

THE GALILEO SOLID-STATE IMAGING EXPERIMENT

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Abstract. The Solid State Imaging (SSI) experiment on the Galileo Orbiter spacecraft utilizes a high-resolution (1500 mm focal length) television camera with an 800×800 pixel virtual-phase, charge-coupled detector. It is designed to return images of Jupiter and its satellites that are characterized by a combination of sensitivity levels, spatial resolution, geometric fidelity, and spectral range unmatched by imaging data obtained previously. The spectral range extends from approximately 375 to 1100 nm and only in the near ultra-violet region (~ 350 nm) is the spectral coverage reduced from previous missions. The camera is approximately 100 times more sensitive than those used in the Voyager mission, and, because of the nature of the satellite encounters, will produce images with approximately 100 times the ground resolution (i.e., ~ 50 m lp $^{-1}$) on the Galilean satellites. We describe aspects of the detector including its sensitivity to energetic particle radiation and how the requirements for a large full-well capacity and long-term stability in operating voltages led to the choice of the virtual phase chip. The $F/8.5$ camera system can reach point sources of $V(\text{mag}) \sim 11$ with $S/N \sim 10$ and extended sources with surface brightness as low as 20 kR in its highest gain state and longest exposure mode. We describe the performance of the system as determined by ground calibration and the improvements that have been made to the telescope (same basic catadioptric design that was used in Mariner 10 and the Voyager high-resolution cameras) to reduce the scattered light reaching the detector. The images are linearly digitized 8-bits deep and, after flat-fielding, are cosmetically clean. Information 'preserving' and 'non-preserving' on-board data compression capabilities are outlined. A special "summation" mode, designed for use deep in the Jovian radiation belts, near Io, is also described. The detector is 'pre flashed' before each exposure to ensure the photometric linearity. The dynamic range is spread over 3 gain states and an exposure range from 4.17 ms to 51.2 s. A low-level of radial, third-order, geometric distortion has been measured in the raw images that is entirely due to the optical design. The distortion is of the pincushion type and amounts to about 1.2 pixels in the corners of the images. It is expected to be very stable.

We discuss the measurement objectives of the SSI experiment in the Jupiter system and emphasize their relationships to those of other experiments in the Galileo project. We outline objectives for Jupiter atmospheric science, noting the relationship of SSI data to that to be returned by experiments on the atmospheric entry Probe. We also outline SSI objectives for satellite surfaces, ring structure, and 'darkside' (e.g., aurorae, lightning, etc.) experiments. Proposed cruise measurement objectives that relate to encounters at Venus, Moon, Earth, Gaspra, and, possibly, Ida are also briefly outlined. The article concludes with a description of a 'fully distributed' data analysis system (HIIPS) that SSI team members intend to use at their home institutions. We also list the nature of systematic data products that will become available to the scientific community. Finally, we append a short 'historical' note outlining the responsibilities and roles of institutions and individuals that have been involved in the 14 year development of the SSI experiment so far.

1. Introduction

Remote sensing experiments on the Voyager mission laid the basis for modern studies of Jupiter and its satellites some 11 years ago (Stone and Lane, 1979a, b). In 1995 a new package of experiments on the Galileo orbiter and its atmospheric Probe will reach the planet and provide a second opportunity for a substantial advance in our understanding. Along the way Galileo will have collected new data on Venus, the Moon, Earth, and one or two asteroids. Among the experiments is a high-resolution, slow-scan television camera called the Solid State Imager (SSI), which is designed to give the same angular resolution as the 'narrow-angle' camera (Snyder, 1980) on Voyager. It features a solid-state, charged-coupled device, detector of a radically different design to the SeS_2 vidicons that were used previously. As a result, the sensitivity of the camera has been increased by a factor of roughly 100; spectral coverage is extended by almost a factor of two into the near-infrared ($\sim 1 \mu\text{m}$), although the sensitivity is curtailed in the ultra-violet; the photometric response is linear and free of residual image; and the geometric fidelity of the images is ultra-stable and free of any dependency on scene

brightness gradients. Because Galileo's orbit will reduce the Galilean satellite encounter distances from the order of 100 000 km to 1000 km (some will be larger, some will be smaller), the ground resolution achievable by the camera will be increased by up to a factor of ~ 100 over Voyager. Repeated flybys of the satellites and a nominal 2-year orbital mission will allow the SSI to greatly extend the existing imaging data base in time, space, and spectral coverage.

During interplanetary cruise, the SSI experiment will return new data on Venus' clouds, extend the existing high-resolution multi-spectral imaging database on the Moon, and provide the first close-up images of at least one asteroid. At Jupiter it should take our knowledge of atmospheric phenomena into previously unexplored combinations of time and spectral coverage. Galileo's orbital tour will allow the long-term evolution of atmospheric structures to be followed at high spatial resolution, while the infra-red spectral sensitivity is expected to allow us to obtain information on the vertical structure of such features at the same time. Moreover, combined with observations from the atmospheric Probe, the SSI will extend some of the locally determined properties at the region of descent to the atmosphere as a whole. SSI observations of Jupiter's rings will not only improve knowledge of their structure and the source regions that produce the short-lived ring particles but, with extended time coverage, they may also yield new insights into their dynamics.

The SSI camera will be operated as a facility instrument in the fullest sense. It will be used to provide 'optical' navigation for essential refinements to the spacecraft trajectory and to calibrate precisely the pointing of the scan-platform. The SSI camera team also expects to provide essential pointing data to other remote sensing experiments on the Orbiter, and cooperative sequences and observations with other experiments are being emphasized.

2. The SSI Camera

A detailed description of many aspects of the camera system design and its operating modes has previously been published by Klaasen *et al.* (1984), and technical aspects of the detector and its response to energetic particle radiation can be found in Janesick *et al.* (1981). Also a preliminary report on the early inflight performance of the system is contained in Belton *et al.* (1992). In this section our intention is to provide a quantitative overview of the system for future reference, while including additional information not published elsewhere. The overall properties of the camera system are displayed in Table I.

2.1. OPTICAL SYSTEM

The optical system of the Galileo camera (Figure 1) is a modified flight spare of the 1500-mm focal length, all-spherical, catadioptric, 'narrow-angle' telescope (Snyder, 1980) flown on Voyager. Its basic design is that of the two telescopes flown on Mariner 10 (cf. Anderson *et al.*, 1978). Modifications include improved baffling to further suppress off-axis scattered light, changes to the design of the thermal coatings

TABLE I
Overview of the properties of the Galileo SSI camera

General	
Mass	28 kg
Peak power	23 W
Dimensions	90 × 25 × 30 cm ³
Optical	
Focal length	1500 mm
Field-of-view	8.1 mrad
Angular resolution	10.16 μrad pixel ⁻¹
Camera speed	<i>F</i> /8.5
	T/10.8 at 576 nm
Filter positions	8 (see Table II)
Minimum exposure time	4.167 ms
Maximum exposure time	51.2 s
Detector	
Type	Silicon Virtual Phase CCD
Dimensions	12.19 × 12.19 mm
Pixel density	65.6 pixels mm ⁻¹
Pixel format	800 × 800
Pixel full-well capacity	108,000 <i>e</i> ⁻ (normal modes)
	432,000 <i>e</i> ⁻ (summation mode)
Noise floor	± 30 <i>e</i> ⁻
Signal digitization	8 bits, 256 DN
1 DN (low gain state)	318 <i>e</i> ⁻
Gain state factors	1:4.8:9.8
Nonlinearity	0.2 DN (normal modes)
	0.45 DN (summation mode)
Charge transfer efficiency	0.99997
Dark counts	< 10 <i>e</i> ⁻ s ⁻¹ pixel ⁻¹
Frame times for operating modes	
Summation mode (2 × 2 pixel)	2.333 s
Normal modes ^a	60.667 s
	30.333 s
Full-resolution record mode	8.667 s
Tape recorder characteristics for SSI data	
Transfer rate (bits s ⁻¹)	8.064 × 10 ⁵
Maximum storage (images):	
Summation mode	478
60 ² / ₃	128
30 ¹ / ₃ compressed	257
8 ² / ₃	128
8 ² / ₃ compressed	257

^a Normal modes can either be recorded or channelled directly for real-time transmission. The summation mode must be recorded. In the normal modes the data can, if necessary, be compressed by a factor of ≈ 2.5 in either an information preserving fashion (lines may be truncated), or in a non-information preserving (lines are complete but pixel values may lose accuracy).

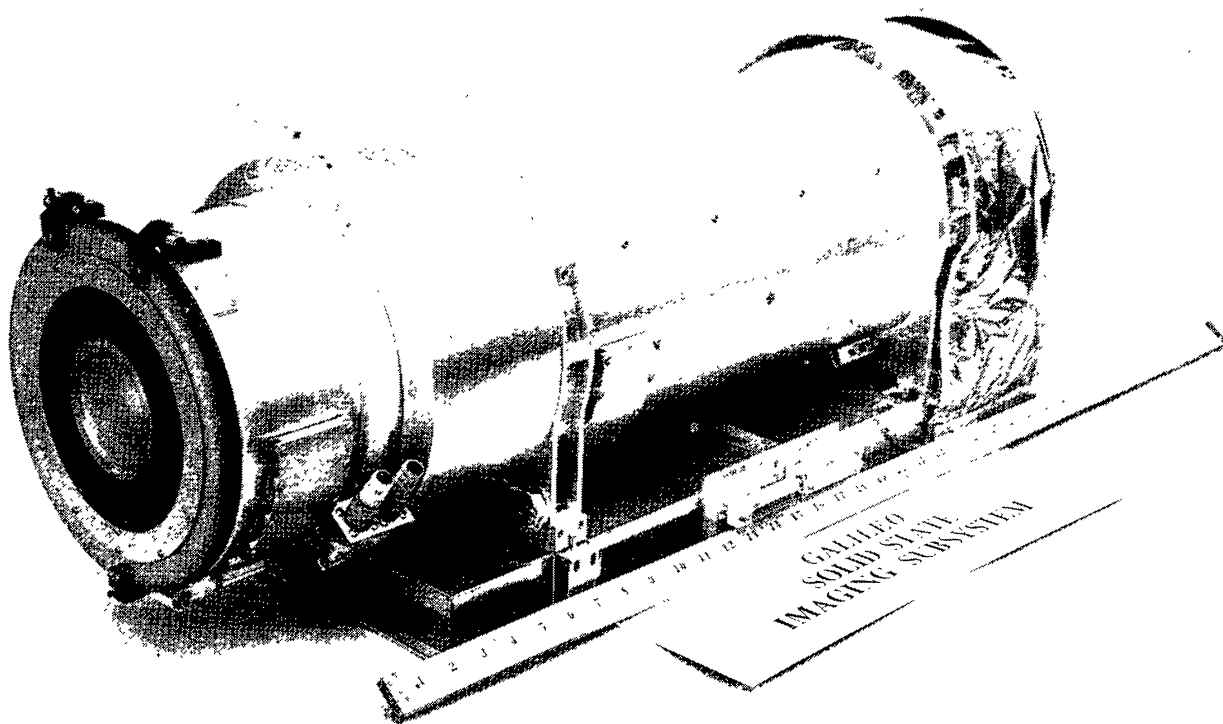


Fig. 1. The SSI camera. The entrance aperture is to the left and is shown with the protective front aperture cover in position. The SSI experiments at Venus and Earth–Moon 1 encounters were performed with the cover in place. The white cylindrical appendage to the right is the radiative cooler for the detector. Camera electronics are in the rectangular box below the main body of the telescope.

to allow for the greater spectral range of the detector, the addition of a front aperture cover to protect exterior optical surfaces from contamination in the launch environment, improved shielding of the detector from high-energy particle radiation, and the addition of a ‘pre-flash’ system used to prepare the detector for an exposure and ensure photometric linearity in the images. A ‘wide-angle’ camera was not included in the Galileo payload due to weight and budget restrictions. Thus there is no redundancy in the instruments able to make high-resolution images.

The SSI camera contains five transmissive elements plus the two mirrors (Figure 2). A front aperture cover, featuring a transparent annulus, was installed to prevent contamination of the optics during the launch phase when the camera was in the space shuttle bay. The cover will be removed before the encounter with the asteroid 951 Gaspra if flight experience indicates negligible contamination rates of exterior optical surfaces during interplanetary cruise. All optical surfaces have anti-reflective coatings, and the camera operates at $F/8.5$ with a transmission factor of 62% at 576 nm. The front

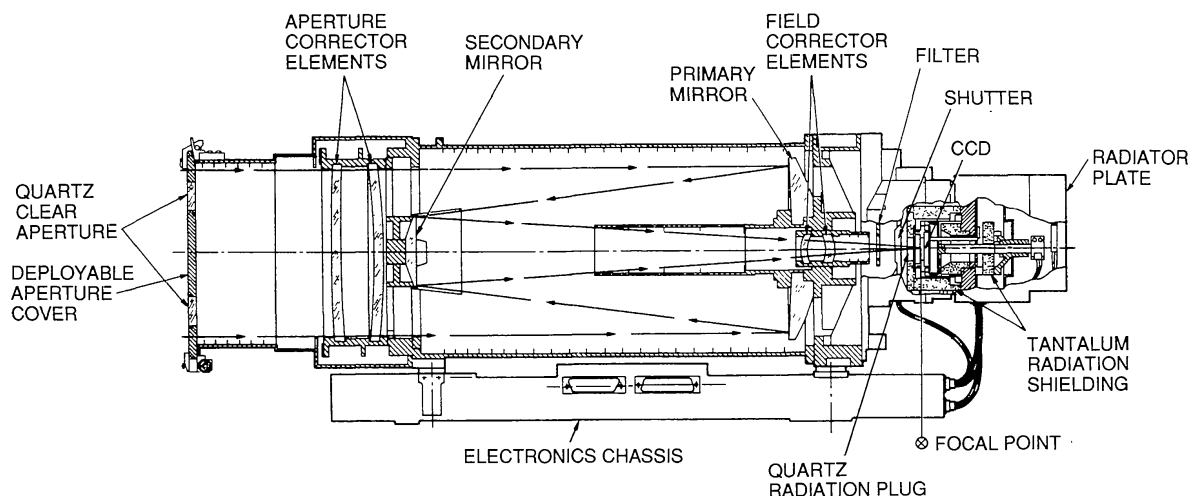


Fig. 2. Cut-away schematic of the SSI camera showing the location of the principal optical components, the particle radiation shield, and the front aperture cover.

optical element is coated to minimize radiative heat loss from the telescope, and heaters are provided to maintain thermal stability across the front aperture and within the body of the telescope. The long wavelength sensitivity limit (≈ 1100 nm) is set by the detector. The short wavelength limit (≈ 375 nm) is set by the properties of the anti-reflection coatings. Only in its short wavelength sensitivity does the previous Voyager camera have superior performance to the Galileo design. There is no analog to the Voyager 'ultra-violet' passband in the Galileo camera.

An eight-position filter wheel was also inherited from the Voyager project (Snyder, 1980). The filters were fabricated by Barr Associates and Microcoatings, Inc., and are of the interference type with out-of-bandpass absorption blocking components. The design of these filters was complicated by the combination of the wide spectral sensitivity of the detector, the desire for narrow spectral passbands, and a requirement for an identical optical thickness in all filters (the camera has a fixed focus). As a result, the filter passbands, while well defined, are far from smooth. The properties of the filters are listed in Table II and illustrated in Figure 3. The choice of filter passbands was based on the following considerations. A clear quartz filter was included to provide maximum sensitivity. The three broad-band filters – violet (404 nm), green (559 nm), and red (671 nm) provide for visible color reconstruction and compatibility with the passbands utilized on Voyager. The remaining filters were chosen to investigate phenomena in the near-infrared spectral region. There are two narrow-band filters centered at 727 nm and 889 nm that are designed to sample Jovian methane absorption bands, and there is a 'continuum' filter centered at 756 nm. Finally, a filter at 986 nm is included to both provide spectral overlap with the Near-Infrared Mapping Spectrometer (NIMS) experiment and to sample any moderately strong electronic absorption features near 1000 nm, such as are often seen in the reflection spectra of common Fe-bearing minerals.

