Solar X-ray Imager

The Solar X-ray Imager (SXI) is used to determine when to issue forecasts and alerts of "space weather" conditions that may interfere with ground and space systems. These conditions include ionospheric changes that affect radio communication (both ground-to-ground and satellite-to-ground) and magnetospheric variations that induce currents in electric power grids and long distance pipelines and can cause navigational errors in magnetic guidance systems, introduce changes in spacecraft charging, produce high energy particles that can cause single event upsets in satellite circuitry, and expose astronauts to increased radiation. SXI will observe solar flares, solar active regions, coronal holes, and coronal mass ejections. Images from SXI will be used by NOAA and U.S. Air Force forecasters to monitor solar conditions that affect space weather conditions that are used to describe the dynamic environment of energetic particles, solar wind streams, and coronal mass ejections emanating from the Sun.

The SXI, performing as a part of the Space Environment Monitor (SEM) instruments, provides the means for obtaining the solar data required to:

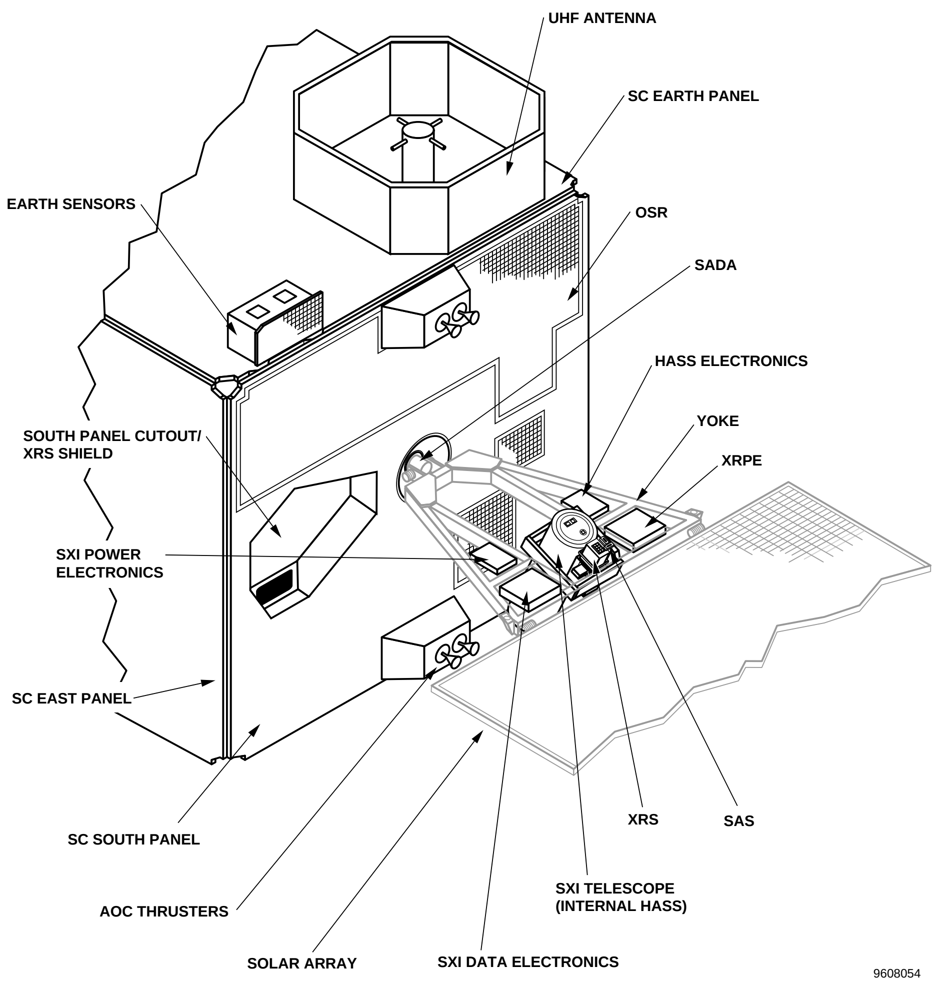
- Locate coronal holes for predicting high speed solar wind streams causing recurrent geomagnetic storms, and also locate transient coronal holes as a source of ejecta.
- Locate flares on the disk and beyond the west limb for proton event warnings.
- Monitor for changes indicating coronal mass ejections (CME) that may impact Earth and cause geomagnetic storms. Large-scale, long duration, possible weakly emitting events, and brightening of coronal filament arcades are used as evidence of CMEs.
- Observe active region size morphology and complexity, and temperature and emissions measure, for flare forecasts. Monitor for active regions beyond east limb that will be rotating onto the solar disk.

