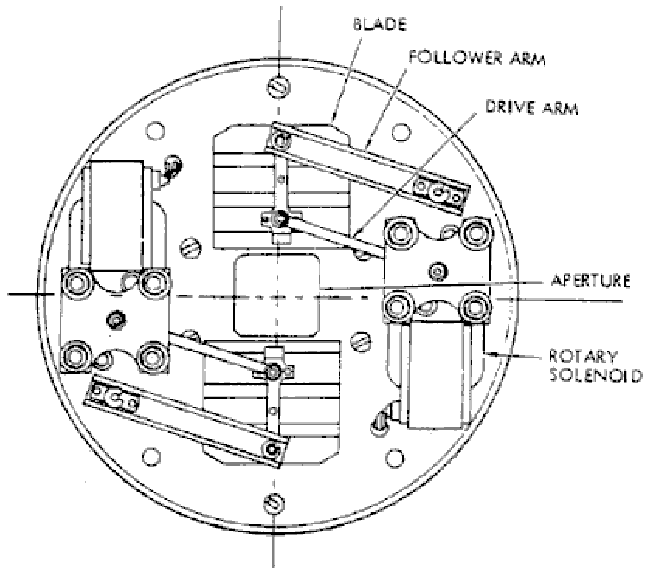


Figure 3 Shutter Assembly

3.2.4 Sensor Head/Detector

The sensor head is a subassebmly that mounts onto the Filter wheel/shutter housing and contains the focal plane for the camera. The sensor head includes the CCD, CCD structural support, CCD radiation shielding, cold finger, field flattener lens and sensor head electronics. The CCD is contained in a hermetically sealed package that is supported on a thin walled fiberglass tube. Since the CCD is relatively rad-soft it is shielded with tungsten. The tunsten shielding protects the CCD from the back and sides but a rad-hard glass (LF5G15) element, called the field flattener, adds protection over the clear aperture. The field flattener also helps remove field curvature from the optical beam. The CCD cold finger is an aluminum rod that removes heat from the CCD and dumps it into a thermal strap that is connected to a radiator mounted on the spacecraft. The sensor head structure is a square aluminum chassis contains two electronics boards and two connectors.

The NC uses a charge coupled device (CCD) detector packaged from the Cassini Imaging Science Subsystem (ISS). The operating temperature range is -60^{o}C to -30^{o}C. The CCD has the performance characteristics outlined in Table. The CCD is mounted in a hermetically sealed package which is back-filled with argon. An operating temperature of around -35^{o}C is needed for suppression of dark current and to minimize proton gamma and neutron radiation effects. The NC employs passive radiative cooling to maintain the detector operating temperature. There is a heater on the CCD cold finger that will used periodically during cruise to warm the CCD up to around 0°C. This will help anneal radiation damage that the CCD experiences during the long cruise.

Table 3 Sensor Characteristics

Format	1024 x 1024 pixels
Pixel size	12 x 12 micrometers
Full well	≥ 100,000 e^-
Dark current	< 0.1 e^-/pixel/sec at operating temperature
Charge transfer efficiency	0.99996 at operating temperature
Read Noise	≤ 15 e^- rms

3.2.5 Scan Mirror Mechanism

The scan mirror mechanism enables the stationary camera head to keep the comet in view during flyby. The scanning mirror, a flat elliptical mirror, is mounted in front of the camera lens at a 45° angle with respect to the camera optical axis. It bends the incoming light 90° into the camera lens. Rotating the mirror about the camera optical axis, at the proper rate, enables comet tracking during flyby. The mechanism is a single DOF device. It requires proper spacecraft orientation so that the comet can be viewed in a plane originating at the scan mirror and oriented perpendicular to the camera optical axis (spacecraft -Y axis). The initial forward looking view (0° position, parallel to the spacecraft +X axis) is through a periscope which protects the scan mirror from particle impacts. The total maximum mirror rotation is 220°, from -20° to + 200°; these points are the hard stops. At -18° and +198° there are micro-switches that will stop mirror rotation; these points are the soft stops. The mirror's stowed position is at the -18° soft stop where it's looking at the back of the periscope structure. The maximum rotational rate is approximately 3.1°/sec.

The mechanism consists of the following components: a cylindrical section with mirror and an anti backlash mechanism, a drive unit with motor, gearbox, slip clutch and a base. The cylindrical section is coaxial with the camera lens. It consists of the rotational housing containing the mirror and a stationary housing with an anti backlash mechanism attached to it. The sections of the housing which hold the main bearings are made from titanium to enable accurate operations over a wide temperature range. A smooth rotational motion is further assured by a duplex bearing pair, precision gears and an anti backlash mechanism utilizing a negator spring to produce a constant torque against the rotational motion. This should suppress pixel smear to less than 2 pixels. The mirror, made of zerodur, is bonded to invar flexures which attach to the rotational housing. Baffling rings along the optical path assure that stray light is being reflected away from the lens.