The camera shutter is also a Voyager flight spare (Snyder, 1980). The minimum exposure time is about 4.167 ms; and 28 discrete exposures are available up to a

maximum of 0.8 s in the ‘normal’ mode, and beginning at 1.067 s up to 51.2 s in the ‘extended’ mode.

TABLE II
Filter data and SSI absolute sensitivity

Filter	Effective ^c wavelength (nm)	Passband ^d (nm)	Sensitivity ^a (W cm ⁻² ster ⁻¹ nm ⁻¹)	Sensitivity ^b (DN ms ⁻¹)
Clear	611	440	1.9 × 10 ⁷	35.0
Violet	404	45	1.2 × 10 ⁶	2.0
Green	559	65	2.5 × 10 ⁶	5.5
Red	671	60	2.8 × 10 ⁶	4.9
‘Methane’ (7270)	734	10	2.9 × 10 ⁵	0.44
‘Continuum’	756	19	5.4 × 10 ⁵	0.78
‘Methane’ (8890)	887	16	1.5 × 10 ⁵	0.17
‘Infrared’	986	50	1.7 × 10 ⁵	0.16

^a Radiance needed to produce a signal of 1 DN ms⁻¹ in the low gain state, assuming constant spectral radiance across the filter bandpass.
^b Sensitivity at 5.2 AU for a scene of unit reflectivity illuminated by sunlight.
^c Assumes a solar spectrum.
^d Full-width at half maximum.

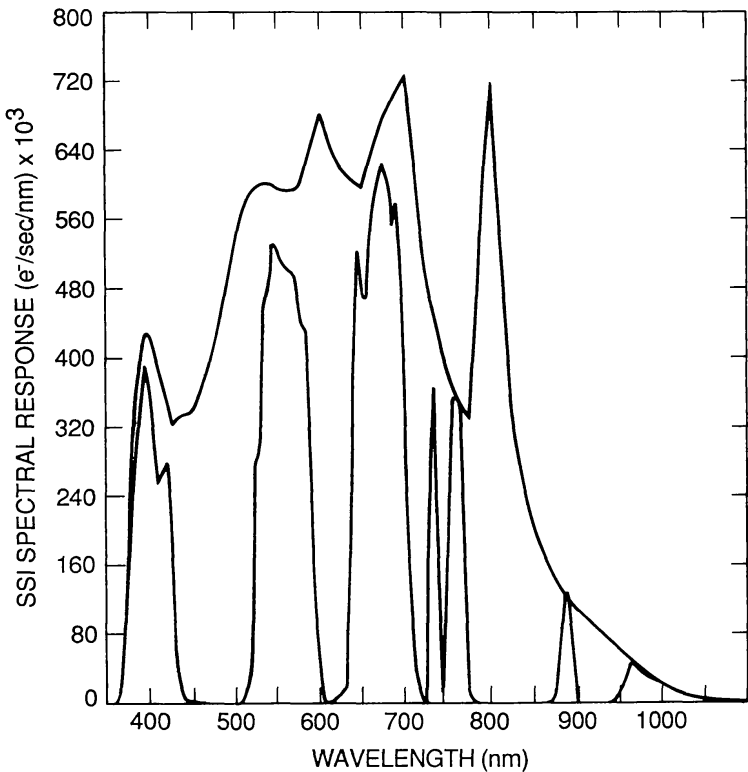


Fig. 3. SSI spectral response to a constant source radiance of π^{-1} watts m⁻² ster⁻¹ nm⁻¹ through each of its eight filters.

2.2. THE DETECTOR

The sensor (cf. Table I) is a virtual-phase ($V\phi$), buried channel, thick, frontside illuminated, 800 line by 800 column, charge-coupled, silicon device (CCD), fabricated by Texas Instruments Corporation in an experimental development program (Janesick *et al.*, 1981) that was directed by the staff of Division 38 of the Jet Propulsion Laboratory (JPL). The initial Galileo design called for a 3ϕ detector of the type that was subsequently incorporated in the Wide Field/Planetary Camera on the Hubble Space Telescope. However, at the time of the Galileo flight hardware development (1978–1982), difficulties in fabricating 3ϕ chips with full-well capacities exceeding $\approx 30\,000\,e^-$, and the discovery that the 3ϕ technology was susceptible to irreversible damage at the levels of particle radiation expected in orbit about Jupiter (see below), caused the SSI to switch to the development of a chip based on $V\phi$ technology. Many thousands of experimental $800 \times 800 V\phi$ CCDs were built for Galileo; however, the yield was such that only two chips were finally judged acceptable for flight. One of these, No. 29, is now on its way to Jupiter, and its characteristics are summarized in Table I.

The $V\phi$ CCD employs a polysilicon gate structure with $15.2\,\mu\text{m}$ center-to-center spacing between pixels. During image read out, all 800 lines are simultaneously shifted one line in the column (parallel) direction causing the first image line to be shifted through a transfer gate into the serial output register. The first image line is then read out through an on-chip amplifier. The line read out rate (and therefore associated read out noise) is identical for all of the SSI operating modes. This procedure is repeated until all 800 lines have been readout. Important characteristics of the $V\phi$ CCD are:

(1) Image geometry which is independent of scene brightness gradients. Unlike earlier planetary camera systems, the SSI will have no *reseaux* (fiducial marks) impressed on the images.

(2) Linear photometric response to incident light. This property greatly simplifies the systematic calibration of the raw images.

(3) High charge transfer efficiency of ~ 0.99997 (Klaasen *et al.*, 1984), which ensures photometric linearity at low light levels.

(4) A high quantum efficiency and low read out noise which makes the SSI approximately 100 times more sensitive than the equivalent Voyager camera.

(5) Wide spectral range. The $V\phi$ CCD has appreciable sensitivity to light out to 1100 nm. This compares favorably with the long wavelength cut-off of earlier planetary cameras near $\approx 650\,\text{nm}$.

During ground calibration tests it was found that read out of the chip did not completely remove the effects of a previous exposure to light at wavelengths $> 650\,\text{nm}$. A faint 'residual image' was impressed on the photometric response of the chip to a succeeding exposure. In order to prevent this effect from corrupting the photometric accuracy of the data, the camera operation was modified so that prior to each exposure the chip is 'pre-flashed', i.e., bathed in near-IR ($\sim 930\,\text{nm}$) light from several photodiodes placed around the chip, and then read out several times at high speed. This preparation cycle is found to remove all traces of previous exposure thistory. Details and an explanation of this phenomenon can be found in Janesick *et al.* (1984).

Much of the hardware incorporated into the SSI camera is equipment left over from the Voyager project. While this approach, which was dictated to the Galileo project, has possibly saved some expenditures – it has also restricted the scientific potential of the SSI experiment. For example, eight filter passbands are insufficient to adequately cover the spectral range of the SSI detector with the result that there are gaps in the spectral coverage; the thermal design of the telescope is in conflict with the requirements for a cold detector (SeS₂ vidicons were operated near ‘room’ temperature) and this is a contributory reason why the SSI lacks the ultra-violet sensitivity of the Voyager cameras; in addition the 8-bit linear encoding of the signal is not well matched to the dynamic range available with a CCD and will lead to the presence of digital ‘contouring’ in certain types of low contrast images. Nevertheless, in spite of these difficulties, the basic sensitivity, linearity, and geometric fidelity of the SSI camera is so great that it is expected to create images that are vastly superior to those obtained in previous planetary missions.

2.3. PARTICLE RADIATION HAZARDS

The effects of the irradiation of the camera by high-energy particles in the Jovian magnetosphere and by the flux of neutrons from the Galileo radioisotope thermoelectric generators (RTG’s) are expected to be severe (Janesick *et al.*, 1981; Klaasen *et al.*, 1984) and, during the development of the SSI, several tests were performed to quantify them. In the first, which used a Co⁶⁰ source, the effects of γ -ray and high-energy electron impacts on candidate 3ϕ devices were investigated at fluence levels expected to be reached during the orbital tour. The CCD, as shielded in the SSI, is predicted to receive a dose of ~ 900 rad (from fluences of $\sim 4 \times 10^{10} e^- \text{ cm}^{-2}$ and $\sim 2 \times 10^7$ protons cm^{-2} with energies above 100 keV) by the end of five orbits about Jupiter. Passage of a high-energy charged particle through the SiO₂ epitaxial layers, which function as insulators between the various 3ϕ gate structures, produces local ionization and possible breakdown in their insulating properties. The observed result was an unacceptable, dose dependent, change in the applied ‘flatband’ operating voltages which control the full-well capacity and the charge transfer efficiency characteristics of the device. In one case, major physical damage occurred and resulted in a large permanent blemish that covered thousands of pixels. It was on the basis of this experiment that the decision was made to switch from the 3ϕ to $V\phi$ chip. Since the latter has only a single gate structure, it is expected that it will be far less susceptible to these effects. $V\phi$ CCD’s were tested to fluences of 10^8 protons cm^{-2} (at 10 MeV) and $7.5 \times 10^{10} e^- \text{ cm}^{-2}$ (at 2.5 MeV) without suffering any unacceptable permanent damage. In addition, a modification to the camera design was made to increase the radiation shielding around the detector. The CCD is encapsulated in a tantalum cavity with 1 cm thick walls. A 0.5 cm thick quartz ‘plug’ was also placed in the optical path directly in front of the sensor.

Although well protected, the $V\phi$ CCD is still an excellent particle detector, and calculations showed that within $10 R_J$ (Jupiter radii) the chip might easily approach full-well saturation in the time (60.667 s) it takes to read it out in the normal, real-time mode. Tests were therefore made to quantify the effects of the expected particle fluxes

on the quality of the images and, in particular, to understand how the camera might operate at $5 R_J$, near Io (cf. Figures 4(a) and 4(b)). A Sr^{90} source of energetic electrons was used, and it was found necessary to increase the maximum read out rate of the detector by a factor of four in order to assure satisfactory operation at Io. The frame time in this special mode is 2.333 s, and in order to match the read-out rate of the camera to the on-board tape recorder, it was necessary to reduce the image format by the same factor. The SSI team chose an option in which adjacent pixels in the image are summed (one 'summed' pixel equals four mutually adjacent pixels; the resulting image is then in a 400×400 pixel format) during the read-out of the chip. This is referred to as the 'summation mode' (Table I). The images at Io are expected to contain a background signal, formed by radiation 'hits' that reaches a maximum of about 8 data numbers (DN) in the summation mode. At $15 R_J$, which is the orbital radius of Ganymede, individual radiation 'spikes' will be present in the images at a rate of about 10^4 frame^{-1} in the 8.667 s mode. The amplitude of the average spike is expected to be about 4 DN in the low gain state.

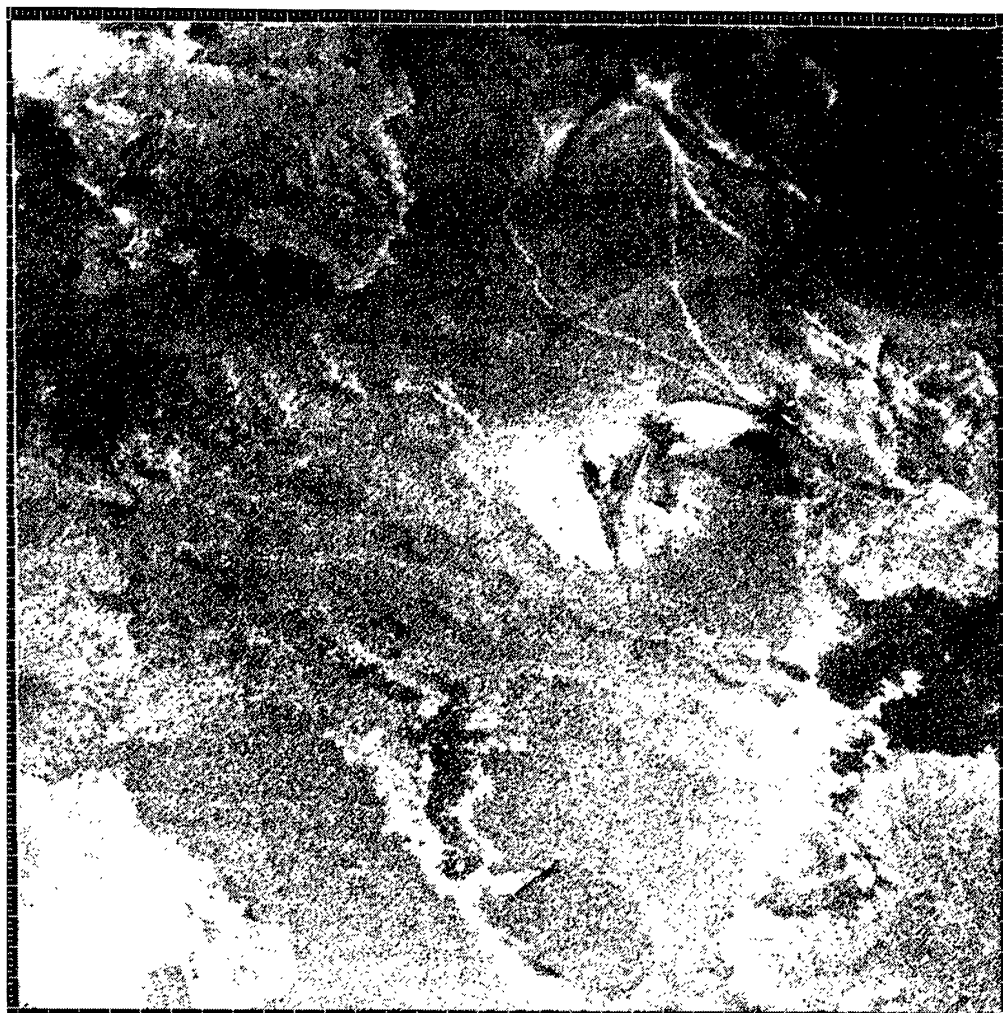


Fig. 4a. Simulation of an Io picture taken by the SSI in the 8.333 s mode showing the anticipated effects of magnetospheric particle bombardment. Because of the low S/N of the picture, the SSI will image Io in the 2.13 s 'summation' mode (see text).