Other solar feature observations include flare properties, newly emerging active regions, X-ray bright points, and following CME ejecta at 1000 km / sec. To meet these objectives, the SXI images the solar corona in the soft X-ray to extreme ultraviolet (XUV) region of the electromagnetic spectrum. Full-disk solar images are provided with a 512 X 512 array with 5 arcsec pixels in several wavelength bands from 6 to 60 Å (0.6 to 6 nm). A regular sequence of exposures that are downlinked at one-minute intervals is used to cover the full dynamic range needed to monitor solar activity. The SXI telescope is mounted on the X-ray Positioner (XRP), and its associated electronics boxes are on the solar array yoke of the GOES-M spacecraft. The SXI is Government-furnished equipment.

THE SUBSYSTEM

The SXI consists of a telescope assembly, and three electronic boxes: the data electronics box for the instrument command and data management system (C&DMS), the power electronics box, and the High Accuracy Sun Sensor (HASS) electronics box. The electronics boxes are mounted on the solar array yoke.

SOLAR X-RAY IMAGER DESIGN



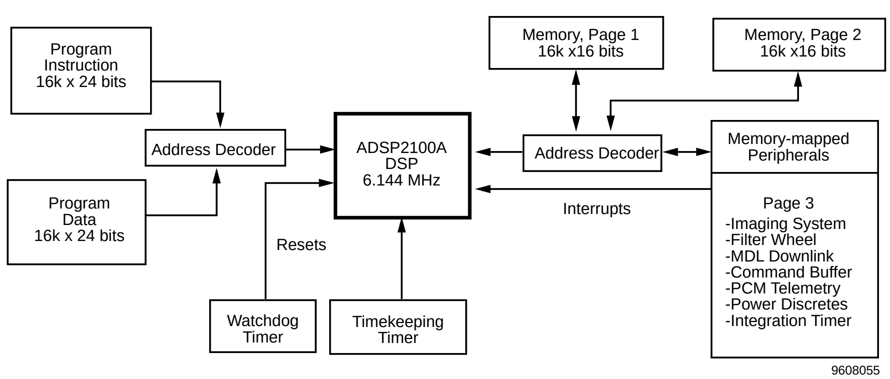
The SXI telescope is mounted to the X-ray positioner (XRP), which is a single-axis gimbal, aligned in the north-south direction. The SXI is coaligned with the X-ray Sensor (XRS) and Sun Analog Sensor (SAS), which are also mounted on the XRP. The XRP is attached to the solar array yoke. The solar array drive assembly (SADA) controls the east-west pointing of the yoke, adjusting the yoke position at a constant rate. The XRP N-S pointing is controlled during routine observations by a closed-loop control system. The solar image will drift within the field of view because the XRP and SADA do not remove all of the orbital effects and spacecraft attitude errors that affect solar pointing. Pointing adjustments to the XRP and SADA are possible through ground command.

The total mass of the SXI (telescope and electronics) is 22.7 kg, of which 14.8 kg is the telescope assembly. Electrical connections to the GOES spacecraft cross the SADA interface through slip rings and nine lines are assigned to the SXI. The SXI image and housekeeping data are interfaced to a dedicated multiuse data link (MDL) in the GOES spacecraft, capable of handling a data rate of 100 kbps, allowing a single image to be transmitted to the ground receiving station in about 36 sec. A limited amount of SXI health and safety data is provided in the pulse code modulated (PCM) data stream.