The drive unit next to the housing consists of a motor, gear train, and slip clutch. The motor is a brushless DC from American Electronics Inc. with Vmax=36V, T=10oz-in and n~1200rpm. This motor was previously space qualified for the MISR project. The motor is flanged onto a four stage planetary gearbox made by American Technology Consortium (e=252.6:1, η=55%). The gearbox was previously space qualified for the Mars Pathfinder project. A slip clutch at the gearbox output shaft utilizes a set of Belleville springs to keep the pinion's transmitted torque within a predetermined limit. It prevents mechanical damage in the event of control failures which might cause the mechanism to over-rotate and to one of the hard stop positions. The pinion is engaged with the main gear on the rotational part, providing a fifth transmission stage. The overall gear ratio is 2518.6:1.

3.2.6 Platform

The Camera and Scan Mirror Mechanism mount to a structural chassis called the Platform that acts as a mechanical interface with the spacecraft. The platform is a light-weighted aluminum standoff that mounts to the spacecraft - Y panel with two #10 bolts and to the - Z panel with two # 10 bolts and four # 6 bolts. The # 6 bolts mount through two titanium flexures that support two corners of the platform. These flexures allow the aluminum chassis to expand/contract relative to the composite spacecraft panels. The platform is also used as a chassis for mounting all of the camera electronics and connectors that are not located in the sensor head. The two spacecraft interface connectors J1 and J2 are located on the platform.

3.2.7 Periscope

The periscope is an optical assembly that protects the scan mirror while it is pointed forward, in a direction parallel to the space craft +X axis. This protection is from particle impingement, that would significantly degrade its' performance, during cruise, upon approach and while flying through the comet coma. The periscope contains two rectangular mirrors mounted at 40° with respect to the space craft +X axis.

The mirrors are made out of aluminum to reduce the rate and amount of degradation from particle impacting. For light weighting, the mirrors are fabricated using an aluminum foam core composite material with solid face sheets braised onto the front and back surfaces. Single point diamond turning will be used to figure the reflective surface of the mirrors. Since the forward (+ X axis) looking mirror is exposed to the impacting particles it will be post polished and receive only a very thin protected aluminum coating. This coating will also be used for the rear (- X axis) looking mirror.

The periscope structure will be a graphite/epoxy composite construction. This material was chosen to make the structure light and to reduce thermally induced distortions from the spacecraft to the periscope assembly. Each mirror will be kinematically mounted to the composite structure using three titanium triangular bipod flexures. The periscope is only utilized when the scan mirror is looking forward. After the scan mirror has rotated approximately 17° down toward the spacecraft -Z axis it no longer imaging through the periscope. The periscope was designed so that the images taken while the mirror was partly looking through periscope would still be acceptable science images and also be good enough for the spacecraft tracking algorithm to keep the comet in the scan mirror field of view.

3.2.8 Electronics

The electronics for the NC consists of two major parts the camera electronics and the scan mirror electronics. The sensor head electronics (part of the camera electronics) are mounted in the sensor head while the rest of the camera electronics and the scan mirror electronics are housed in the platform. The NC electronics control NC functions and process NC commands and telemetry. The NC electronics is powered from the spacecraft 28 volt regulated and 34 volt unregulated supplies. Table 7 lists the power operating states for the NC electronics.

3.2.8.1 Camera Electronics

The portion of the camera electronics mounted behind the camera is called the sensor head electronics. These electronics support the operation of the CCD detector and the preprocessing of the detector data; in addition they include: CCD clock generator, image compressor, image buffer, bus controller and UARTs. The pixel data is quantized to 12 bits giving an intra-frame dynamic range of 4096. Detector readout rate is fixed at 300 kpixels/s. A direct access port is included in the sensor head electronics to send telemetry to the NC ground support equipment. This port is used for ground testing only.

The remainder of the camera electronics is mounted in the platform. The main electronics provides the power and is the direct camera interface with the spacecraft through a 37 pin connector designated J1 that is mounted to the NC platform. This includes: mechanism and lamp drivers, telemetry mux and converter, and power supplies. The spacecraft specified RS-422 Bus is used for communication with the Command and Handling (C&DH). A high speed bus is used for transmission of image data and an low speed bus is used for sending and receiving commands and telemetry.

3.2.8.2 Scan Mirror Electronics

The NC scan mirror mechanism has its' own interface with the space craft. This includes a separate 34 volt unregulated power interface, a bi-directional low speed RS-422 bus for telemetry and commanding transmission, a low speed RS-422 bus for outputting for motor rotation pulses, a discrete output for motor direction. All interfaces with the scan mirror mechanism are done through one 25 pin connector designated J2 that is mounted in the NC platform.

3.3 NC Commanding

All commands are transmitted and received by the NC over the low rate RS-422 bus. Commands received by NC are echoed back to the S/C, including parity errors, so that commands with errors can be ignored. A list of NC commands is shown in Table 4.

