CCD IMAGING INSTRUMENTS FOR PLANETARY SPACECRAFT APPLICATIONS*

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Aware of the great potential for improved planetary imaging, NASA has been an early and continuing supporter of CCD research. The purpose of this paper is to report on a companion effort, also sponsored by NASA, aimed at developing new spacecraft camera systems to be used in conjunction with the CCD sensors. We begin with a brief overview of the science objectives and engineering constraints which influence the design of cameras for deep space. This is followed by a review of two current development programs at JPL, one leading to a line scan imager and the other to an area array frame camera. For each of these, a general description of the imager will be given, with emphasis on the unique features. From the discussion, it will be evident that currently available CCDs fall short of our requirements in some respects. Therefore, we conclude by showing how the future of these CCD cameras is tied to the continued successful development of the sensors.

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*This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. NAS 7-100, sponsored by the National Aeronautics and Space Administration.

I. DESIGN CONSIDERATIONS FOR PLANETARY IMAGERS

The camera on a planetary spacecraft is a compromise between the wishes of the science community and the constraints imposed by technology. The first section of this paper is given over to a review of these objectives and constraints. At the invitation of NASA, planetary scientists define imaging objectives for each new mission. The original objective might be stated as: Measure the equatorial diameter of the satellite Io to ±1/2%. Given the spacecraft trajectory, the camera designer then translates this science objective into the equivalent combination of angular resolution, geometric fidelity, and image format.

The science objectives may be either absolute or relative. Absolute objectives follow from natural phenomena. For example, to study absorption by methane in the clouds of Jupiter, the camera must respond at 890 nanometers. Relative objectives are tied to a previous accomplishment or an advance in the state of the art. The scientist accustomed to 800-line television pictures is reluctant to settle for a smaller format.

The following is a brief summary of typical science objectives stated in terms of camera and sensor parameters.

(1) Resolution. Objectives range from 100 to 10 microradians per pixel. For reasonable telescopes (focal length 1.5 m or less), this requires a sample frequency of 20-40 line pairs per millimeter on the sensor. Modulation transfer for the entire camera should be at least 20% at the sample frequency.

(2) Format. A square image with 1000 elements in each dimension is considered good by most scientists; 700 elements is OK. A smaller format will be considered if some particularly attractive tradeoff is available or in case of duress (e.g., a rigid weight limitation). Larger images can be built up by mosaicking several pictures, but the metric data in a mosaic does not compare with the accuracy of a single frame. Also, ground processing costs are proportional to the number of frames, thereby making many small pictures an unattractive solution.

(3) Spectral response. Figure 1 shows several spectral bands of interest, ranging from the near-UV to the near-IR. Typical spectral filters have passbands from 20 to 100 nanometers.

(4) Geometric fidelity. In decalibrated images, it should be possible to locate features to a fraction of a picture element. This is required for stereo measurements, color registration, mapping, and other photogrammetric applications.

(5) Photometry/polarimetry. Although difficult to achieve, the request is typically for 10% absolute and 1% relative photometry. This level of performance allows the scientist to study chemical composition of the planetary surface and to detect time-dependent variations in brightness.

(6) Dynamic range. Planetary scenes frequently have low illumination and contrast, so the image modulation does not fill the entire dynamic range of the sensor. The objective is to obtain enough distinguishable grey levels in the image to permit a strong contrast enhancement when the picture is displayed. If a particular image occupies only 1/8 of the sensor dynamic range, and the contrast will be stretched to fill 16 grey levels in a photographic print, then the camera dynamic range must be at least 8 × 16 = 128. A dynamic range in excess of 200 is preferred.

(7) Image processing. For reasons of time and cost, the scientist favors an instrument which does not require elaborate image processing to produce a usable picture.

The camera must also cope with the hardships of life on an unmanned spacecraft. Listed below are the major constraints imposed by the capabilities of the spacecraft and the nature of the missions.

(1) Minimum size/weight/power. Reasonable allocations for these parameters are:

Size:	0.25 × 0.25 × 0.25 to 1.0 m
Weight:	5 - 25 kg
Power:	10 - 20 W

These numbers apply to a single camera; some spacecraft carry two.

(2) Life and reliability. Typical life requirements are 5 - 10 years shelf, 3000 hours operating. The design must withstand up to 250 g of shock and 20 g of random vibration. Simplicity is sought after, and moving parts are used reluctantly. Use of the camera as a scientific instrument requires that it hold a calibration, and this implies long-term stability. In contrast to ground-based instruments, problems with drift cannot be solved with tweaks. Exceptions to this rule must be designed in at an early stage, and substantially increase the complexity of the camera.

(3) Data bandwidth. Because of the communication distance, digital data systems are used. Each picture element is quantized to 8 - 10 bits, so 25 kHz becomes 250 kilobits per second (kbps). The real-time capability of the downlink telecommunication channel is in the range 2 - 150 kbps. The actual rate used at any point in the mission depends on the design of the spacecraft, the earth-spacecraft range, and the signal-to-noise ratio required on the channel. Under these circumstances, the ideal camera is one capable of operating at several rather low data rates.