OPERATION

Operation of the SXI is controlled through the Data Electronics Box (DEB) via a microprocessor operating at 2.0 MHz. The microprocessor receives and interprets uplinked commands, controls image sequencing, processes image data, controls interface peripherals, downlinks image and housekeeping data, and keeps the internal time to a resolution of better than one ms.

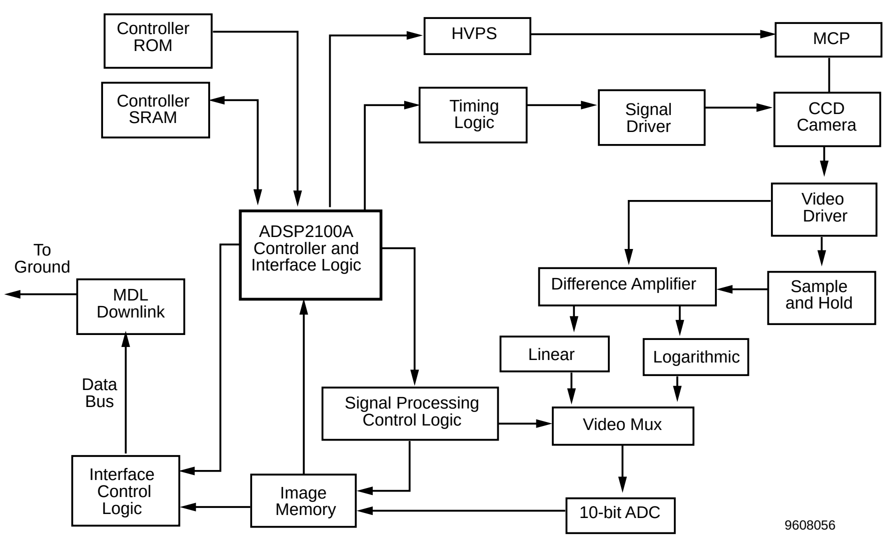
Functional Flow Diagram of SXI Microprocessor



A watchdog timer provides closed-loop recovery from single event upset (SEU)-induced errors or other anomalous conditions that may cause the instrument to enter an undesirable state. Flight software periodically strobes the watchdog timer, resetting the count, as a method of indicating continued health and functionality.

The microprocessor controls the acquisition of image data, as well as processing data and transmitting it to the ground. Based on tables stored in read only memory (ROM) or uplinked into Random Access Memory (RAM), the processor generates commands to the high voltage power supply (HVPS) and the charge coupled device (CCD) timing logic to begin an image-taking sequence. At the start of imaging, a clock in the camera is reset. The clock automatically advances the CCD one column if the exposure exceeds 333 ms, or multiples thereof, to compensate for orbital motion of the spacecraft. Once the exposure is complete, the CCD is read out at a 500 kHz pixel rate and transferred to either of two channels which provide a linear or a logarithmic transfer function. The latter improves sampling at the low end of the dynamic range. Either channel output can be selected and then passed to the input of the 10-bit analog/digital converter (ADC) in the Data Electronics Box.

SXI Control System Logical Flow Diagram



Solar X-ray Imager Performance Summary

SXI Parameter		Performance
Imaging exposure times		
Solar flare sites		<10 ms
Active regions		<100 ms
Coronal loops		<1 s
Coronal hole boundaries		<10 s
Spacecraft SXI boresight pointing (to center of solar disk)		Within 3 arc-min elevation, within 3.5 arc-min azimuth
Field of view		42 by 42 arc-min, minimum
Pixel size		5 by 5 arc-sec, squared pixels, maximum
Spectral sensitivity (integration time ≤100 ms)		
Spectral band	Source	Minimum detectable photon radiance incident on the telescope entrance (photon cm^{-2} arcsec^{-2} sec^{-1})
6 to 20 Å	Al (8.3 Å)	7
6 to 60 Å	C (44.7 Å)	132
Dynamic range		1000 when measured with mono-chromatic illumination at 44.7 Å
Telemetry amplitude digitization		10 bits (linear or logarithmic channels)
Point response (image on pixel array) Percentage of total energy incident on detector falling inside		
1 by 1 pixel		25%
2 by 2 pixel		40%
HASS resolution		±5 arc-sec or better
SXI on-orbit useful life		3 years with a goal of 5 years (after 5 years ground storage)