Table 4 NC Commands

Command	States/Contents
Discrete Commands	
Camera power off	Turn camera power off
Camera power on/reset state	Turn camera power on/reset camera
Camera Function Commands	
Sample Analog telemetry	1 of 8 possible channels
Sample Digital telemetry	8 registers
Move filter wheel	1- 8 positions
Take picture (indicated exposure time)	shutter exposure and return image data/digital telemetry
Select analog telemetry channel	1 of 8 possible channels
Calibration lamp	On or Off
Data compression	On or Off
Shutter bulb mode	Open or close
CCD heater Power	On or Off
Camera Low Power State	Low or Normal Power
Scan Mirror Commands	
Sample telemetry	4 registers
Move mirror	Mirror is rotated at specified velocity
Scan Motor power	On or Off
Scan Mirror Heater	On or Off

3.3.1 NavCam Inputs and Register Description

The commands passed to the NavCam over the low rate NavCam RS-422 interface shall be:

Command Description		7 (MSB)	6	5	4	3	2	1	0 (LSB)
Execute	register #0	0	0	0	0	T_A	T_D	F_N	E_N
Shutter time, lower LSBs	register #1	0	0	0	1	E_4	E_3	E_2	E_1
Shutter time, mid bits	register #2	0	0	1	0	E_8	E_7	E_6	E_5
Shutter time, high bits	register #3	0	0	1	1	E_{12}	E_{11}	E_{10}	E_9
Telemetry mux select	register #4	0	1	0	0	x	T_3	T_2	T_1
Lamps, compression, FIFO.	register #5	0	1	0	1	F_F	F_E	C_1	L_1
Bulb Mode/ Wheel steps	register #6	0	1	1	0	B_N	W_3	W_2	W_1
Filter Wheel Position	register #7	0	1	1	1	P_P	P_3	P_2	P_1

x is a spare or unused bit location.

Register 0 allows the execution of commands as depicted in the command bits below. Only 1 bit can be set in this byte per command submission.
T_A enables the NavCam telemetry mux to sample a pre-selected analog engineering measurement, and will supply four bytes of data back to the low rate port with the value of the requested channel. The NavCam zeros this bit once the engineering data has been queued up for delivery. FSW commands with T_A=0 will be ignored by the NavCam and not clear the NavCam's value for T_A when this command is busy.
T_D enables the NavCam telemetry mux to sample all digital engineering measurements (the above registers 0 through 7), and will supply eight bytes of data back to the low rate port. The NavCam zeros this bit once the engineering data has been queued up for delivery. FSW commands with T_D=0 will be ignored by the NavCam and not clear the NavCam's value for T_D when this command is busy.
F_N enables the filter wheel to move a pre-entered number of filter positions. The NavCam zeros this bit once the filter wheel motion is complete, which is approximately 1 second per postition moved. FSW commands with F_N=0 will be ignored by the NavCam and not clear the NavCam's value for F_N when this command is busy.
E_N enables a shutter timed exposure and the read of all registers (T_D internally generated) when set to a one (1). This command takes an image with a pre-entered exposure duration. The NavCam returns the bit to a zero (0), when the shutter exposure time has elapsed and the FIFO empty bit is cleared. However if this E_N is still set 5 seconds after the shutter has closed, it will be forced to a zero (0). FSW commands with E_N=0 will be ignored by the NavCam and not clear the NavCam's value for E_N when this command is busy. This command supplies eight bytes of data back to the low rate port, and 1,073,152 8 bit bytes (for compressed images), or 2,142,208 8 bit bytes (for uncompressed images) out the high rate interface.

Registers 1, 2, 3 store the 12 bit exposure time for the shutter, bit E_{12} is the MSB. The exposure time will be 5ms * the binary number with a maximum exposure of 20.48 seconds. Taking an image with a 0ms exposure duration will take a black image without opening the shutter, which is useful for test purposes.

Register 4 selects which 12 bit analog telemetry channel is to be read back to the S/C, bit T_3 is the MSB of the register select field, and T_A is the enable. The data return is 4 bytes.

Register 5 has several bit types defined below:
L_1turns on (1) and off (0) the calibration test lamp. This bit is not set or reset by the NavCam, and the light stays on as long as the bit is a one (1); there is no enable.
C_1 turns on data compression (1), causing each pixel to be scaled to 8 bits. If zero (0), then the pixels are 12 bits each right justified with leading zeros in a 16 bit word. The NavCam does not set or reset this bit position and there is no enable command.
F_F and F_E bits are read only bits to indicate when the NavCam image FIFO buffer is empty (F_E =1) or full (F_F =1). When the buffer becomes full, pixel data is overwritten in the NavCam's FIFO. F_F is a latched value which is cleared only when E_N is set to a 1 to take a new image. In the normal course of action, therefore, the F_F delivered as a result of the E command will represent the state of the FIFO just before the new image was taken and represent the previous image's success. F_F is not latched and is set to a one (1) whenever there is no data in the FIFO.