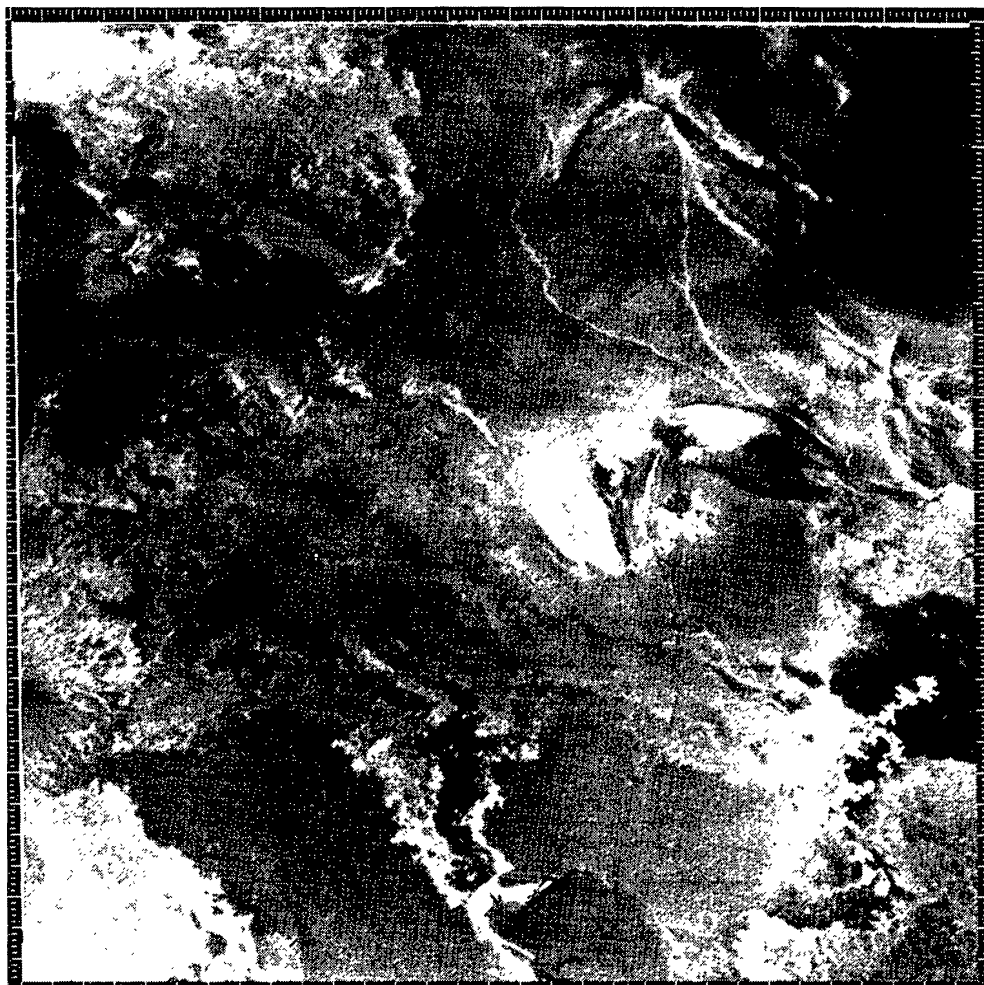


Fig. 4b. Same as Figure 4(a) but without the effects of energetic particle irradiance.

A further, insidious source of particle radiation is the spacecraft RTGs, which produce a steady flux of neutrons. These particles cause irreparable dislocations in the lattice structure of the detector material which can then act as sites for the copious thermal production of charge. These sites are sometimes referred to as 'hot pixels' or 'dark spikes' in the images. To quantify this effect, the Northrop Corporation's Triga reactor was used as a neutron source to simulate the dose expected from Galileo's RTGs. As expected, lattice displacement damage was observed to occur and permanent 'dark spikes' were produced in the output images. To ameliorate the effects of this unavoidable phenomenon, the operating temperature of the detector was reduced from -70°C to -110°C by enlarging the thermal radiator. Lattice dislocations are expected to occur at a rate of about 10^5 yr^{-1} and are expected to slowly reduce the charge transfer efficiency of the flight chip. However, its operating lifetime is expected to far exceed the duration of the nominal Galileo mission.

The fact that the $V\phi$ CCD is sensitive to particle radiation is the price that must be paid for increased quantum efficiency and spectral range. Already during an inflight checkout of the camera, and in a later 'mini-calibration sequence', we have seen the

deleterious effects of cosmic rays and energetic particles of solar origin in the images (Belton *et al.*, 1992). However, because of the tests and modifications described above, the hardware is expected to return excellent images throughout the nominal mission.

2.4. GROUND CALIBRATION AND PERFORMANCE

The process of calibrating the images involves three basic steps. First the zero-exposure bias in the signal is subtracted. This is followed by the removal of small pixel-to-pixel variations in sensitivity (fixed-pattern noise) by division of the image by a second image (a 'flat-field') of a uniformly illuminated, extended source. Finally, the signal in the images is placed on an absolute scale through the application of factors that are determined in ground calibrations. It is intended to update the absolute calibration during the flight mission through a program of inflight calibration sequences.

The performance characteristics of the camera have been thoroughly evaluated. Figure 5 shows a typical flat-field image. The dark circular 'donuts' are shadows of small, $\sim 10\ \mu\text{m}$ in diameter, dust specks, most of which are located on the surfaces of

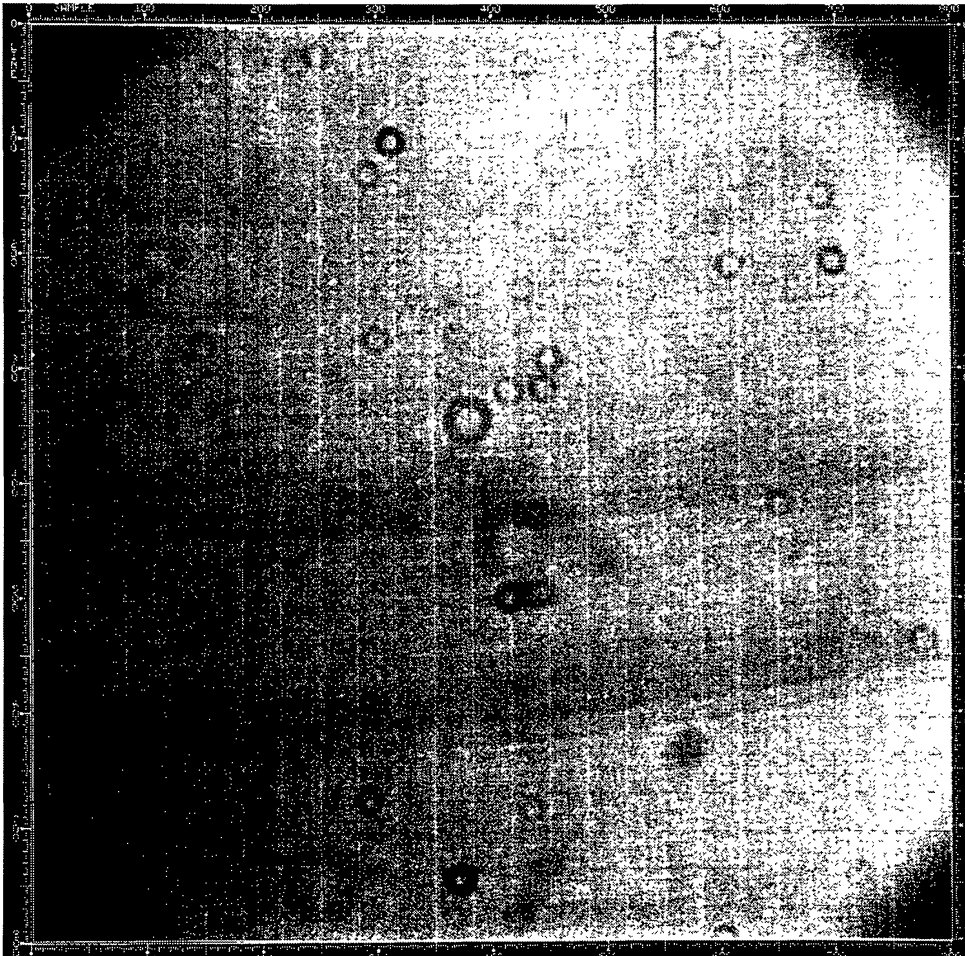


Fig. 5. Contrast enhanced image of a flat field target which shows the non-uniformities in the camera response. The circular features are shadows of dust particles on the window of the detector package. These features are completely removed from the images after flat-field calibration (see text). The picture has been contrast enhanced by a factor of 25 in order to bring out the non-uniformities.

the window of the detector package. The darkening at the corners of the image is due to a slight vignetting of the field-of-view by the filter aperture. The light vertical columns, which occur every 33 pixels, are due to an increased pixel area in these columns. This, in turn, is an artifact of the step-and-repeat photolithographic technique that is used in fabricating the $V\phi$ CCD.

The mechanical shutter was shown to be very repeatable. Actual exposure times were found to be slightly less than the commanded time by about 1.2 ms, averaged across the frame. This shutter time offset varies from about 1.5 ms at the top of the frame (line 1) to about 1.05 ms at the bottom (line 800). When the shutter offset is properly taken into account, the SSI response to a fixed source radiance over a 50×50 pixel test area in the center of the image was found to be linear with exposure time to better than 1% over its entire dynamic range.

The absolute sensitivity of the system through each filter was determined to an accuracy of about 10% and is shown in Table II. Also listed is the SSI sensitivity to a scene normally illuminated by sunlight at a distance of 5.2 AU (Jupiter's distance from the Sun) at zero phase, assuming unit reflectivity. The signal from each pixel is encoded linearly into 256 DN (data numbers). The portion of the CCD dynamic range that is actually encoded is determined by the settings of two commandable gain switches in the SSI signal processing electronics. Table II is computed for the 'low' gain state in which one DN equals $380 e^-$. The gain can be increased (i.e., the number of electrons per pixel decreased) by factors of 4.8 or 9.8 on command. Full-well is at about $108\,000 e^- \text{ pixel}^{-1}$. Figure 3 shows the overall SSI system spectral response function for each filter position.

The camera sensitivity is such that, for unresolved objects, it can detect a solar-type star with $V = 11$ mag at a $S/N \sim 10$, through the clear filter in the high gain state. On extended targets, it can reach surface brightnesses down to 20 kilorayleighs at 60 nm using the longest available exposure.

The radiometric response has been calibrated for every pixel in the CCD array and with the exception of a few blemishes, the spatial nonuniformities in response across the array can be corrected using a linear calibration function. Figure 6 shows the calibrated version of the flat-field image in Figure 5. Note that all traces of dust shadows, corner vignetting, and the step-and-repeat pattern are completely removed. Most of the remaining blemishes are located in columns 1, 2, and 170 and rows 799 and 800. Also, nine columns were found to contain pixels that have lower than average full-well capacities. These, under certain conditions, can lead to 'bad' columns in the output image. Because they have a limited charge transfer capability (in the range from 30 000 to $85\,000 e^-$), images that have high average signal levels may show bad, or partially bad, columns as a result of these low-full-well pixels.

Raw 'dark' (i.e., unexposed) images have a random noise level of about ± 0.95 DN in the highest gain state (equivalent to about $\pm 40 e^-$) and a coherent noise level of about ± 0.35 DN. The random component is primarily due to spurious charge generation produced in the $V\phi$ CCD during clocking. The level of this component stays at the same level in all of the readout modes (for a particular gain state) since the line

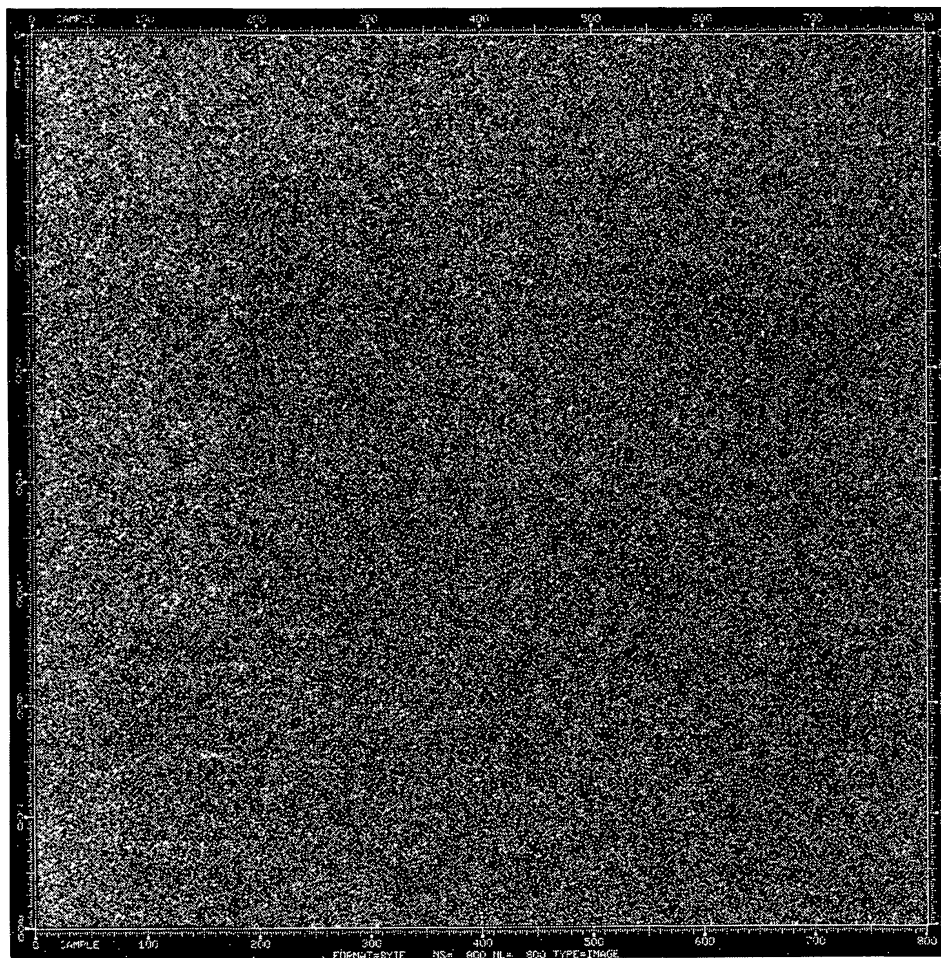


Fig. 6. Contrast enhanced image of a flat-field target after calibration. In this case (compare Figure 5) the picture has been stretched by a factor of 65.

clocking rate is independent of the mode. Thermal generation of charge at SSI operating temperatures is negligible. The primary source of coherent noise is the spacecraft power supply (at 2400 Hz). This shows up as a very faint pattern of vertical stripes in the images spaced 42 pixels apart. However, the amplitude of the coherent noise is small enough that it will not normally be visible in the images. The random noise component noted above includes the effects of CCD spatial sensitivity variations and blemishes. The noise level in a high-gain dark frame was found to be reduced to ± 0.82 DN by the calibration process, and the coherent noise is reduced to ± 0.17 DN. This is equivalent to the theoretical level expected for a CCD with a read noise of $\pm 31 e^-$, combined with a quantization error of ± 0.37 DN, a residual uncalibrated component equal to 0.78% of the mean signal level. In the lower gain states, the uncalibrated component is found to be smaller (around 0.3%).

Quantization noise was found to be larger than the theoretical level of ± 0.29 DN expected for a perfect analog-to-digital converter (ADC). The flight ADC exhibits some unevenness in the widths of its DN bins, particularly for DN levels that are multiples

of 8. By adjusting the SSI output DN levels by fractions of a DN in the calibration process, the quantization error can be reduced to about ± 0.31 DN.

The SSI shutter was tested for light leakage and was found not to be perfectly light tight; approximately 10^{-7} of the incident light is transmitted when the blades are closed. This is equivalent to a signal level of about $300 e^- \text{ min}^{-1}$ if it is assumed that the camera is pointing directly at Jupiter at 0° phase angle in the clear filter.