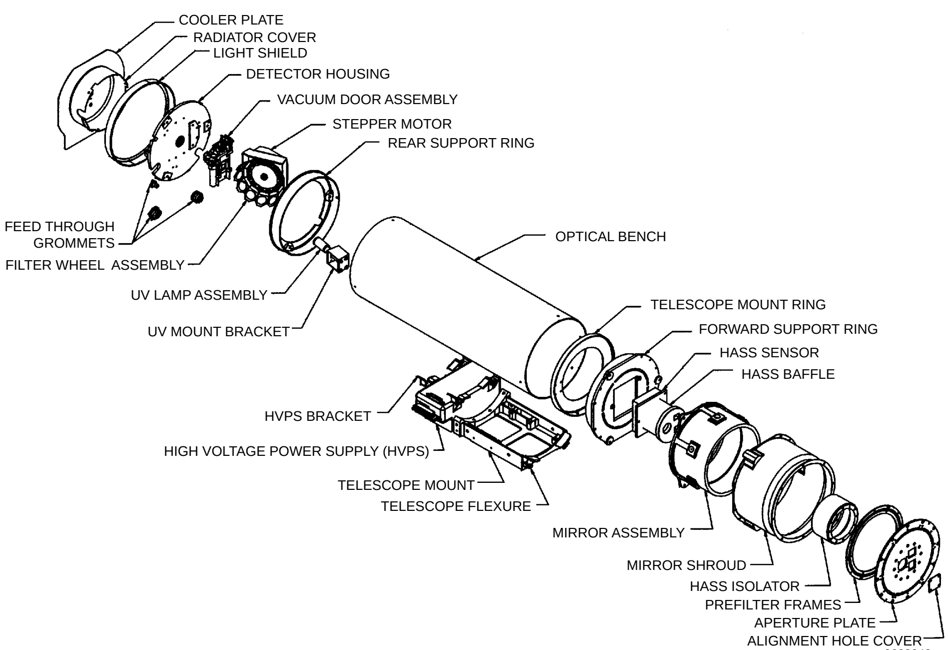
At this point, the microprocessor can select one of two modes: pixel conversion or pixel readback. In pixel conversion mode, the pixels from the CCD camera are read, passed through the ADC, and stored in image memory (static RAM). This memory has the capacity to store a complete 512 by 512 image. In readback mode, the microprocessor reads 16 bits at a time from the X-ray Pixel Processor (XPP). The lower 10 bits of each word are pixel intensity and the next two bits are parity.

One of the two parity bits is generated over the 10-bit pixel value at the time of digitization and is stored in the RAMs. The other is not and is generated at the time the data are read from the RAMs, and is generated over the 11-bit field which includes both the 10-bit pixel value and the 1-bit parity. This scheme allows any parity error to be identified as originating from a single event upset (SEU) in the memories, or an RF bit-flip during downlink. Housekeeping and ancillary data have no parity checks but are repeated several times per frame.

The data are transmitted to the ground through the MDL interface with a 100 kb/s capacity using a split phase data coding. The data are downlinked as transfer frames that are in close compliance with the Consultative Committee for Space Data Systems (CCSDS) format. These data are received directly at the Space Environment Center (SEC) in Boulder, CO. In general, image data are downlinked as rapidly as possible after they are acquired.

TELESCOPE ASSEMBLY

The basic telescope design consists of a Wolter I design grazing incidence x-ray mirror, a twelve position broadband filter wheel, and a focal plane subassembly containing an intensified MCP/CCD camera with 5 arcsec pixels.