Register 6 has bulb and filter wheel control:
B_N is a bulb enable where the shutter stays open as long as this bit is a one (1). This bit is not set or reset by the NavCam and there is no execute command enable. The bit is cleared (0) as a result of a S/C command. No picture is taken, only the shutter is controlled. To take long exposures, an E_N command must also be sent via primitive sequence commands after the desired exposure delay and B_N is cleared to zero (0).
W_3 - W_1 is the number of steps or filter wheel positions to be moved. Each step takes one second, so a three step move would take three seconds. Moving 0 steps causes no action. F_N is the enable which causes the advance by W_3 W_2 W_1 steps (W_3 is the MSB).

Register 7 contains a read-only current filter wheel position. P_3 contains the MSB, and P_1 contains the LSB. P_P contains a special even(TBR) parity bit for the 3 bit field.

3.3.2 NavMirr Inputs and Register Description

The commands passed to the NavCam over the low rate NavCam RS-422 interface shall be:

Command Description		7 (MSB)	6	5	4	3	2	1	0 (LSB)
Execute	register #0	0	0	0	0	x	T_D	x	V_N
Velocity, lower nibble	register #1	0	0	0	1	V_4	V_3	V_2	V_1
Velocity, high nibble	register #2	0	0	1	0	V_8	V_7	V_6	V_5
Motor, Heater and Direction	register #3	0	0	1	1	x	M_1	H_1	D_1

x is a spare or unused bit location.

Register 0 allows the execution of commands as depicted in the command bits below. Only 1 bit can be set in this byte per command submission.
T_D when set to one (1), enables the NavMirr telemetry mux to sample all digital engineering measurement (the above registers 0 through 3), and will supply four bytes of data back to the low rate port. The NavMirr zeros this bit once the engineering data has been queued up for delivery (<3ms).

V_N when set to one (1), enables the preenterd mirror velocity V_8 -V_1 to execute. This bit is zeroed by the NavMirr after the V_8 -V_1 bits are strobed to the DAC to execute the new mirror velocity (<=1ms).

Registers 1 and 2 preset the 8 bit desired mirror velocity, bit V_8 is the MSB. The mirror velocity time will be the 8 bit binary number * 0.0137 degrees/sec (TBR).

Register 3 has several different bit fields:
M_1 turns on the NavMirr when set to one (1), and turns off the NavMirr when set to zero (0). The NavMirr will not set or reset this bit.
H_1 turns on (1) and off (0) the NavMirr heater. This bit is not set or reset by the NavMirr.

D_1 when set to one (1), presets the NavMirr rotation to be front to back (body +x to -x), and if set to zero (0), enables the rotation to be back to front (body -x to +x). The NavMirr does not set or reset this bit.

3.4 Telemetry Collection

The NC collects pixel data, engineering data and status data. This data is divided into three categories as shown in Table 5. A list of items which have been defined as the result of science or system requirements are given in Table 5.

Table 5 NC Telemetry

Camera Analog	Camera Digital
Filter Wheel voltage	Image data
CCD Temperature	Shutter exposure time
+ 5 Volt supply voltage	Lamp status (on/off)
- 5 Volt supply voltage	Compression status (on/off)
+ 12 Volt supply voltage	FIFO status
- 12 Volt supply voltage	Filter Wheel move steps
	Filter Wheel position
	CCD Heater (on/off)
Scan Mirror	
Mirror velocity	
Scan motor status (on/off)	
Heater Status (on/off)	
Motor direction	
Motor rotation pulses (ticky marks)	

3.4.1 NavCam Status/Telemetry Outputs

The data passed to the S/C over the low rate NavCam RS-422 interface shall be:

Command Description	7 (MSB)	6	5	4	3	2	1	0 (LSB)
Analog Channel selected (1 of 8)	1	0	0	0	1	T_3	T_2	T_1
Analog lower nibble data	1	0	0	1	A_4	A_3	A_2	A_1
Analog middle nibble data	1	0	1	0	A_8	A_7	A_6	A_5
Analog high nibble data	1	0	1	1	A_{12}	A_{11}	A_{10}	A_9
Read All Registers								
register #0	1	0	0	0	T_A	T_D	F_N	E_N
register #1	1	0	0	1	E_4	E_3	E_2	E_1
register #2	1	0	1	0	E_8	E_7	E_6	E_5
register #3	1	0	1	1	E_{12}	E_{11}	E_{10}	E_9
register #4	1	1	0	0	x	T_3	T_2	T_1
register #5	1	1	0	1	F_F	F_E	C_1	L_1
register #6	1	1	1	0	B_N	W_3	W_2	W_1
register #7	1	1	1	1	P_P	P_3	P_2	P_1

where A_{12} - A_1 is a 12 bit analog value with A_{12} being the msb.
T_A will always be a 0 by the nature of the timing.
T_D will always be a 1 by the nature of the timing.