The achievable spatial resolution is illustrated in Figure 7. Unaliased contrast is

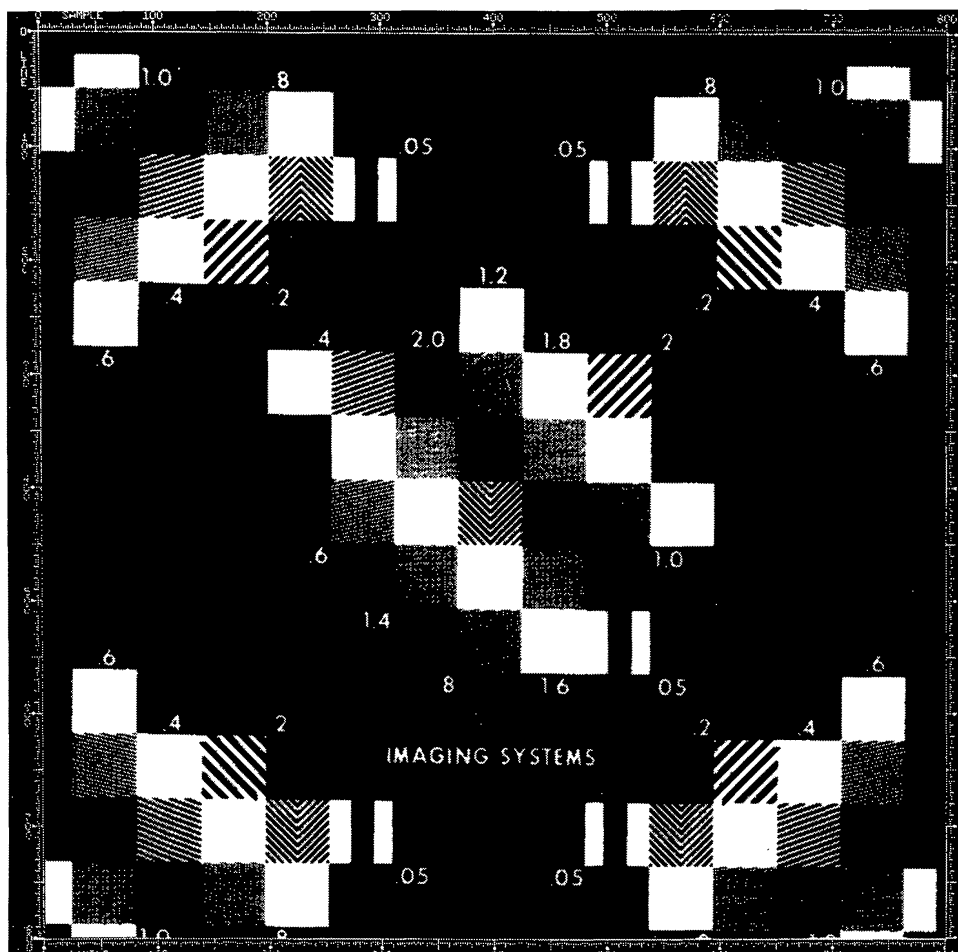


Fig. 7. Slant-bar test target showing the spatial resolution of the camera. The numbers next to the boxes indicate the fraction of the SSI Nyquist frequency ($33 \text{ cycles mm}^{-1}$) represented by the slant bar pattern in the box.

visible down to 80% of the Nyquist frequency ($0.049 \text{ cycles } \mu\text{rad}^{-1}$). SSI inflight performance is expected to be at least as good as this as the test setup which was used to acquire Figure 7 results in some degradation. Images of wide horizontal and vertical bar targets were also acquired and analyzed to determine the modulation transfer function (MTF) of the system. At the Nyquist frequency, the MTF ranges systematically from about 0.2 in the violet filter, to about 0.08 in the infrared filter. This is consistent with the expected diffraction-limited performance of the telescope. The point-spread response was also characterized by imaging targets containing pinholes. The observed

standard deviation of the resulting charge distributions about the location of the center of the distribution ranged between 0.75 and 1.1 pixels. As a rough 'rule-of-thumb', the camera has a useful resolution of about 1 km ($0.5 \text{ km pixel}^{-1}$) at a range of 50 000 km.

Geometric distortion in SSI images was investigated by measuring the locations of intersections of a set of regular horizontal and vertical lines in an image of a regular target projected through a distortion-free collimator. A low level of pincushion distortion was observed, as expected from analysis of the optical design. This distortion is azimuthally symmetric and increases as the cube of the distance from the center of the image. It reaches a maximum value of about 1.2 pixels at the corner of the array. The coefficient of the cubic term is about $6.58 \times 10^{-9} \text{ pixel}^{-3}$.

2.5. INFLIGHT CALIBRATION

Because of possible detector drift during the very long flight time to Jupiter and the potential for changes in the performance of the camera while immersed in the Jovian magnetosphere, the SSI experiment includes a major inflight calibration effort, already underway. We are using photometric standard stars, star clusters, and observations of a 'calibration plaque' (permanently mounted on the spinning section of the spacecraft) to acquire absolute calibrations and flat-fields, and thereby follow the evolution of the SSI calibration parameters. It is planned to perform a major inflight calibration sequence just prior to each encounter and, if possible, twice every orbit in the Jovian magnetosphere. Early data on the inflight performance of the system *with the front aperture cover in place* are reported by Belton *et al.* (1992). The camera performance was found to be nominal, although the aperture cover introduced anomalies.

3. Scientific Objectives and Measurement Strategy

The scientific objectives for the orbital mission were determined very early in the mission planning and were derived directly from high-level mission goals (Yeates *et al.*, 1985). After the mission was reconfigured to the VEEGA trajectory in 1987, additional science objectives were included that cover the cruise encounters. In this section we give an overview of the SSI objectives for the orbital tour and a brief outline of the scientific focus of the SSI experiment at each of the planetary bodies that we expect to encounter.

There are many possibilities for cooperative investigations with the other orbiter experiments, and reasonable efforts have been made to identify them. Several of Galileo's interdisciplinary scientists (IDSs) have become intimately involved in the design of the SSI experiment with this purpose in mind. Particularly strong cooperative investigations are expected between the SSI and NIMS, the Photo-Polarimeter and Radiometer (PPR), and UltraViolet Spectrometer (UVS) experiments.

3.1. SATELLITE OBSERVATIONS

(1) For each Galilean satellite, determine the morphology of at least 50% of the surface at a resolution of 1 km or better (in particular in those areas for which Voyager resolution is poorer than 5 km) and selected areas of the surface at 100 m or better.

(2) Map the spatial variation in color and albedo of each Galilean satellite over at least 50% of its surface at a resolution of 2 km or better and monitor any temporal variations.

(3) Determine the photometric function at several locations on each Galilean satellite.

(4) Determine the location of the spin axis, the rotation rate, and the geometric figures of the Galilean satellites to an absolute accuracy of ± 3 km.

(5) Determine what photometric phenomena result from the interaction of the Galilean satellites with Jupiter's magnetosphere.

(6) Determine the surface morphology, color, and albedo, and measure the global properties of the non-Galilean satellites as opportunities arise.

3.2. JUPITER ATMOSPHERIC OBSERVATIONS

(7) Characterize the state of the atmosphere in the vicinity of the Probe descent region as closely as possible to the time of the descent of the Probe through the atmosphere.

(8) Separate atmospheric mass motions from wave motions on global scales. Identify any wave propagation modes that are present and the level of the atmosphere in which they exist. Characterize fields of atmospheric flow, cloud structures, and waves.

(9) Investigate the vertical structure of a few specific types of atmospheric features by center-to-limb, and multi-spectral observations. Characterize any relationships between vertical cloud structure, color, and morphology.

(10) Measure the mean vertical wind profile through relative cloud motions at the boundaries of major belts and zones and in the region of descent of the Galileo atmospheric Probe.

(11) Measure the scattering properties of individual cloud features at several wavelengths and at as wide a range of phase angles as possible.

3.3. OBSERVATIONS OF MAGNETOSPHERIC INTERACTIONS

(12) Map and characterize auroral phenomena in the Jovian atmosphere and on the satellites. Correlate them with *in situ* particle and field observations made from the Orbiter.

3.4. JOVIAN RING OBSERVATIONS

(13) Map the ring structure and search for any temporal variations.

(14) Search for new small satellites in the vicinity of the Jovian ring and observe all small inner satellites at the highest possible resolution to improve our knowledge of their sizes, shapes, colors, albedos, surface textures, and spin states.

(15) Measure the color, albedo, and column densities and infer the size distribution of the ring particles.

3.5. COOPERATIVE OBSERVATIONS AND TARGETS OF OPPORTUNITY

(16) Pursue cooperative observations with other Galileo investigations.

(17) Make observations of objects which can be expected to present special target opportunities during the course of the mission.

(18) Make observations of the photometric, geometric, and geological character of at least one asteroid.

(19) Make 'best effort' investigations of Venus, Earth, and the Moon during encounters that occur during interplanetary transit to Jupiter.

4. Measurement Strategy at Major Encounters

4.1. OVERVIEW OF THE GALILEO TRAJECTORY

The mission trajectory has the following components: (1) Interplanetary cruise, which includes major encounters at Venus, the Earth–Moon system (twice), and, hopefully, two asteroids (951 Gaspra and 243 Ida); (2) Approach to Jupiter and Jupiter Orbital Insertion (JOI), which includes an 'observatory phase' study of Jupiter, encounters with Europa and Io, a detailed characterization of the Probe descent region, and observations of the planet's darkside; (3) The orbital tour (Yeates *et al.*, 1985) at distances $> 10 R_J$ from Jupiter, which includes 10 orbits each characterized by an encounter with the planet itself, a close (100–1000 km) encounter with a specific Galilean satellite, and in some cases an 'untargeted' (20 000–100 000 km) encounter with one of the other satellites. Major opportunities exist for the SSI in all these mission phases. As the orbital tour progresses, Io and Europa will be monitored continuously. Also, in suitable orbital configurations, the rings, darkside phenomena on the planet, and non-Galilean satellites will be targeted. The Galileo spacecraft will reach Jupiter in late 1995 and JOI is expected to occur on December 7, 1995. The subsequent orbital tour will nominally conclude on October 7, 1997.

4.2. VENUS

The Galileo spacecraft encountered Venus on UT February 10, 1990 and, at the time of writing, has returned three images of the planet. One of these, taken through the violet filter (with the front aperture cover in place), is shown in Figure 8. A preliminary description of these images has been given by Belton *et al.* (1992). The full tapeload of 81 Venus frames will be played back to the Earth when the telecommunications link improves in late November, 1990.

The spacecraft trajectory was favorable for an investigation of small-scale motions in the Venus clouds. The spacecraft flew behind Venus to receive acceleration from the planet, and then receded from Venus over the afternoon quadrant of the atmosphere. Previous imaging experiments (e.g., Belton *et al.*, 1976; Rossow *et al.*, 1980) have shown that small-scale motions are most intense and most clearly visible in the afternoon quadrant.

The observational strategy was to track a region of clouds as it passed from morning to afternoon across the disk and follow the evolution of specific markings as the Sun's elevation changed. Internal waves should be detectable by phase propagation relative to the general drift of features. Waves are of special interest because they are capable of transporting momentum for large distances, producing accelerations where they are

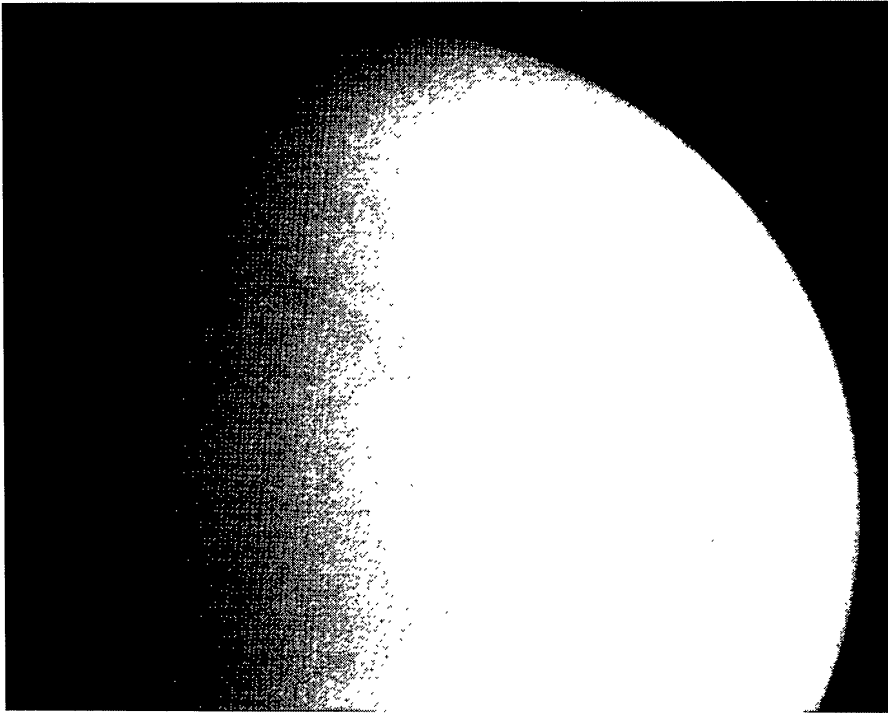


Fig. 8. Violet (404 nm) image of Venus taken by the SSI on UT February 13, 1990. The picture has been calibrated and stretched but not filtered. It was taken with the front aperture cover in place. Cosmetic removal of dust shadow residuals has been performed (cf. Belton *et al.*, 1990).

absorbed. Convective activity should be detectable by the appearance of time-dependent cellular structures. In addition to the study of small-scale motions by feature tracking, images were sequenced at larger ranges to determine the general circulation over the entire planet. This should be particularly useful for comparison with the infrared spectral-imaging data from the NIMS experiment, which will determine the rate of motion of the newly discovered thermal emission features deep in the Venus cloud layers (Allen, 1987).

Other SSI objectives included a search for optical evidence of lightning flashes, a survey of limb haze structure from the equator to the pole, and an attempt to image cloud structure in the near-infrared near $1\ \mu\text{m}$. One of the three Venus test images indicated that cloud markings, with a contrast of 3%, do exist at $1\ \mu\text{m}$. The morphology of these markings is different from those seen in violet and ultraviolet images.