Mirror

The mirror design consists of a Wolter Type I grazing incidence mirror in a parabola-hyperbola configuration. Both optical surfaces are fabricated from a single Zerodur element. The mirror is supported by six equally spaced titanium fingers bonded to super invar pads which are in turn bonded to the mirror. The fingers mate to a mounting ring attached to the optical bench.

Nominal Mirror Parameters

Optical design	Paraboloid-hyperboloid(Wolter I)
Radius at principal plane	8.0 cm
Axial mirror element	4.75 cm
Separation of principal and focal planes	65.0 cm
Microroughness	10Å rms (goal 5 Å rms)
Mirror material	Zerodur
Surface coating	Nickel
Geometrical area	7.3 cm^2

Optical Bench

The optical bench is both a metering structure for the optical system and a structural support member for the telescope assembly. As a metering structure, the optical bench maintains the separation between the mirror and the focal plane subassembly to ±0.001 cm over an expected temperature range of ±40˚C. The bench is hand laid up using sheets of carbon fibers impregnated with a cyanate ester resin. The bench material is highly hydrophobic and thermally stable, varying from 2.5% to less than 0.2% by weight, thereby avoiding water vapor outgassing and possible condensation on the detector array.

Focal Plane

The focal plane design incorporates three components: a microchannel plate (MCP) as the detecting element, and a phosphor-coated fiber optic taper (FOT), and a CCD. The MCP is a high output technology device of greatly improved dynamic range. The plate has 8 micron pores on 10 micron centers and is capable of a resolution of 42 line pairs/mm.

The electron avalanche from the MCP strikes the phosphor deposited on the face of the FOT. The phosphor is yttrium oxysulphide which matches the peak sensitivity of the CCD. The optical coupler provides a magnification of 1.2 which matches the plate scale of the focal plane to the CCD; i.e., the fiber pitch increases from 5 to 6 microns, changing the plate scale from 15.8 to 19 microns so that one CCD pixel corresponds to 5 arcsec. At 42 line pairs/mm, the modulation transfer function (MTF) of the taper is about 80%.

The CCD, a 512 x 512 device, has full well depths of 450,000 e^-. The practical dynamic range is of order 1000. This is achieved by adjusting the gain of the MCP so that the average signal per photon is 150 e^- (dynamic range of 300 photons). The average signal per photon of 150 e^- is well above the CCD's thermal noise level.

This configuration allows the detector to be electronically shuttered by controlling the accelerating voltage across the MCP. This voltage can be as high as 1200V and must be turned on and off with rise times on the order of 100 µs in order to accommodate exposure times as short as one ms. The voltages are generated using voltage doublers whose capacitance is much larger than the external load. The capacitance of the voltage doublers determines the rise time.

A shutdown circuit is connected across the output load and is controlled by a pulse width modulator. The signal which inhibits the modulator also activates the shutdown circuit, effectively shorting the output.

The detector assembly is contained within an evacuated titanium housing, allowing the MCP to be operated and tested on the ground. The electrical penetrations are through glass-to-metal seals, and a vacuum port is provided that can be closed with a valve. The base of the chamber is formed by a metal disk. The optical taper is bonded to a ring which mates to the detector housing with an O-ring between them.

In this configuration, the CCD and its front-end electronics lie outside the chamber, providing easier access. The forward end of the vacuum chamber contains a door that can be opened automatically but must be closed manually. The operation of the door is controlled by a paraffin actuator. The actuator is a cylinder filled with paraffin. When heated electrically, the paraffin changes state and provides the driving force for a piston. The piston lifts the door away from its seal and releases a locking pin, allowing a torsion spring to open the door.

The door contains a sapphire window which allows the MCP to be illuminated with ultraviolet (UV) light when the door is closed. The MCP is sensitive to the UV light which can be used to demonstrate functional operation during ground testing and storage. A small UV lamp is incorporated into the SXI instrument to enable functional testing and limited flat field tests to be performed before launch and in flight.