NOTE: ***All telemetry data will have bit 7=1, but FSW must resolve whether a measurement is analog or digital by the timing of the requests.***

3.4.2 NavMirr Status/Telemetry Outputs

The NavMirr only outputs digital status and telemetry data over the low rate RS422 interface. The format for reading all registers is detailed below.

Command Description	7 (MSB)	6	5	4	3	2	1	0 (LSB)
Read All Registers								
register #0	1	0	0	0	x	T_D	x	V_N
register #1	1	0	0	1	V_4	V_3	V_2	V_1
register #2	1	0	1	0	V_8	V_7	V_6	V_5
register #3	1	0	1	1	x	M_1	H_1	D_1

where T_D will always be a 1 by the nature of the timing.

NOTE: ***All telemetry data will have bit 7=1.***

3.5 Effective Data Rates

NC Electronics provides one data rate of 300 kbpxls per second.

3.6 Encoding and Compression

The pixel data from the NC can be processed within the NC in several ways. The default processing is to transmit the converted 12 bit data. When the data compression is turned on the 12 bit data is compressed to 8 bits using a square-root compression algorithm. This is accomplished via a look-up table stored in ROM.

3.7 Power Management

The camera electronics is required to draw less than 8 watts and the scan mirror less than 10 watts steady state. Operational constraints are placed on the NC to limit the power drawn by NC from the spacecraft at any one time. See Table 6 for a list of the power operating states.

Table 6 NC Power Operating States

State	Definition
Camera Off	28 volt power to the NC is off. Heaters controlled by the space craft can still be on.
Camera On	28 volt power is applied to the NC to receive commands, send telemetry and take data.
Camera Low Power State	28 volt power is applied to the NC but some camera function disabled to reduce camera power to less than 2 watts.
Scan motor Off	Power supply to scan mirror is off. Scan mirror survival heater can still be on.
Scan motor On	Power is applied to scan motor to receive commands, send telemetry and scan.

3.8 Power On/Initialization and Power Off

At power turn on, the NC registers are all set to zero. At this point the camera is in an "idle mode" with all clocks running, waiting to receive commands. The camera will remain in this state until the first command is received. The state of the mechanism will be what they were when the camera was last turned off.

3.8.1 NC Safe State

In response to a concern that the NC boresight may, in a spacecraft fault condition, be exposed to the sun (accidentally incident sunlight), a methodology to protect the shutter and focal plane of the camera was developed. The NC safe state is defined as placing a narrow band filter in the optical path and opening the shutter. To reset the NC to a normal operating state a power on reset will clear the FPGA lockup. In addition the scan mirror will kept in the stowed position when the Nav Cam is not on. In the stowed position the scan mirror is looking at the back of the periscope which will not allow sunlight directly into the camera.

4.0 Requirements

Listed below in Table 7 are all of the requirements that are flowed down to the Nav Cam from the Project Documents listed in section 2.0.

Table 7 Nav Camera Requirements

DOCUMENT	REQUIREMENT NAME	REQUIREMENT
SD-30000-200 3.3.1.1.2	Flight System to Nav Camera Interface	The Flight System and the Nav Camera shall interface per ICD SD-62200-220.
3.3.5.2.1.1	Image Rate	The Nav Camera shall be capable of obtaining and transmitting to the Flight System images at a maximum rate of one every 5 seconds.
3.3.5.2.1.2	Image Commands	The Nav Camera shall provide images of the comet through the appropriate filter as commanded by the Flight System.
3.3.5.2.1.3	Nav Camera Comet Flyby Tracking	At encounter flyby distances of 115 km to 1000 km and an encounter velocity of 6.1 +/-1 km/s, the Nav Camera shall be capable of tracking the comet nucleus using commands issued by the Flight System.
3.3.5.2.2.1	Science Camera Resolution	The Nav Camera shall have the capability to provide resolution of less than or equal to 100 m/pixel at a distance of 1500 km.
3.3.5.2.2.2	Navigation Image Resolution	The Nav Camera shall have the capability to provide a resolution of less than or equal to 60 microradians/pixel for navigation images.
3.3.5.2.2.3	Imaging Stability	The Nav Camera shall have the capability to obtain close-in images ("close-in" images are images obtained while in the coma) with maximum Flight System angular rates about each axis of 0.1 deg/s and other images with Flight System angular rates of 0.03 deg/s.
3.3.5.2.3.1	Filter Wheel	The Nav Camera shall contain an eight-position filter wheel with at least six narrow-band filters and one broad-band "clear" filter.
3.3.5.2.3.2	Clear Filter	The Nav Camera shall contain a clear filter for the 5000 to 10,000 angstrom range.
3.3.5.2.4	Nav Camera Data	The Nav Camera shall provide a 12-bit per pixel dynamic range.