4.3. THE MOON

Lunar observations will have the highest priority in the SSI experiment during the Earth Gravity Assist (EGA) encounters. Combined with NIMS observations, the data should permit ground-truth calibrations by observing regions on the nearside from which samples have been returned by Apollo and Luna missions (Adams and McCord, 1971, 1972). We then plan multispectral imaging of the north polar region, limbs, and farside that should allow extension of our knowledge of nearside mineralogical sample and unit compositions to these regions for the first time. The SSI spectral coverage, particularly

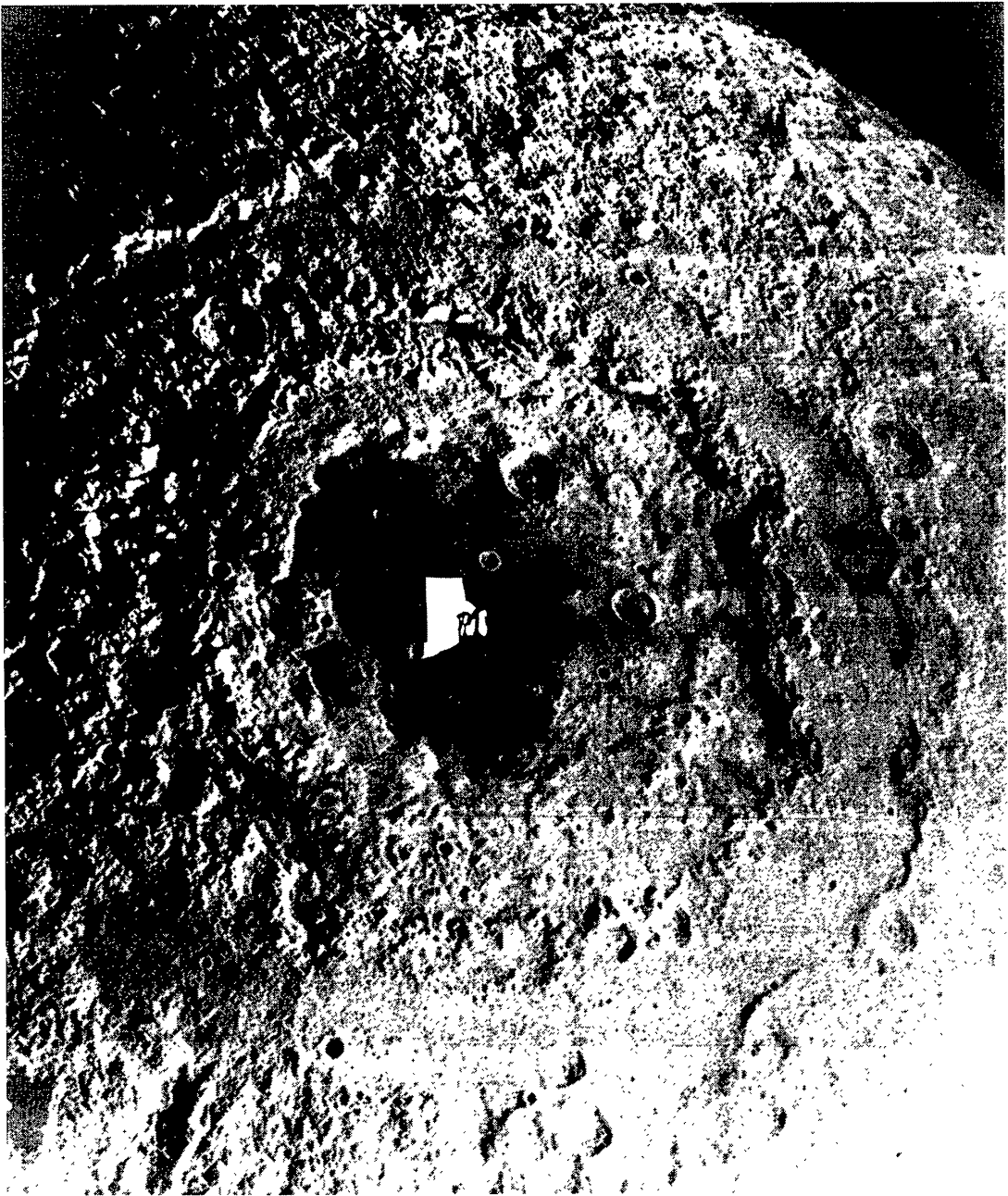


Fig. 9. The Orientale basin on the Moon, which is the highest priority target in the SSI experiment at EGA 1. It is about 900 km in diameter and is thought to have been formed slightly less than 4 billion years ago from the impact of a large projectile. The small white patch is the outline of a map of the State of Rhode Island and gives some idea of the scale of the basin.

in filters at 404, 756, and 986 nm, will allow *ratio* images (e.g., 404/756, 986/756) to be formed that track the spatial distributions of minerals with differing Fe, Ti, or Ca contents.

During EGA-1 the SSI will obtain excellent coverage of the Orientale Basin (Figure 9), the youngest major basin on the Moon (Head, 1974; Wilhelms, 1987). This impact feature has excavated and ejected crustal and perhaps mantle material from considerable depths. Multispectral images will provide information on the distribution

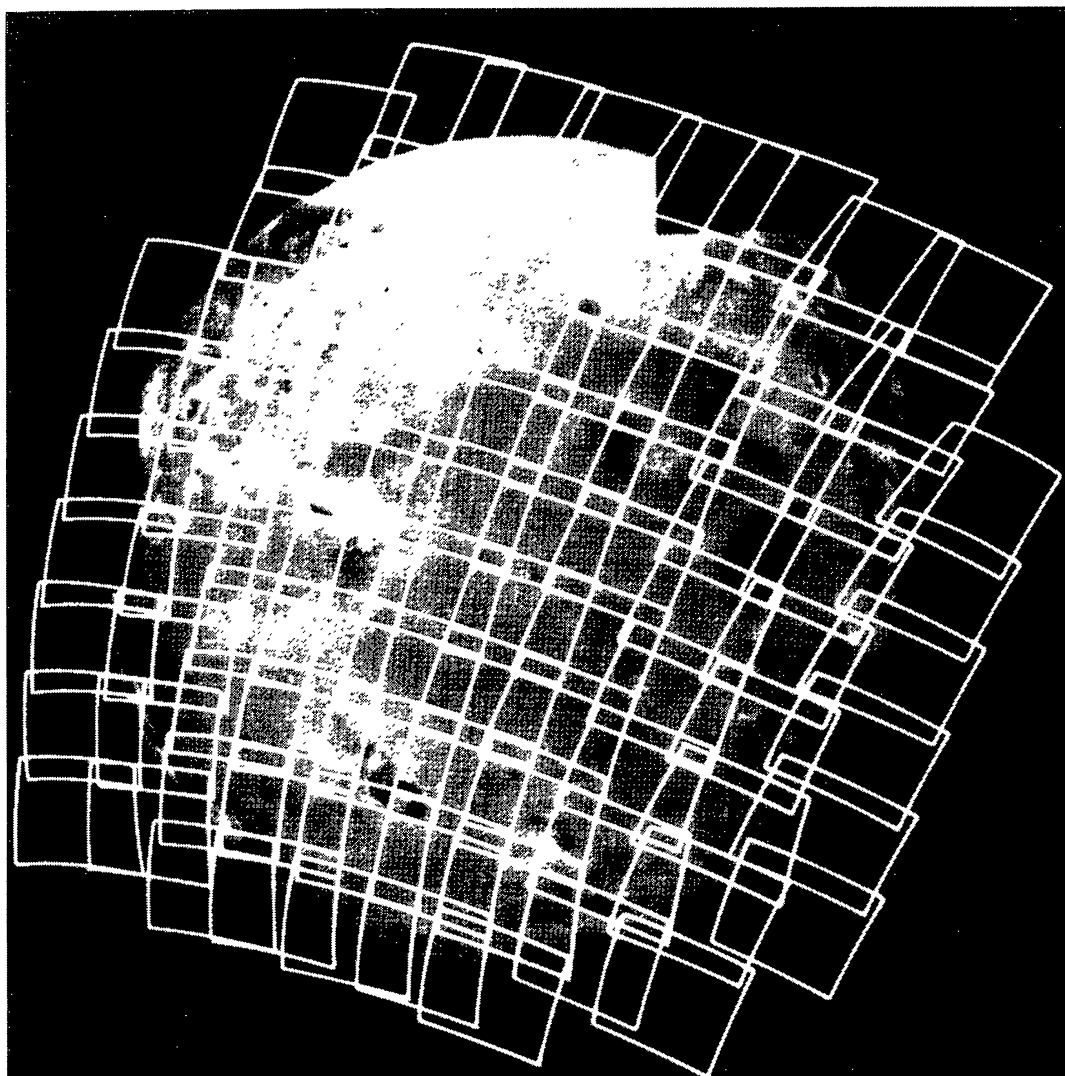


Fig. 10. The presently planned last, full disk, highest resolution SSI mosaic of Io superimposed on a Voyager color mosaic.

of different compositional units associated with Orientale and other basins, possibly providing clues to crustal stratigraphy. Together with NIMS data, it may be possible to correlate compositional units with known rock types. Analysis of the images is expected to yield new information on problems of impact basin formation (e.g., do large basins penetrate through the crust and into the mantle?), on the composition of the lunar farside and polar crust (are the nearside and farside crusts of different compositions?), and on the stratigraphy of the lunar crust (is it layered or has it been largely homogenized by impact basin reworking (Pieters *et al.*, 1985; Pieters, 1986)?).

Other questions that we will address include a determination of the global distribution of lunar maria, the melt products of early differentiation (Pieters, 1978; Pieters *et al.*, 1980). It is well known that there is a nearside-farside asymmetry in distribution of the maria, but there has been insufficient compositional data to determine the distribution mare types on the farside. SSI will provide new information on the farside and in north polar regions.

In addition, we intend to make observations of previously unexplored areas of the south polar region and to provide geodetic control points between the front and back sides to improve the mapping control network.

4.4. EARTH

Galileo's two flybys of the Earth are expected to generate considerable public interest. However, our planet is already under constant surveillance by an array of specialized spacecraft, which are specially instrumented for Earth studies. New measurements by the SSI are therefore not expected to add a great deal that is of high scientific interest. For this reason SSI measurement priorities at the two EGAs are being directed towards the Moon. When opportunities permit, SSI will acquire sequences of multi-spectral images of planet Earth from a variety of distances and, in essence, build-up short movie clips of cloud motions and planetary rotation. These activities will focus on developing the team's expertise in creating similar, but far more extensive, Jupiter sequences. In addition, we intend to obtain images of well understood geological features on the Earth (chiefly in Australia and in the western hemisphere) at a range of resolutions comparable to those that will be acquired on the Galilean satellites. In this way we expect to be able to understand the value and limitations of Galileo images by making comparisons of Galileo data with observations made from the air or directly from the ground.

4.5. ASTEROIDS

As soon as it was generally appreciated that flybys of mainbelt asteroids were possible as part of missions to the outer planets at a very modest cost of resources, NASA established a policy that such flybys would be a part of all future missions to the outer solar system. This policy is to be implemented for the first time by the Galileo mission, and the spacecraft will encounter 951 Gaspra on October 29, 1991, and, probably, 243 Ida on August 28, 1993. The known physical characteristics of these asteroids are summarized in Table III. The encounter distance remains to be decided, but is expected to be in the range of 500–5000 km. Two major factors, spacecraft safety and expected science return, need to be considered to determine the optimum distance for an asteroid

TABLE III
Characteristics of asteroids to encountered by Galileo

	951 Gaspra	243 Ida
Diameter (km)	16	32
Taxonomic type	S ^a	S
Rotational period (hr)	7.04	4.1
Light curve amplitude (mag)	0.7	> 0.4
Possible family membership	Flora	Koronis
Flyby Speed (km s ⁻¹) ^b	8	12.5
Approach phase angle	32°	19°

^a Gaspra is an 'unusual' S-type (C. Chapman).

^b The encounter distance is not yet decided (see text).

flyby. After much effort by several study groups, the Galileo project has adopted the position that no 'circum-asteroid' dust hazard will be encountered beyond one hundred radii of the target.

For an asteroid as small as 951 Gaspra, the Radio Science Experiment requires a flyby distance of 200 km or less to achieve a mass determination to an accuracy of about 10%. Scan platform instruments, especially NIMS and SSI, currently prefer larger flyby distances (800 and 2000 km, respectively) in order to optimize the competing requirements for high-resolution and substantial areal coverage at a wide range of phase-angles. As both of the flybys involve approach at low phase angles, which is optimum for NIMS spectral mapping, but not for high-resolution imaging, the SSI attaches great significance to targeting frames successfully near the time of closest approach when surface features will be illuminated at low Sun angles, i.e., high incidence angles where shadows accentuate the topographic relief. Given the possibility of significant downtrack errors in the position of the asteroid, the SSI desires to encounter the asteroids at larger distances than desired by NIMS, in order to ensure that at least one frame at moderate phase angle has a high probability of containing the asteroid. At the time of writing, a consensus on the optimum targeting strategy has yet to be achieved.

The SSI asteroid strategy has two major aims. The first is to obtain as much global, multicolor coverage of the asteroid as possible during the approach phase. As the camera achieves a resolution of about 1 km lp^{-1} at 10^5 km , it should be possible to resolve Gaspra at about one day before closest approach for a flyby speed near 10 km s^{-1} thus defining the useful duration of the approach phase. The second goal is to obtain as much coverage of the illuminated part of the asteroid near the time of closest approach when the range is minimum and the phase angle is near 90° . This produces the low-Sun illumination conditions needed to bring out surface morphology. Most of the visible, illuminated face of the asteroid can be imaged at $100\text{--}200 \text{ m pixel}^{-1}$ and some data may be obtained in the terminator regions at resolutions approaching 20 m pixel^{-1} .

The SSI asteroid science objectives are outlined in Table IV. It is our intention that

TABLE IV
SSI asteroid measurement and scientific objectives

Global properties	Surface morphology
Accurate size/shape	Crater morphology as function of diameter
Volume estimate	Ejecta patterns
Period and pole position	Evidence of past internal activity
Cratering statistics and 'age' of surface	Search for spallation features
Search for satellites	
Compositional properties	Regolith properties
Surface composition	Ejecta dispersal
Compositional heterogeneity	Stratigraphy
	Photometric properties

the objectives relating to surface composition will be carried out in conjunction with the NIMS investigation. While the SSI spectral range (Table I) is more restricted than that of NIMS (Yeates *et al.*, 1985), the two instruments clearly complement one another as the SSI extends the 1–5 μm spectral coverage of NIMS down to 0.42 μm . More important, the far greater spatial resolution of SSI should make it sensitive for detecting the small-scale albedo/color differences that can be used to define compositional units and relate them to small-scale topography.

Both Gaspra and Ida are classified as S-asteroids (Chapman *et al.*, 1975). But the precise nature of S-asteroids remains a hotly contested issue. On one hand, several pieces of evidence suggest that S-objects are related to ordinary chondrites (Wetherill and Chapman, 1988); on the other, the observed spectra of S-asteroids and ordinary chondrites do not match precisely (Feierberg *et al.*, 1982; Gaffey, 1984). The differences are considered significant by some who believe S-types may be differentiated cores of broken up parent bodies (Bell *et al.*, 1989). But others argue that poorly understood regolith processes could possibly modify the spectral reflectance properties of ordinary chondrite materials on S-asteroid surfaces (Britt and Pieters, 1988). The issue is a fundamental one: if S-asteroids are not related to ordinary chondrites, then we have the problem of finding a source for these most abundant meteorites. Worse still, we must explain why those S-asteroids, which are placed best to deliver fragments to Earth (i.e., those in specific locations in the asteroid belt, e.g., near the 3:1 resonance zone with Jupiter, and those in Earth-approaching orbits), fail to contribute significantly to the meteorite population.

An important clue to the nature of S-asteroids would result if it proves possible to determine masses to $\sim 10\text{--}20\%$ during the flybys. Such a measurement, combined with an accurate volume determination from the SSI images, will give mean densities that may eliminate, or at least constrain, some existing models. For instance, in one model S-asteroids are viewed as collisionally stripped-down cores of metallic asteroids (Chapman, 1976). Mean densities of such objects should be significantly greater than 3.5 g cm^{-3} .

The SSI images will certainly reveal what the surfaces of small asteroids look like. Will they be as densely cratered as current ideas predict? Will they look something like the surface of Phobos – a body intermediate in size to Gaspra and Ida (Veverka and Thomas, 1979), and will we perhaps find evidence of surface fractures associated with large craters (Thomas and Veverka, 1979)? Or will we find evidence for downslope movement of regolith similar to that discovered on Deimos (Thomas and Veverka, 1980) and on the walls of young craters on Phobos (Avanesov *et al.*, 1991)? Will the surface be spectrally bland or heterogeneous, as in the case of Phobos where the crater Stickney appears to have excavated material with color properties distinct from that of surrounding regolith (Murchie *et al.*, 1990a)?