Pre-filters

Pre-filters are used to block solar ultraviolet, visible, and infrared radiation from the interior of the telescope. The pre-filters are composed of a sandwich of titanium, polyimide, and aluminum. The outermost layer is of aluminum about 1000 Å thick, which is the primary rejection element. Aluminum has a transmission window between 200-800 Å, whereas titanium is strongly absorbing in this region. A titanium layer is therefore used to suppress a very strong chromospheric line, He 304 Å, which falls in this band. The polyimide provides the strength needed to survive the acoustic launch loads.

Spectral Filtering

A filter wheel with 12 positions is provided for broadband spectral filters, with one position reserved for radiation shield. There are nine broadband filters, four made from beryllium (0.05 mm, 0.025 mm, 0.0127 mm) and five made from aluminum/polyimide/titanium (4800Å, 7300Å, 11,800Å). Of the remaining positions, one is open and the other contains a UV diffuser for use with the UV lamp. The filter system is designed to minimize the effect on the image of any non-uniformity in the filter materials. The position of the filter wheel is commandable from the ground. The filters are sized so as to not obstruct or vignette the field of view. The various wavebands are selectable by the filters in conjunction with the pre-filter.

Spectral Filtering

Position	Wavelength (Å)	Filter	Filter Material (mm)	Poly Layers (mm)
1	6 to 65	Poly thin	Al/Poly/Ti	0.003/0.0010/0.0008
2	6 to 60	Poly med	Al/Poly/Ti	0.005/0.0015/0.0008
3	6 to 50	Poly thick	Al/Poly/Ti	0.008/0.0030/0.0008
4	6 to 20	Be thin	0.0127 Be	
5	6 to 80	Open	Blank	
6	0	Radn	Radiation shield	
7	6 to 12	Be thick	0.05 Be	
8	6 to 16	Be med	0.025 Be	
9	6 to 20	Be thin	0.0127 Be	
10	6 to 60	Poly med	Al/Poly/Ti	0.005/0.0015/0.0008
11	6 to 65	Poly thin	Al/Poly/Ti	0.003/0.0010/0.0008
12	UV	UV	UV diffuser	

HIGH ACCURACY SUN SENSOR

The pointing knowledge required of the SXI is ±10 arcsec, which is met by the HASS. The HASS consists of a Sun sensor head and a Sun sensor electronics box. Various reticles and associated solar cells form the optics of the sensor head. The electronics package provides multiplexed processors for the coarse and fine Sun data, and for detecting Sun presence. The Sun angle output signals are passed through shift registers. The HASS output to the data electronics box is digital. Serial data interface circuits and control circuits provide command capability. The HASS provides pointing knowledge, but no pointing control, during image integration.

HASS Features

Field of view	±2° square
Resolution	5 arcsec (each axis)
Sampling rate	32 Hz
Stray light rejection	>10.5° from optical axis
Power	35 mA from 5 to 20 V dc bus
Mass: - Sun sensor - Electronics	 0.6 kg 1.4 kg