3.3.5.2.5	Nav Camera Compression	The Nav Camera shall have the capability to compress data to 8 bits per pixel.
3.3.5.2.6	Camera Calibration	The Nav Camera shall have the capability for in-flight calibration adequate for 5% relative photometry.
3.3.5.2.7	Camera Mass	The Nav Camera mass, including tracking mirror and periscope, shall be 12.0 kg maximum.
4.3.1.1.3.1	Comet Imaging Verification	The ability to provide images during flyby shall be by system test of the capability to adjust the view of the camera, for unobstructed camera views, and by analysis of the flyby parameters.
4.3.1.1.3.2	Camera Pointing Verification	The ability to autonomously track the nucleus during flyby shall be verified by system test of the camera response to software generated commands and by the correct commands being given to the Flight System for roll maneuver.
4.3.3.1.1.2	Nav Camera Interface Verification	The Nav Camera interface shall be verified inspection and test
4.3.3.1.2.1.3	Camera Pointing Verification	The issuing of pointing commands to the Navigation camera by the Flight System shall be verified by systems test.
4.3.3.1.2.1.7.3	Imaging Pointing Accuracy Verification	The ability to provide navigation camera pointing accuracy shall be verified by inspection, test, and analysis. The inspections will verify manufacturing tolerances of Camera to flight system mounting and the inspection results will be combined with the analytical flight system orientation with respect to the comet flyby combined with test results on flyby tracking.
4.3.3.1.2.1.8	Image Acquisition Verification	Verification that the Flight System onboard sequences will command all required images shall be by system test of the flight software and commands issued to the Nav Camera.
4.3.3.1.8.5	Nav Camera Field of View Verification	Verification that the required Nav Camera view exists shall be by system test.
4.3.3.5.2.1.2	Encounter Image Verification	Verification the Navigation camera can obtain the required images shall be by system test.
4.3.3.5.2.1.3	Flyby tracking Verification	Verification the Navigation camera can track the nucleus shall be by system test.
4.3.3.5.2.2.1	Science Image Resolution Verification	Verification that the Navigation camera provides the required image quality shall be by analysis.
4.3.3.5.2.2.2	Navigation Image Resolution Verification	Verification that the Nav Camera has the required resolution for navigation images shall be by analysis.
4.3.3.5.2.2.3	Image Stability Verification	Verification that the Navigation camera can obtain images with specified roll rates shall be by analysis.
4.3.3.5.2.3.1	Filter Wheel Verification	Verification of Navigation camera required filters shall be by inspection.
4.3.3.5.2.3.2	Clear Filter Verification	Verification the Nav camera's clear filter is as required shall be by component test.
4.3.3.5.2.4	Image Signal Verification	Verification that the Navigation camera provides the required digital conversion shall be by subsystem test.
4.3.3.5.2.5	Nav Camera Compression Verification	Verification that the Nav Camera can provide the required compression shall be by test of the camera data handling.
4.3.3.5.2.6	Calibration Verification	Verification of the Navigation camera calibration shall be by test.
4.3.3.5.2.7	Nav Camera Mass Verification	Verification that the Nav Camera is less than the required mass shall be by direct measurement.
SD-40000-200 3.1.1.1	Near Encounter Images - During Rapid Phase Change	Provide at least 48 images through a single wideband filter during this period. The duration of this period will vary depending upon the distance of closest approach, with exposures occurring as rapidly as every five seconds, if needed (as would be the case for a 100 km miss distance, which has a rapid phase change period of 4 minutes).
3.1.1.2	Near Encounter Images -	Provide at least one image through each continuum filter before the time

	During Relatively Constant Phase	of rapid phase change and one image through each continuum filter after the time of rapid phase change.
3.1.1.3	Far Encounter Images	a.) Provide a single image to be transmitted in real time immediately before the roll maneuver to near-encounter attitude. b.) Provide images through each continuum filter, to be stored in memory for reconstruction of a color image, at the closest possible distance to the nucleus immediately before the real-time image of Section a.). c.) Provide as many images as possible through each of the filters for real-time transmission or for storage, but with the provision that stored images constitute no more than half of the space available in memory after allowing for storage of the near-encounter images.
3.1.1.4	Post Encounter Images	a.) Provide images through each continuum filter, to be stored in memory for reconstruction of a color image, at the closest possible distance to the nucleus after rolling back to normal attitude. b.) Provide as many images as possible through each of the filters to the extent that storage is available in memory. (At this time, the transmission link to Earth will be utilized solely for transmission of already stored pictures.)
3.1.1.5	Modeling Images	Provide two sets of exposures through each of the narrowband filters approximately weekly whenever communication with Earth is possible during the period of 100 days before encounter, the sets differing in exposure time by at least a factor of ten.
3.1.2.1	Camera Resolution	Provide capability for <=100 m/pixel on the cometary nucleus at a distance of 1500 km.
3.1.2.2	Camera Filters	Provide an eight position filter wheel with at least six filter positions.
3.1.2.3	Camera Dynamic Range	Provide a dynamic range of 12 bits per pixel.
3.1.2.4	Camera Calibration	Provide the capability for in-flight flat fielding frames adequate to assure at least 5% relative photometry of all images. Provide for dark current frames to check camera noise before and after encounter.
SD-60000-200 3.2.2.1.2.4.6	Nav Camera Alignment	The Nav Camera shall be aligned per the Interface Control Document for Navigation Camera (SD-62200-220) requirements.
3.2.5.1	Flight System to Nav Camera Interface	The Flight System and the Nav Camera shall interface per the Interface Control Document for Navigation Camera (SD-62200-220).
4.3.2.2.1.2.4.6	Nav Camera Alignment Verification	Verification that the Nav Camera is aligned as required shall be by measurement of the flight hardware.
4.3.2.5.1	Nav Camera Interface Verification	The Nav Camera interface shall be verified by drawing and/or hardware inspection and test
Nav Plan 2.6	Optical Navigation Camera	Optical navigation images shall be acquired with a Milstar/Cassini inherited camera with the following characteristics. CD array size: 1024x1024 pixels pixel size: 12 micro meters full well: > 100000 electrons focal length: 200 mm pixel FOV: 60 micro radians focal ratio: f/3.5 shutter speeds: 5 ms to 1 sec readout rate: 3 seconds A/D conv: 12 bit
2.12	Compression of Optical Navigation Images	Optical Navigation images shall be compressed using widowing , Rice and square root compression to assure that Optical Navigation downlink demands are compatible with other demands on the datalink.
3.2.2	Image Compression and Detectability	Image compression shall not result in the loss of information such that a star image signal to noise ratio after compression will be less than that before compression.