4.6. JUPITER

In interpreting the mission objectives for Jupiter's atmosphere (Yeates *et al.*, 1985), it is important to remember that the atmosphere covers an enormous area, extends to great

depths, varies on all horizontal scales, and changes with time. The Galileo atmospheric Probe will satisfy the objectives at one latitude, one longitude, and one instant in time. The SSI, in combination with other remote sensing experiments on the orbiter, will provide the spatial and temporal coverage (motion picture sequences with 10 times better resolution than Voyager, for example) and long time base (10 orbits over 2 years plus a possible extended mission) that are needed to complete the picture.

Imaging is the most straightforward way to measure the spatial and temporal structure of the clouds. The SSI experiment is capable of resolving features smaller than half a scale height (~ 10 km) and as large as the radius of the planet. The appropriate temporal resolution depends on how fast the smallest resolvable features are changing or moving relative to each other. Analysis of Voyager images shows that relative velocities, v , are of order $L^{-1/2}$, where v is in m s^{-1} and L is the size of the features in kilometers. For example, $v = 10 \text{ m s}^{-1}$ for $L = 100 \text{ km}$ and $v = 32 \text{ m s}^{-1}$ for $L = 1000 \text{ km}$. The largest sampling interval capable of resolving these motions is $\sim L/2v$, or $500L^{-1/2} \text{ s}$. Thus for spatial scales L of order 10 and 100 km, the appropriate sampling intervals are 0.4 hr and 1.4 hr, respectively.

At a resolution of 10 km, we expect to see vertical structure (clouds, haze, molecular scattering) on the planetary limb. On the planet's disk, SSI will observe processes such as convection, gravity waves, and shear instability whose horizontal scale is comparable to the atmospheric scale height. For example, Flasar and Gierasch (1986) have shown that an interesting class of mesoscale waves occurs near the cores of atmospheric jets. They were unable to establish phase speeds with Voyager images. This will be possible with Galileo data, and analysis of these waves should yield information about vertical structure of the mean wind fields. At a resolution of 100 km, the latitudinal bands and large ovals will be imaged, as well as intermediate-scale features (100 to 1000 km in size, 1 to 10 days in lifetime) that coexist with the long-lived structures but do not destroy them. For example, Dowling and Ingersoll (1989) have shown that mapping of the vorticity field at cloud top level can give information about the latitudinal variations in motions that exist much deeper in the atmosphere.

The wavelengths of the SSI filters, ranging from violet to near-infrared, should enable the effects due to molecular and aerosol scattering, different chromophores in the clouds, and absorption by gases such as methane to be separated out. By observing features at different positions on the disk (morning, noon, evening) and under different viewing geometries (forward and backward scattering, low and high emission angles), it is expected that the effects of vertical structure, aerosol abundance, particle size, and composition can be separated. It may also be possible to measure vertical shear in the zonal wind fields. Coordination of SSI sequences with those of the other orbiter instruments, and those on the Probe, is essential to this process.

SSI's observational strategy is to be highly selective as regards the atmospheric features to be studied. We will attempt to gather as much information as possible in order to ensure a substantial advance in our understanding of a few distinct classes of features (e.g., the great red spot, equatorial plumes, white ovals, barges, etc.). The planet is just too large and bewildering in its complexity to be studied with full comprehension

by a single narrow-angle camera on a single spacecraft with a limited picture budget (budgeting for the experiment has been based on a limitation of 60 000 frames for the nominal mission excluding cruise science).

In what follows, we highlight a sample of the measurement sequences that the SSI team plans to use for atmospheric studies. While we highlight the role of the SSI, cooperative experiments with the other remote sensing instruments will be the central focus of the measurement strategy at Jupiter.

Probe entry site (PES) observations. Basically a combination of the sequences outlined below in which the evolution of the PES and its environment are observed, first at low and then at high resolution, starting two months before Probe entry. The Probe data will provide *in situ* truth to help in the interpretation of these observations. The Orbiter data, in turn, will provide information on the larger scale processes that are occurring at the PES and help extrapolate them to global conditions.

Full feature track (FFT). This sequence follows a selected region from limb to limb during one half rotation (5 hr) in order to obtain vertical structure information on clouds, winds and temperature. Our intent is to schedule FFT's at various longitudes and phase angles throughout the mission, all in the range of distances of 10–40 R_J . The inversion of the data to obtain information on vertical structure is the primary objective.

Feature velocity map (FVM). A variant of the FFT, the objective is to measure the velocity (SSI), temperature (PPR), composition and clouds (NIMS and UVS) over an area roughly 20° in latitude, 60° in longitude. The sequence takes about 4 h and will be conducted at phase angles less than 35° and a range inside of 20 R_J . A larger area is covered near the center of the disk than for the FFT, which samples more frequently in time.

High-resolution north–south scan (HRNSS). This is a cooperative sequence with the PPR which will be used to characterize spatial structures at 1000 to 2000 km scales for temperature and cloud microphysical properties and for which the SSI provides contextual imaging. Full longitudinal coverage will require a duration of 10 h. To maximize the spatial resolution (especially for scan platform instruments other than SSI) the measurement will, when possible, be conducted at minimum range ($\sim 15 R_J$). HRNSS can be done at phase angles greater than 90°, but SSI will either have to look 'through' the spinning RTG booms or rely on observations from an earlier rotation of the planet.

High-resolution cylindrical map (HRCM). This is a cooperative sequence with NIMS, in which we intend to acquire high-resolution spectral data on the aerosol opacity and minor species throughout the near equatorial ($\sim 20^\circ$ – 30° N–S) region. Primarily a search for hot spots, the emphasis will be on obtaining data on a number of latitudinal regions with later repeats to look for temporal variations. The measurement requires 10 hr of observing time and must be conducted within 15 or 20 R_J to obtain the required spatial resolution.

Global velocity map (GVM). This is a moderate resolution (30 km pixel⁻¹) sequence in which we intend to measure the velocity field over the entire planet from a range of 50 R_J , at phase angles less than 110°, over two full rotations (20 hr). The measurement is built on imaging mosaics that are frequently repeated (every 40–50 min) over the

duration of the sequence. Displacements (motions) will be measured using images obtained 10 hr apart.

High-resolution velocity map (HRVM). A combined SSI and PPR sequence designed to measure the meridional transport of heat and momentum across a latitude circle. The SSI data will be used to measure velocities by feature displacement over 2 hr time increments, and temperature via overlapping PPR field-of-views. The duration of the measurement will be about 12 hr, the range must be less than $20 R_J$, and the phase angle less than 40° .

4.7. Io

Io is the most volcanically active body in the solar system, and the SSI experiment will focus primarily, although not exclusively, on this aspect of the satellite. Voyager observed several volcanic plumes extending up to 300 km above the surface, numerous volcanic hot spots on the surface, and a wide variety of landforms suggestive of both sulfur and silicate volcanism (Smith *et al.*, 1979a). Dissipation of tidal energy (Peale *et al.*, 1979) is believed to be the cause of the volcanism, but precisely how and where within the satellite the tidal energy is released is not known. Nor is it known what fraction of the tidal energy released within the satellite is conducted to the surface and what fraction is dissipated by transport of magma. Another major issue is the chemical nature of the volcanism. Are the eruptions primarily of sulfur, as is suggested by the spectral properties of the surface, or are they primarily of silicates as is suggested by the apparent strength of the surface materials (Carr *et al.*, 1979)?

Voyager was able to place some lower limits on resurfacing rates from the absence of impact craters and from modelling of the plumes (Johnson *et al.*, 1979), but the estimates are quite uncertain. While almost everything on Io's surface is probably the result of some form of volcanism, some of the landforms observed in the Voyager images are strongly suggestive of crustal deformation and erosion. Yet how does erosion occur on what is effectively an airless body? Possibilities include thermal erosion and sublimation, but other, as yet undiscovered, processes may also be involved. The SSI experiment will include a variety of observations designed to address all of these issues.

The single Galileo encounter at Io, at the beginning of the orbital tour, is typical of the satellite flybys that will occur later in the orbital tour. During approach to JOI there will be a period at relatively small phase angles, which will be devoted to multi-spectral mapping of the surface with moderate resolution ($< 2\text{--}4 \text{ km pixel}^{-1}$). Just prior to the encounter a full-disk mosaic of images will be acquired at the highest resolution possible ($\sim 1\text{--}2 \text{ km pixel}^{-1}$) in the clear filter (Figure 10). The actual encounter distance for Io will be $\sim 1000 \text{ km}$, i.e., 20 times closer than the closest Voyager 1 encounter, and will allow images to be taken of specific localities with ground resolutions $\sim 20 \text{ m pixel}^{-1}$ (Figure 11). By comparison, the highest resolution achieved by Voyager on Io was $\sim 200 \text{ m pixel}^{-1}$. Because Io is deep in the Jovian magnetosphere ($5 R_J$), the SSI must operate in a hostile particle radiation environment described above. As a consequence, the entire sequence will be performed in the lower resolution 'summation' mode (cf. Table I) so that the quality of the images is maximized.

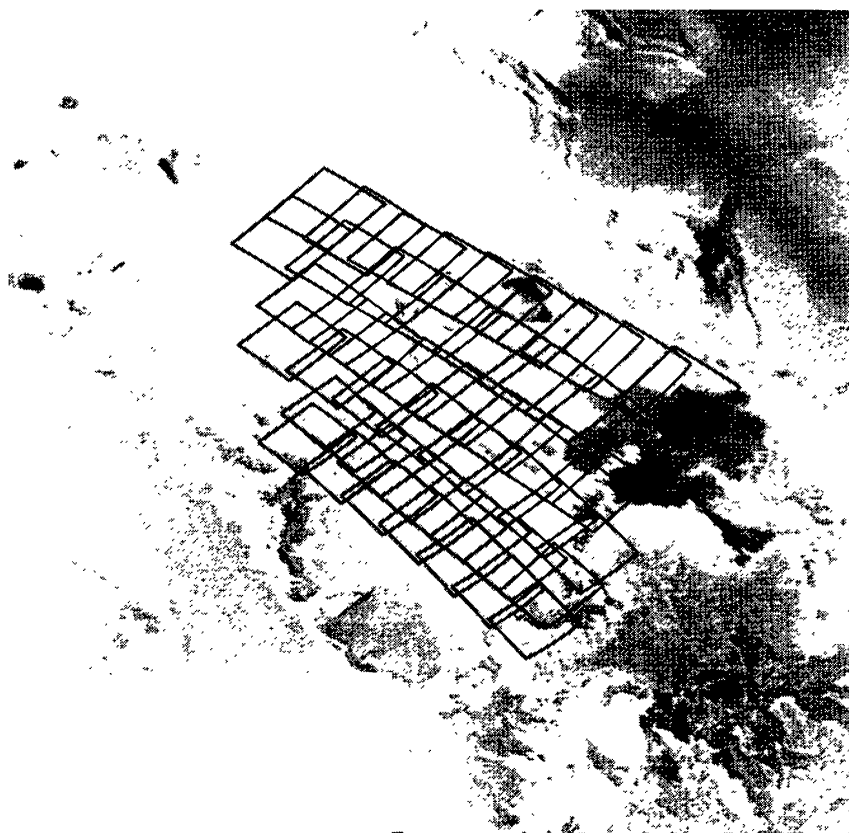


Fig. 11. An example of the anticipated coverage by the SSI of a specific region on Io at the time of encounter when the ground resolution will approach $\sim 20 \text{ m pixel}^{-1}$.

High-resolution imaging will help assess the nature of volcanism on Io. For example, estimates of long-term global volcanic rates will be possible from the presence or absence of impact craters in the highest resolution images. The nature of the volcanic activity will be assessed primarily from the highest resolution images, those with 20 m pixel^{-1} to 1 km pixel^{-1} resolution. At such high resolutions a variety of volcanic features, such as lava channels, levees, flow fronts, vents, and fumarolic deposits should be visible, and key measurements of flow thicknesses, caldera depths, slopes of walls, and so forth can be made. In this way we expect to place much more precise limits on the properties of the erupted materials and their probable compositions. In addition, high-resolution images will give an indication of what types of volcanic activity are occurring, particularly the relative importance of flow eruptions, pyroclastic activity, and various forms of remobilization of near surface volatiles.

Although the high-resolution imaging of Io will take place during only a single encounter, we will be able to monitor Io with spatial resolution comparable to that of Voyager 2 ($5\text{--}10 \text{ km pixel}^{-1}$) during most of the two year orbital phase of Galileo. A program of continual monitoring will allow us to explore time variations, in addition to what we can learn from comparisons over the eighteen-week interval between the Voyagers and the 16-year interval between Voyager and Galileo.

The longer interval is likely to reveal significant surface changes due to the active and

changing volcanism. Substantial portions of the surface may have been resurfaced with volcanic plume deposits. Earth-based observations over the past decade show that volcanic hotspots have bloomed and faded so that individual volcanic source sites, including vents and hot lava lakes, may be quite different in the mid-1990's from what was imaged by Voyager (McEwen *et al.*, 1989; Howell and Sinton, 1989; Greenberg, 1989). Plume activity will likely be changed considerably as well. Less dramatic, but still possible, may be changes in lava flow features. Another category of change to be explored over this longer time-scale is the rotational orientation of Io with respect to the direction of Jupiter. The lunar analogy would predict that Io rotates synchronously, but Greenberg and Weidenschilling (1984) have shown that flaws in that analogy admit the possibility of some deviation.

Monitoring during the orbital phase of the mission will allow us to explore the more rapid variations in volcanic activity. A strategy for this monitoring has been developed, taking into account our understanding of the various temporal and spatial scales of expected changes. Based on Voyager data, volcanic plumes of the Pele class (order of 300 km in height) have life spans less than a few weeks, while the Prometheus-class plumes (75 km) may endure for several years (Strom *et al.*, 1981; McEwen and Soderblom, 1983). Monitoring for the existence of plumes will be appropriate over the time-scale of the orbital mission and will be possible from distances as great as $100 R_J$. Morphology of the plumes may well change on much shorter time-scales. The Loki plume showed significant variation over the course of hours, although Loki does not fit into either of the above plume classes. Monitoring such short term changes will only be possible at ranges $< 30 R_J$ for Pele-class plumes and only at close approach for the smaller Prometheus class. The monitoring strategy will include sequences that may provide a movie of plume variation.

Monitoring will also be used to investigate the phenomenon of post-eclipse brightening, which has been observed with mysterious inconsistencies from the Earth. Repeated observations of Io's emergence from eclipse with moderate resolution may help reveal the mechanism for this phenomenon.

4.8. THE IO TORUS

Io is unusual not only for its active volcanism, but also for the material it contributes to the Jovian environment. The Io torus is the ring of neutrals and plasma that surround Jupiter at approximately Io's orbital distance. The neutral clouds of sodium and potassium atoms and the torus of sulfur and oxygen ions that make up the optically observable torus all originate on Io (Krimigis *et al.*, 1979; Brown *et al.*, 1983)).

The neutrals are concentrated around Io itself. Within a few Io radii of the satellite's surface, the maximum sodium D-line brightness probably exceeds 100 kilorayleighs and should be easily accessible to the SSI camera giving signals of several tens of DN in images taken in highest gain state with extended exposure. Although the sodium cloud is bright relative to other components of the torus, observing this emission will be made difficult by the proximity of the bright Io surface and the absence of a narrow-band filter to optically isolate the sodium emission. Nonetheless, we expect that the high photo-

metric accuracy of the CCD detector and our efforts to minimize scattering in the SSI optics should allow us to subtract the scattered light from Io, enabling measurements of the near-Io sodium. Such measurements might reveal source regions or streamlines in the outflow of sodium and contribute greatly to our understanding of the mechanisms by which neutrals are removed from Io.