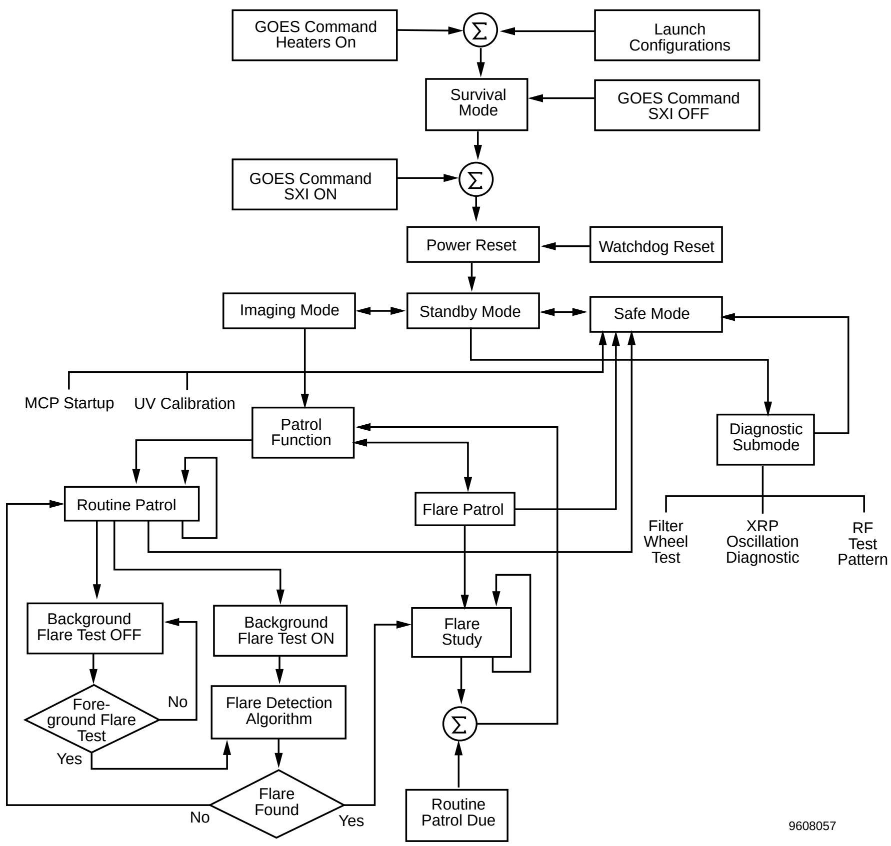
OPERATIONAL MODES

The SXI status and configuration are controlled or monitored during five operational modes.

Survival Mode

The SXI data system is unpowered and the outputs from the SXI dc/dc converters are inhibited. Survival power is provided for thermostatically controlled heaters. The temperatures are monitored by the GOES PCM telemetry system during this mode. The GOES systems provide the conditioning circuitry, with SXI providing calibrated thermistors. Temperatures monitored in this mode are mirror assembly, CCD assembly, data electronics box, and power electronics box.

SXI Control System Logical Flow Diagram



Standby Mode

The SXI defaults to this mode at power-up. The HVPS is inactive and no imaging is performed. Commands to perform diagnostics and housekeeping are allowed in this mode. Modifications to imaging tables are also allowed, and housekeeping is downlinked.

Imaging Mode

This is the operational mode for the SXI. This mode may be entered only by ground command. In this mode the SXI can:

- Image the sun
- Take UV bulb image for diagnostic purposes
- Background flux images (radiation shield in place)

Windowing

The windowing option allows selected arrays of data to be transmitted to the ground at a higher cadence than is available with the full disk downlink normally utilized. When commanded into windowing, the SXI downlinks the pixel values from up to six ground-defined windows. The size of the windows can range from 16 x 16 pixels, up to the entire CCD. (Windowing is not a mode, but an option.)

Diagnostic Mode

Diagnostics mode is entered from Standby Mode when executing the Filter Wheel Diagnostics, MCP startup, XRP Oscillation Diagnostics, and RF Test Pattern.

Safe Mode

The Safe Mode is entered either by ground command or, if a serious hardware or commanding error is detected, by software. When transitioning to Safe Mode, the HVPS is deactivated and the filter wheel is rotated to the radiation shield and disabled. The Safe Mode is used to prepare the instrument to lose power and effects a graceful shutdown of the SXI subsystems.

POWER

Electrical power is provided to the SXI via the power electronics module from the spacecraft electrical power subsystem. The electrical interfaces to the spacecraft are connections across the yoke gimbal via slip rings. The power required by the SXI is 57 watts. The spacecraft provides power to the SXI instrument from the primary bus that is regulated at 42.0 ± 0.5 V dc during sunlight operation. During eclipse, this primary power bus is controlled by battery voltage, which may vary between 29.0 and 43.0 V dc. All of the SXI power needs come from this supply.

The power source for the SXI primary input power and for its heaters is the spacecraft primary power bus. The primary bus and heater power provided to the SXI are protected with fuses within the spacecraft.

The input power consumption by the SXI is:

Sunlight: 57 W maximum from the main bus and heater bus, combined.

Eclipse: 15 W; this power represents the heater power allocated to the SXI during eclipse, to maintain SXI temperatures within allowable limits.