3.2.3	Image Compression and Image Location Accuracy	Image compression shall not result in the loss of information such that image location accuracy after compression is degraded from that before compression.
3.2.4	Requirements on Camera Image Deflecting Mirror	The single axis camera image deflecting mirror shall be placed on the spacecraft and have the range of motion to be able to allow the camera to image Wild2 free from any spacecraft structural obscurations of the scene and without the need to re-orient the spacecraft, from comet encounter -100 days to the start of the spacecraft banking maneuver.
3.2.6	Imaging Frequency for On-board Nucleus Tracking	In order to track the nucleus through closest approach on-board image processing and steering command generation need to be accomplished at a rate of at least once every 10 seconds. This is based on the 3σ values of the trajectory uncertainties given in table 2.1 (i.e. 3 times the values shown for the comet closest approach delivery accuracy).
3.2.7	Navigation Filter	A filter shall be provided for acquiring Optical Navigation Pictures. The filter shall be clear for the range of 5000 - 10000 angstroms. The filter shall not introduce chromatic aberrations which contribute more than 0.1 pixels to point source centroiding errors. Other available filters may also be used for navigation and nucleus tracking imaging.
SD-62200-220 3.1.1	Electrical Grounding	The Spacecraft to the NAVCAM and Periscope grounding is shown in Figure 3.1.1-1. The NAVCAM and Periscope shall be grounded to the spacecraft with a resistance of 2.5 milli-ohms maximum.
3.1.3.2	Connector Keying Requirements	NAVCAM connectors shall be such that it will be impossible to misconnect connectors.
3.1.4.1.1	Power Source Current Limit	a. The unregulated 34 Vdc power line shall not draw more than 3 Amps, steady. b. The regulated 28 Vdc power line shall not draw more than 3 Amps steady state.
3.1.4.2	+28 Vdc Power Requirements	The NAVCAM regulated line shall draw not more than 8.0 W, The Scan Motor shall draw not more than 10 W steady state. Peak power shall not exceed the profile shown in **TBD** and 2.5W standby from the Spacecraft's power supply (excluding heaters). Peak power occurs during closest approach to the comet.
3.1.4.3.1	Power Line Conducted Emissions	NAVCAM shall conform to the conducted emissions requirement contained in the STARDUST EMC Control Plan.
3.1.4.3.2	Power Line Current Ripple	NAVCAM shall conform to the current ripple requirements contained in the STARDUST EMC Control Plan.
3.1.4.3.3	Power Line In-Rush and Transient Currents	a. NACAM unregulated power in-rush or transient currents shall not exceed 7 amps for 100 msec (**TBR**). b. NAVCAM regulated power in-rush or transient currents shall not exceed **TBD.**
3.1.4.3.4	Power Line Conducted Susceptibility	NAVCAM shall conform to the conducted susceptibility requirements contained in the STARDUST EMC Control Plan.
3.1.4.3.5	Radiated Susceptibility	NAVCAM shall conform to the radiated susceptibility requirements contained in the STARDUST EMC Control Plan.
3.1.4.3.6	Radiated Emissions	NAVCAM shall conform to the radiated emissions requirements contained in the STARDUST EMC Control Plan.
3.2.1.7	Stow and Safing Operations	Upon entering safing mode, the narrow band filter shall be selected and the shutter shall be locked open to protect the shutter from sunshine down the boresight, then the NavCam box shall be powered off.
3.3.1.1	Envelope	The entire NAVCAM volume, including flight protective covers (if required) shall fit within the exterior envelope shown in Figure 3.3.1.1-1
3.3.1.5	Fields of View	a. The minimum NAVCAM field of view shall be 3.5^0 full cone angle as shown in Figure 3.3.1.1-1 b. Stray light field of view shall be 7.5^0 half cone angle (TBR) as