The plasma component of the torus is distributed in a large circum-Jovian ring, with the brightest emission often occurring at great distances from Io. However, the brightest of the plasma emissions in the wavelength range of the SSI are less than 1 kilorayleigh. These low brightness levels are not expected to be detectable owing to the absence of narrow-band filters and the 54-s limit on SSI exposures.

4.9 EUROPA

Europa is probably the least understood of the Galilean satellites due to comparatively poor resolution in the Voyager images, but it certainly is one of the most intriguing. It is believed to have a relatively thick, icy crust, and a silicate interior. The most prominent feature on its surface is a global system of intersecting dark and light linear markings. Several recent studies have investigated the origin of these marking; possible generic mechanisms include tidal deformation (Helfenstein and Parmentier, 1983), nonsynchronous rotation of a decoupled ice shell (Helfenstein and Parmentier, 1985), and polar wander of a decoupled ice shell (Ojakangas and Stevenson, 1989). Impact craters are extremely rare, so the surface is young and Europa is likely to have been actively resurfaced throughout its recent history (Lucchitta and Soderblom, 1982) and is, perhaps, continuing today. Although Voyager observed no obvious volcanic plumes, some equivocal evidence of brightening above its limb has been interpreted as indicating very low-level emissions of material from the surface (Helfenstein and Cook, 1984), and results of photometric studies indicating a very high surface porosity have been interpreted as being more consistent with 'pyroclastic' resurfacing than with an impact-gardened regolith (Domingue *et al.*, 1989).

The best Voyager images have a resolution of about 4 km pixel^{-1} . The best SSI images should approach $\sim 10 \text{ m pixel}^{-1}$, i.e., two orders of magnitude improvement in ground resolution. With this improved resolution, discrimination between different theories for the formation of the network of linear markings, should be possible. For example, at SSI resolutions, we should be able to characterize the morphology of the different types of markings in detail and determine the extent to which each originated by tectonic or volcanic activity. High-resolution images may also enable us to detect small craters and, through counts, establish the relative rates of resurfacing in different areas. With such a dramatic improvement in resolution, we may expect a whole new panoply of European features and phenomena to study. We anticipate that Europa may turn out to be the source of some of the most exciting and novel discoveries to be made by Galileo orbiter. The surface and limb will also be monitored throughout the mission in order to detect any changes that might occur and look for any indication of active 'ice-volcano' plumes.

4.10. GANYMEDE AND CALLISTO

Ganymede and Callisto, by virtue of their similar sizes and densities (indicative of a mixture of rock and ice) present an extremely important case study in comparative planetary evolution. The surface of Callisto consists almost entirely of heavily cratered terrain exhibiting little obvious evidence of volcanic and tectonic modification (Smith *et al.*, 1979a, b); the most notable exception is the vicinity of the Valhalla multi-ring structure, where at least minor volcanic resurfacing has occurred (Remsberg, 1981). About half of Ganymede's surface consists of dark terrain which is superficially similar in appearance, but is pervasively cut by systems of linear and curvilinear furrows (Smith *et al.*, 1979a, b). Early interpretations of the geology of dark terrain were that it is an impact-fractured primordial surface, perhaps capping a deep, differentiated water-ice mantle (e.g., Passey and Shoemaker, 1982; Shoemaker *et al.*, 1982; McKinnon and Parmentier, 1986). More recent investigations of the stratigraphic relations of furrows with deposits of dark material and the crater size-frequency distribution in dark terrain suggest a volcanic surface deformed at least in part by endogenic processes (e.g., Croft and Goudreau, 1987; Murchie *et al.*, 1989, 1990b).

The remaining half of Ganymede's surface consists of lighter-colored material pervasively deformed by sets of linear grooves (Smith *et al.*, 1979a, b). Studies of crater morphology and size-frequency distribution suggest that the light material forms a layer undreds of meters to a few kilometers thick burying underlying dark terrain (Schenk and McKinnon, 1985; Murchie *et al.*, 1989). The grooves themselves are widely thought to be extensional in origin, formed as tension fractures or graben modified by mass wasting, volcanism, or other processes (cf. McKinnon and Parmentier, 1986, for a review). Large areas of grooved light terrain appear to have been formed by downdropping of blocks of lithosphere followed by resurfacing and fracturing (Parmentier *et al.*, 1982). This process occurred as a sequence of initial fracturing of the blocks followed by formation of different morphologic classes of grooved terrain, for which a generalized sequence of events have been worked out (Murchie *et al.*, 1986). On a global scale these structures form a coherent pattern, with both global 'fabric' and regionally dominant groove orientations in evidence (Bianchi *et al.*, 1986). Although the dominant form of deformation in grooved terrain clearly was extensional, in some locations there is evidence for shear and compressional deformation (Murchie and Head, 1988). More detailed examinations of these locations and assessment of the roles of different types of deformation in the formation of grooved terrain could be some of the more important geologic observations by SSI.

The difference in the geology of Ganymede and Callisto despite their similar bulk properties, i.e., the 'Ganymede-Callisto dichotomy', is thought to be a consequence of divergent thermal and dynamical evolutions (McKinnon and Parmentier, 1986). Evidence for the cause of the divergence occurs in the spatial and temporal patterns of volcanic and tectonic surface modification, but also in the form of other indicators of the satellites' thermal evolutions. One such indicator, applicable to Ganymede, is the evolution of the widths of tectonic troughs, which is a function of the evolution of the

thickness and thermal gradient in the lithosphere (Golombek and Banerdt, 1986). Another indicator is the history of viscous relaxation of craters and palimpsests. Passey and Shoemaker (1982) have attempted to reconstruct the thermal history of Ganymede using such observations, but this technique is complicated by uncertainty about the roles of impact melting and subsequent resurfacing in also degrading crater morphologies (Croft, 1983; Murchie *et al.*, 1989).

SSI imaging of these satellites will emphasize multi-phase-angle coverage of selected areas, multi-spectral images and the acquisition of the very highest spatial resolution image data of selected regions (down to ~ 10 m pixel $^{-1}$). Details of structural features, such as morphologic modification of furrow, groove, and crater rims, and walls and floors (possibly by resurfacing or mass wasting), should be easily visible. New features may be detected, e.g., further subdivision of undivided material units, detection of extrusion vents, flow features, and possibly, ancient volcanic constructs. The spectrum of crater forms will be enlarged by details involved with ejecta material emplacement (pedestal craters, bright and dark rays), central peak and pit modification, rim morphology, terraces, and secondary crater chains. These investigations will be aided by photometric material classification at all SSI wavelengths. Thus, the aim of the SSI experiment at Ganymede and Callisto is to greatly refine the preliminary Voyager reconnaissance of geological features as well as to investigate some types of features more intensively.

With the spatial resolution capability noted above, it should be possible to easily discriminate between small primary craters and secondary craters, as well as differentiate impact craters from craters of other origin. It should be possible to improve our knowledge of the crater size-frequency distribution over all crater sizes and for all the different geologic units on the surfaces of Ganymede and Callisto. From this, improved comparisons will be possible with the cratering record in the inner solar system. These investigations should yield further insight into the nature of the impactor populations which are responsible for the cratering record both in the Jovian system as well as the inner solar system, and may clarify the relative abundance of heliocentric impactors versus planetocentric impactors as a function of time (Chapman and McKinnon, 1986; Murchie *et al.*, 1989). Thus we may learn about early accretional and post-accretional processes in the satellite system of Jupiter and, especially, about the bombardment history of the satellites in terms of possible catastrophic impacts that may have led to destruction and re-accretion of the satellites.

Rheologic properties derived from morphology of surface features will also be an important tool to better determine the thermal histories of both satellites. Detailed analysis of crater morphology and the age sequence of widths of tectonic features may provide important tools for establishing a time scale for any changes in the rheologic properties of Ganymede's lithosphere. Also, detailed mapping of furrows and grooves may help in determining regional or local stress domains associated with conditions of the interior.

4.11. JUPITER'S RINGS

The main ring of Jupiter extends from a very sharp edge at $1.8086 R_J$ inward to a fuzzy boundary at about $1.71 R_J$ and lies in the equatorial plane of the planet. The slant optical thickness of the brightest component of the rings is about 10^{-5} to 10^{-6} , which gives some idea of how ethereal these rings are. Embedded in the main ring are (at least) two small satellites, both near the outer edge (Metis at $1.792 R_J$ and Adrastea at $1.807 R_J$). The ring is probably sustained by ejecta from these satellites due to meteoroid impact, even as radiation drag drives ring particles in towards the planet.

Just interior to the main ring, from about $1.71 R_J$ to a very fuzzy inner boundary at 1.3 to $1.4 R_J$, is the toroidally shaped 'halo' component of the ring system, whose thickness is comparable to its radial extent. The halo is thought to be produced by the interaction of electric charges on small ring particles with the Jovian magnetic field: As ring particles reach the inner edge of the main ring, Lorentz forces drive them into increasingly inclined orbits, generating the thickness of the swarm inside $1.71 R_J$ (Schaffer and Burns, 1987). The total amount of material in the halo is thought to be comparable to that in the main ring, although the halo appears to have a much lower surface brightness in edge-on view because the material has a much greater vertical extent. Voyager images also revealed a 'gossamer ring', which stretches from the main ring out to $\sim 3 R_J$, where it became too faint to detect. The size of the optically important particles in the rings lies in the range from 0.1 to 10μ .

We plan to obtain multi-spectral images to map the details of any structures in the main ring and better characterize its particle size distribution. We will search for time-dependencies and for presently undiscovered satellites that may be substantially contributing to the source of the particles. The intriguing structure of the gossamer ring, which has an intensity maximum near the distance where Keplerian orbits would be synchronous with Jupiter's rotation, will be mapped more comprehensively than was possible from Voyager.

Other issues that we plan to address include the radial and vertical structure and extent of the halo. Does it, for example, really agree with the Lorentz resonance hypothesis? A logistical complication is that observations at high phase angle will require the SSI to be looking back towards the Sun through the spinning RTG and magnetometer booms and scattered sunlight may mask the signature of the rings. The solution will probably be to make such high-phase-angle observations only during occasional 'science turns' or while the spacecraft is in the shadow of Jupiter, which may, in turn, substantially limit the coverage of the rings that is possible.

An equally important part of the SSI ring experiment will be to obtain image data that will further elucidate the nature of the larger objects that presumably serve as the basic sources of ring material. These range from the satellites that have already been discovered, down through a possibly continuous range of intermediate and smaller sizes. These source objects will be best seen at low-phase-angles in backscattered light from as small a range as possible. Multi-spectral images in backscattered light may help characterize the surface composition of the larger objects.

4.12. AURORAL, AIRGLOW AND DARK-SIDE PHENOMENA

As a result of the high sensitivity of the $V\phi$ CCD, it will be possible to observe a variety of low-light-level phenomena on the dark faces of Jupiter and its satellites. The Voyager imaging experiment (and other investigations) has already shown that intense optical auroras are present on Jupiter. However, their global patterns, distribution, and dynamics remain poorly understood. Two-dimensional maps of Jovian aurorae made with SSI images will provide unique information on the occurrence of precipitating plasma; therefore accurate mapping of their rate of occurrence and locality is a critical measurement for a deeper understanding of Jovian magnetospheric dynamics. The SSI has a sensitivity to extended sources that is some 20 times that of the Voyager *wide angle* camera (clear filter, $S/N \sim 10$). It is, therefore, expected that the SSI will be able to make unique measurements of these phenomena.

Some key questions which we expect to address are: What is the time scale for changes in the Jupiter aurora? What is the relative importance of particles in the torus compared with those in the magnetotail plasma sheet for producing auroral phenomena? What differences, if any, in auroral intensities and structure occur in the vicinity of the magnetic anomaly ('active sector')? What differences exist between visible aurorae in the northern and southern hemispheres? Can we characterize the auroral emissions in visible wavelengths at the foot of the Io fluxtube?

Although we believe the SSI is capable of making significant contributions to magnetospheric science on its own, the prospects are multiplied when its capability is combined with those of other Galileo instruments. For example, cooperative observations with the UVS and with *in situ* magnetometer, plasma, and energetic particle experiments should make it possible to trace magnetospheric field lines back to their source in the ionosphere.

Other 'darkside', low-surface-brightness phenomena that we plan to investigate include: atmospheric lightning discharges that were originally discovered (Cook *et al.*, 1979) during the Voyager mission (is it possible to trace out the global distribution of convective activity deep in tropospheric clouds with the spatial distribution of visible lightning flashes?); glows associated with volcanic activity on Io; and meteor fireballs.

5. Data Analysis System

5.1. OVERVIEW OF THE SSI DATA SET

We estimate that the SSI will generate $\sim 70\,000$ useful images during the entire mission. Of these we expect 81 of Venus, 5000 of the Earth–Moon system, 2000 of asteroids, 40000 of Jupiter's atmosphere, and 20000 of Jupiter's satellites and its rings. It is our intention to rapidly (see below) and systematically produce calibrated versions of these images and to perform a preliminary analysis of them as the mission proceeds. In order to constrain the substantial costs which are involved in producing photographic hardcopy, we will rely on modern computer techniques to interact with the vast bulk of the data. Photographic hardcopy will be produced for only a fraction of the images.

The data are expected to be made available to the general scientific community within one year of their receipt from the spacecraft and will be distributed through NASA's Planetary Data System and through the NASA Regional Planetary Image Facilities.

5.2. HIIPS: HOME INSTITUTION IMAGE PROCESSING SYSTEM

The 1980's saw a rapid spread of computer-based image processing capabilities into the hands of individual research scientists. What was once the domain of a relatively few large research centers has become commonplace throughout the scientific community.

The scientific data analysis for the SSI experiment will largely be accomplished during the flight mission using a 'fully distributed', networked computing system called HIIPS, which features nodes at each team members' home institutions. When HIIPS was first conceived in the early 1980s, only a few institutions were capable of conducting large-scale image processing. It was argued that it would cost much less for each team member to operate a dedicated image processing system rather than to be supported by a large cadre of computer analysts at JPL, the production of large quantities of 'hard-copy' photographic prints, and the support of extensive travel and subsistence in residence at mission control, as had been the case in previous missions. These arguments became stronger when it was recognized that each team member would require research associates who would also need support in residence at mission control. Thus, it was found not only less expensive, but more efficient to develop a system of dedicated image processing capabilities at each team member's home institution. As capabilities of image-processing computers has improved during the mission delays of the 1980's, these arguments seem all the more cogent.

A typical HIIPS station consists of a microcomputer, tape drive, mass storage, display processor, and various peripherals such as digitizers, hard copy devices, etc. (Figure 12). Most are configured for multiple users. All HIIPS are networked and linked to the Jet Propulsion Laboratory (Figures 13(a-c)). The linkage is currently over the SPAN network and works at a rate of 9.6 kbaud. During mission operations it is planned to increase this to 56 kbaud. The image processing software consists of Jet Propulsion Laboratory's VICAR routines (LaVoie, 1989) running under the Transportable Applications Executive (TAE). Both VMS and UNIX versions are employed. Other packages, e.g., IRAF (Tody, 1986), are also expected to be used for special applications. Special software to address specific scientific problems is also being developed by individual team members, by staff at MIPL, and as a joint SSI Team/MIPL activity.

We anticipate that well before the time of the primary mission a medium other than magnetic tape will be available for the distribution of SSI data. The rapid development of CD-ROM's and erasable optical disks holds great potential for fast and relatively inexpensive, distribution of the large Galileo data set.

5.3. SYSTEMATIC PROCESSING

SSI systematic products differ from those made for specific scientific investigations. Their primary purpose is to meet the operational and archival requirements of the

The diagram illustrates a central **Computer Workstation** connected to several peripheral devices. The connections are as follows:

- 1600/6260 BPI Tape Drive**: Connected to the workstation.
- Disk Drive**: Connected to the workstation.
- Printer**: Connected to the workstation.
- Network Link to Galileo Investigators**: Connected to the workstation.
- Digitizer Tablet**: Connected to the workstation.
- CDROM/Optical Disk Drive**: Connected to the workstation.
- Display Processor**: Connected to the workstation. It includes:
 - 1024x1024 /512x512 Display
 - 24-bit Color
- Mouse**: Connected to the Display Processor.
- Hi-Res Monitor**: Connected to the Display Processor.
- Hardcopy Device**: Connected to the Display Processor.

Galileo project. In doing this they also represent the materials on which much future research will be based. These products will be produced in great volume and according to a strict schedule in order to support ongoing mission operations, e.g., a combination of approximately 5000 monochrome, color, and mosaicked images are expected to be produced on short time scales (~ 30 days) every orbit in order to recognize changes that may have occurred from one orbit to the next and plan modifications in encounter and orbital sequences.

HIIPS End-End Flow Chart

1992SSRV...60...413B

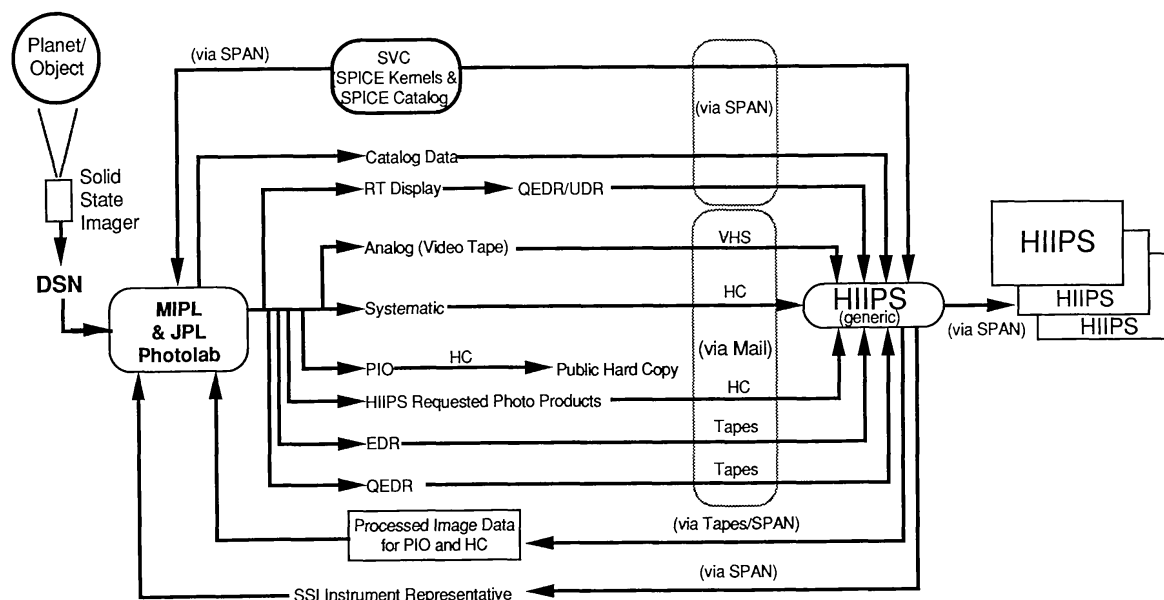


Fig. 13a. The SSI HIIPS network showing the relationship of HIIPS to the computers and data flow functions at mission control (JPL). The acronyms are defined in Figure 13(b).

Various photoproducts required for inflight sequence generation and updating, will also be systematically produced. These include duplicate negatives, duplicate positives, paper positive contact prints and paper positive enlargements of a small fraction of the data. All SSI images of solid surfaces will be enhanced and film-recorded in black and white. However, only about 10% of atmospheric images are expected to be enhanced and film recorded in this way. Atmospheric investigations will rely largely on the volatile image displays at the HIIPS workstations.

These products also include a 'reduced' data set, or EDR (Experiment Data Record), that will be made available in the scientific community for subsequent research analysis within a year of the receipt of the data. This data set will be consistently processed, will be radiometrically calibrated, and will include all requisite calibration files. Since these operations are all linear the original, or 'raw', form of the data will always be recoverable.

An introductory explanation to some of the basic systematic enhancement operations that will be performed on the SSI images is given by Cutts (1974). Systematic enhancement operations that we intend to apply to the SSI data include: blemish removal, replacement of invalid pixels by an average computed from their near neighbors; map projection and registration to allow accurate mosaicking and color, or time-sequence, registration; photometric function removal; contrast enhancement; high-pass spatial filtering; modulation transfer function compensation; and color enhancement.

For the EDR, the SSI images will be radiometrically calibrated and distributed as 16-bit files in a special VICAR, project defined, format. During early cruise the distribution media will be magnetic tape. However, we expect that by the time of orbital operations at Jupiter, CD-ROM's will be used.

Glossary for HIIPS End-End Flow Chart

Abbreviation	Full Name	Definition
Analog	Analog (Video Tape) Data	VHS format video tape with still frames of EDR's and "movies" from Encounter Time Lapse sequences.
DSN	Deep Space Network	A world-wide system of sensitive radio receivers and antennas built to capture faint signals transmitted from NASA spacecraft.
EDR	Experimental Data Record	Scientifically useful digital data provided by MIPL on magnetic tape to all HIIPS sites on a best effort basis.
HC	Hard Copy	Photographic negatives and prints, movies on video or film, and paper documents.
HIIPS	Home Institution Image Processing System	An image processing hardware and software system located in a scientist's own local laboratory.
MIPL	Multi-Mission Image Processing Laboratory	An organization at JPL (the NASA Jet Propulsion Lab, Pasadena) which processes spacecraft data received by the DSN into a scientifically useful form.
Photolab	Photographic Laboratory	A group at JPL that accepts exposed negatives and produces photographic prints and negatives.
PIO	Public Information Office	The office at JPL that distributes information to the press and public. Commonly PIO refers to hard copy officially released to the press by the JPL Public Information Office.
QEDR	Quick-look Experimental Data Record	Scientifically useful digital data which is partially processed and incompletely characterized, provided to the HIIPS sites by request of individual scientists before EDR's are available.
RT Display	Real-Time Display	A MIPL system which displays spacecraft data as soon as practical after it is received and processed.
SPAN	Space Physics Analysis Network	The general-purpose, world-wide NASA science network. SPAN is used by all NASA science, not just physicists. SPAN uses the DECnet protocol.
SVC	Galileo Science VAX Cluster	System available for some Galileo science data analysis, where the SPICE Kernels are stored. The SPICE Kernels provide navigation and pointing information for the Galileo instruments.
Systematic	Systematic Processing	Pre-planned sequence of processing operations by which MIPL produces hard copy (PIO) and digital products (EDR's and QEDR's)
UDR	Unprocessed Data Record	Digital data on disk at MIPL, available through SPAN, but not yet processed to remove noise, fill in missing lines, etc.

Fig. 13b. Definition of the acronyms used in Figure 13(a).

Calibration files and other information that will be included in the EDR are: radometric calibrations for each camera operational mode; statistics on signal chain noise; dark current files for each camera readout rate and for a range of radiation environments; the modulation transfer function as determined both on the ground and in flight; and, finally, blemish files that also include information on any changes that occur.

Another systematic product will be a set of VHS video tapes to provide an informal visual catalog of the images. These are intended to allow rapid visual searches through the data using inexpensive VCR/TV equipment immediately after receipt of the data.

HIIPS Electronic Network

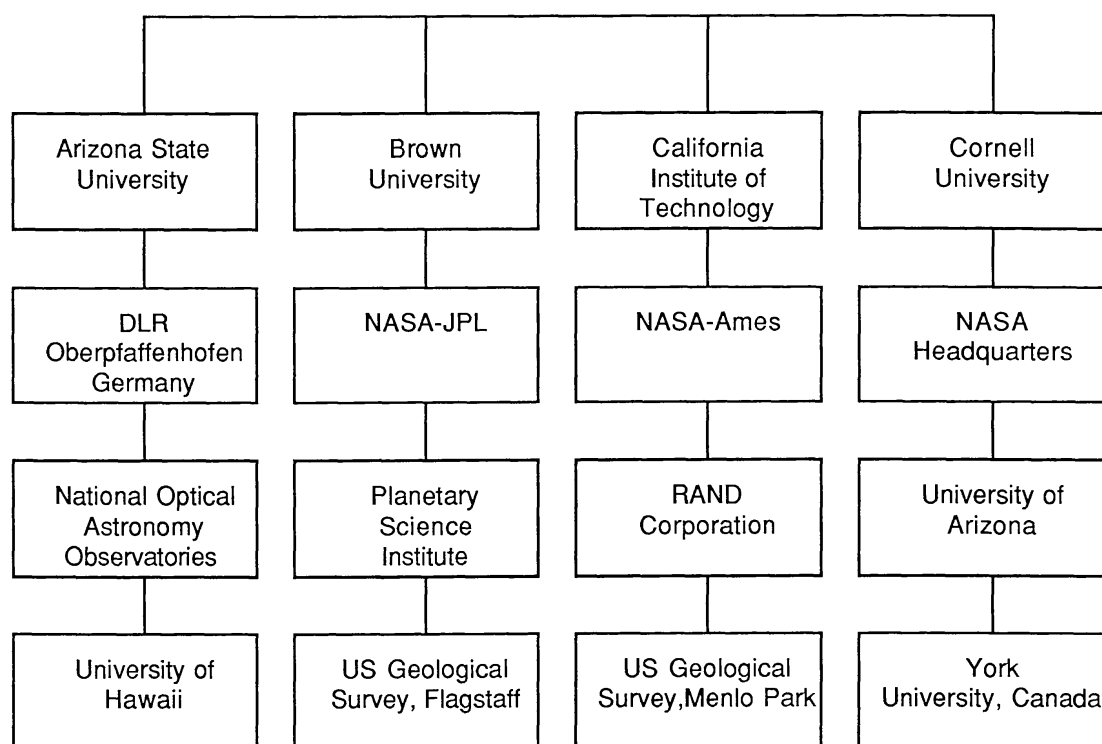


Fig. 13c. The SSI HIIPS network identifying the names and locations of the nodes. The sixteen HIIPS sites are electronically linked via the NSI (NASA Science Internet), which uses both the DECnet (SPAN network) and TCP/IP (NSN network) protocols. Individual HIIPS also connect to other scientific networks such as NSFnet and ARPANET. Network link speeds range from 9.6 kbaud to 1.5 Mbaud.

Information specifying the camera pointing geometry and other instrument and spacecraft conditions at the time of the creation of each image will be generated using the NAIF/SPICE system (Acton, 1990). This essential ancillary data will be provided in both predict and 'final' form on mission computers and on the HIIPS system. A set of records, companion to the EDRs, will also be produced as a systematic product on CD-ROMs.

Historical Notes and Acknowledgements

The SSI team was formed by NASA in 1977. The original members were M. J. S. Belton (Team Leader), C. D. Anger, M. H. Carr, C. R. Chapman, M. E. Davies, R. Greeley, R. Greenberg, J. W. Head III, G. Neukum, C. B. Pilcher, G. Schubert, J. Veverka, and J. Wellman. The Jet Propulsion Laboratory (JPL) science coordinator is K. P. Klaasen. The original JPL hardware manager was F. Landauer. The hardware was designed and fabricated in JPL Division 38. The SSI team acknowledges the work of D. Norris, J. Janesick, M. Blouke, F. Vescelus, L. Snyder, R. Locke, D. Johnson (who was responsible for the image compressor). The ground calibration was done under the

direction of K. P. Klaasen in conjunction with the staff of the MIPL, and the SSI team wishes to acknowledge the work done by D. Alexander, E. Korsmo, M. Pestana, L. Wainio, L. Wynn, and G. Yagi.

In the intervening years J. Wellman and G. Schubert have left the team to follow other pursuits – however G. Schubert remains as an interdisciplinary scientist in the Galileo project. In 1979 the hardware management passed to F. Vesceles and then to M. C. Clary in 1980. Shortly after launch M. C. Clary retired and was replaced by the present hardware manager, W. Cunningham. In 1988 K. P. Klaasen was formally added as a member of the team. The SSI team has striven for close associations with other Galileo experimenters and, as a result, special arrangements have been made with several Galileo interdisciplinary scientists (IDS's) who have formally associated themselves with the SSI experiment and have accepted major responsibilities in the experiment. These *Associated IDS's* are in effect regular members of the team and form an intellectual and experimental bridge between the SSI and other experiments. They are F. P. Fanale, P. J. Gierasch, A. P. Ingersoll, D. Morrison, and J. B. Pollack. The late Dr H. Masursky was also an Associated IDS and contributed greatly to the development of the experiment. His responsibilities to the SSI experiment have now been undertaken by A. McEwen.

The team was structured into several subgroups during the pre-launch project development. These were *Scientific Data Processing* (R. Greeley); *Systematic Data Processing* (K. P. Klaasen); *Hardware Oversight* (M. E. Davies); *Satellite Science* (M. H. Carr); *Asteroid Science* (J. Veverka); and *Atmospheric Science* (C. Chapman and M. J. S. Belton). The Scientific Data Processing Group has been largely responsible for the development of the HIIPS concept, and its implementation was managed by D. Anderson. The ongoing effort to maximize the power and reliability of the HIIPS and to develop scientific applications software in the team was first managed by the late T. E. Townsend, who has now been replaced by L. Bolef.

The interface between the team, the project, and the resources at JPL is managed by K. P. Klaasen and the members of his 'photoscience' group. The team acknowledges the work done on its behalf by B. Paczkowski, H. Breneman, S. Edberg, G. Johnson, C. Kahn, D. Speer, and W. James.

A second interface of great significance to the SSI experiment is that between the team and the Multimission Image Processing Laboratory (MIPL). This responsibility is undertaken by J. L. Anderson and L. Wainio. The team acknowledges the work done on its behalf by R. Bamberg, G. Bothwell, R. Brill, M. Girard, P. Jepsen, K. Jones, L. Kamp, S. LaVoie, S. Pohorsky, N. Sirri, S. Tews, and P. Zamani. This group is also responsible for stripping the SSI data from the real-time telemetry stream, and for making it rapidly available at JPL and to the HIIPS at the time of an encounter.

For the flight mission some of the responsibilities in the team have been changed. The Hardware group will oversee the continuing inflight calibration of the SSI. It is planned to delegate the prime responsibility for planning each encounter to two or three team members per encounter plus one lead member for the photoscience team. The encounters during the orbital mission are so close in time that we are planning for a great deal of

parallel activity. The planning of the Venus encounter was undertaken by P. J. Gierasch, M. J. S. Belton and H. Breneman; the team activities for the Moon 1 encounter are being lead by J. W. Head III, M. H. Carr, and B. Paczkowski; Earth 1 by C. Chapman, C. D. Anger and B. Paczkowski. J. Veverka and C. Chapman will be the team members primarily responsible for the Gaspra encounter. Other future encounters remain to be assigned.

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