		shown in Figure 3.3.1.1-1. c. Radiator field of view shall be as shown in Figure 3.3.1.1-1
3.3.1.6	Natural Frequency	The NAVCAM/Scan Mirror and periscope, when assumed to be rigidly mounted, shall have a minimum first mode fundamental frequency of 50 Hz.
3.3.1.7	Instrument Mass	The total mass allocated by the Spacecraft to all NAVCAM elements shall not to exceed 12 kg. The nominal equipment mass breakdown by component is as follows: Camera System 9.5 kg Periscope 2.5 kg Total 12.0 kg
3.3.3.3	Mounting Accuracy	The NAVCAM shall be aligned to the spacecraft a-axis with an accuracy of 0.1°.
3.3.3.3	Mounting Knowledge	The knowledge of the NAVCAM alignment to the spacecraft shall be within 0.1°.
3.3.4	Instrument Alignment	Optical cubes shall be used for the purpose of aligning the instrument with the spacecraft coordinate system. Optical cube locations are shown in Figure 3.3.1.2-1.
3.4.3	NAVCAM Component Thermal Interfaces	a. The NAVCAM camera and motor electronics, located internal to the spacecraft structure will be maintained within the limits shown in Table 3.4.3-1 b. The maximum temperature gradient along the platform should be less than 10°C. c. The minimum turn on temperature shall be the same as the cold operating temperature limit.
3.5.2	Random Vibration	It is the Instrument Supplier's responsibility to design its equipment so that it is capable of operating satisfactorily in the random vibration environment shown in Figure 3.5.2-1.
3.5.4	Shock Environment	It is the Instrument Supplier's responsibility to design its equipment so that it is capable of operating satisfactorily in the shock environment the NAVCAM will experience during launch shown in figure 3.5.4-1.
3.5.5	Launch Loads	It is the Instrument Supplier's responsibility to design its equipment so that it is capable of operating satisfactorily in the limit launch inertia load the NAVCAM will experience as shown in Figure 3.5.5-1 Criteria: NAVCAM will not experience performance failure or detrimental deformation when subjected to yield environments and loads (yield fs = 1.25). NAVCAM will not experience mechanical failure when subjected to ultimate environments and loads (ult fs = 1.4).
3.5.6	Radiation	It is the Instrument Supplier's responsibility to design its equipment so that it is capable of operating satisfactorily in the radiation environment the NAVCAM will experience as shown in Figure 3.5.6-1.
3.5.7	Pressure	It is the Instrument Supplier's responsibility to design its equipment so that it is capable of operating after exposure to the launch pressure decay environment as shown in Figure 3.5.7-1.
4.1	Test Requirements	All NAVCAM qualification and acceptance testing shall be performed before delivery to LMA for integration with the spacecraft.
JPL D-13000-100 2.3.1	Reliability Analyses	As a minimum the following analyses shall be accomplished either by design engineers or reliability engineers: a) Subsystem and System/External Interface FMECA's b) Electronic Parts Stress c) Mechanical fault tree analysis on safety-critical devices d) Worst Case circuit analysis or Temperature/Voltage

		Margin Test (in lieu of WCA) e) Worst Case analysis of Power Supply Transients f) Selected SEE Analysis
2.3.4	Cumulative Operating Time	All subsystems shall accumulate as much operating time as possible both prior to integration and as an integrated Spacecraft. The goal is 100 hours of operating time prior to integration. and an additional 1000 hours (including System Thermal/Vacuum Testing) as an integrated system prior to Launch
2.5.2	Parts Class	Grade 2 (Class B) parts are the standard for the STARDUST Flight System. Upgrades to Grade I (Class S) shall be considered where significantly increased reliability results, known vendor issues exist, existing parts stocks improve availability, or the cost delta is negligible

Appendix A

Acronym List

Acronym	
C&DH	Command and Data Handling
CCD	Charged Coupled Device
DC	Direct Current
DOF	Degree of Freedom
FIFO	Fist In First Out
FMEC	Failure Modes and Effects Analysis
FPGA	Filed Programmable Gate Array
fs	factor of saftey
FSW	Flight Software
HiRes	High Resolution
ICD	Interface Control Drawing
ISS	Imaging Science Subsystem
MISR	Multi-angle Imaging Spectroradiometer
MSB	Most Significant Bit
MTF	Modulation Transfer Function
MUX	Multiplexor
NavMirr	Navigation Mirror
NC	Navigation Camera
Op Nav	Optical Navigation
rad	radiation
ROM	Read Only Memmory
S/C	Spacecraft
TBD	To be Dtermined
TBR	To Be Required
UART	
ult	ultimate