The traditional approach has been to operate the camera at a single rate in conjunction with an external buffer on the spacecraft. The buffering is often done by a digital tape recorder with rates to 2 Mbps and capacity to 5×10^8 bits. Solid-state buffers are faster (to 10 Mbps) but have less capacity (less than 10^7 bits). Since even the buffers do not operate as fast as we might like, a slow-scan camera is often required. This means that the sensor itself must be capable of storing a shuttered image for times ranging to tens of seconds. Once the data is in the buffer, however, it can easily be read onto the radio channel at any desired rate.

For reasons of reliability and increased data return, current spacecraft design permits a bypass of the data buffer when the real-time channel is operating at high rates. In the past, matching a single-rate camera to the real-time channel has been possible only with some loss of image size or quality. To take full advantage of this real-time option, future cameras should operate in a variety of image formats and at several of the higher real-time rates.

(4) Environment. Irrespective of how the camera is mounted on the spacecraft, the electronics compartment will be at room temperature or slightly below. The telescope, on the other hand, is looking at cold space. The thermal design must control the gradients and maintain the components of the camera, particularly the telescope and sensor, within prescribed limits. The difficulty of this task depends on the temperature sensitivity of the sensor and whether or not it must be cooled.

For many current and future missions, there is a radiation hazard due to the planet, the spacecraft power generator, or both. A typical dose is 10^6 rads ionizing radiation and 10^{11} neutrons/cm^2 at 1 MeV.

(5) Low light. As planetary exploration turns toward the outer planets, the problem of low illumination level becomes severe. This is illustrated by comparing the solar illumination level at the superior planets with that at earth: earth = 1.00, Mars = 0.44, Jupiter = 0.04, Saturn = 0.01, and Uranus = 0.0025. At close encounter, integration times are limited to the millisecond range by the relative motions of spacecraft and planet. A broadband exposure at the farther planets can be less than 100 $\mu J/m^2$ in 6000°K light.

The particular strengths and weaknesses of CCDs can be seen by measuring these imagers against the foregoing list of objectives and constraints. The spectral response, particularly in the red and near-IR, would greatly expand the scope of future imaging experiments. Geometric fidelity might well prove adequate without extensive decalibration. Dynamic range and low light sensitivity are remarkable by any standard. The life and reliability of solid-state devices are potentially very good. And the size/weight/power advantage over electron beam sensors is obvious.

The known shortcomings of the CCD are not too alarming for a device still in the developmental stage. The largest arrays currently available are still marginal for planetary work. The response nonuniformities must be offset by computer processing to produce a research quality image. And the susceptibility to radiation damage has not been thoroughly explored.

On balance, therefore, NASA and JPL have found CCDs sufficiently promising to justify the camera development programs described in Sections II and III below.

II. LINE SCAN IMAGER

The objective of the line scan imager program is to develop a new camera for use on Pioneer-class missions to the outer planets. The current effort will lead to completion of a breadboard version of the instrument in 1976, and could result in a flight version for launch as early as 1979.

The Pioneer spacecraft is one-axis stabilized, i. e., it spins at a nominal 5 RPM about its roll axis. This motion permits the use of scanning-type cameras, which generally offer a weight advantage over the more familiar framing cameras. For this application, a line scan camera has been chosen, and the method of operation is illustrated in Figure 2. The camera sensor is a linear array of detectors, and this array is swept over the planet surface by the spacecraft rotation to produce a two-dimensional image. Each time the linear sensor advances by its own width, the integrated photo charge is sampled and recorded.

The line scan imager is configured in two parts: an electronic compartment located in the equipment bay of the spacecraft and a sensor/telescope package which extends outside. A stepper motor and reducing gears are used to point the telescope package fore and aft with respect to the spin axis. The second degree of freedom is obtained by allowing the rotating spacecraft to carry the telescope to the desired roll angle. Table 1 summarizes the principal characteristics of the line scan imager. Several entries in this table will require additional explanation.

The sensor chosen is a 160 pixel linear array CCD now under development at Texas Instruments, Inc. Buried-channel operation was specified to provide a higher threshold for radiation damage and better charge transfer efficiency. The sensor will be thinned and illuminated from the backside to maximize quantum efficiency. Three sensors are used in the image plane, each covering a different spectral band. The optical filters will be permanently affixed over the sensors.

For a simple line scan imager, the sensor would consist of a single line of 160 elements. The CCD, however, offers an opportunity to incorporate image motion compensation (IMC) with only a minor increase in camera complexity. On the Pioneer spacecraft, the major contributor to the image motion is the rotation of the spacecraft itself. This motion is quite uniform in rate and direction, so complex logic is not needed. As viewed in the image plane of the telescope, the scene appears to sweep over the linear sensor in a direction nearly perpendicular to the long dimension.

The image motion compensation is achieved by replacing the one-line sensor with another consisting of several lines (5 to 10). The charge transfer rate is then chosen to match the velocity of the optical image moving over the sensor. Thus, when the rotation of the spacecraft carries a point in the optical image from line 1 to line 2 of the sensor, the photo charge generated in line 1 is also transferred to line 2. After the image charge has accumulated over the space of several lines, it reaches the output register and is read by the sampling electronics. The scanning camera has no shutter, so the charge packet for line N + 1 immediately follows that for line N as they move across the CCD. Since the optical image is always present on the sensor, all parts except the active lines in the parallel registers must be covered by an opaque shield.

The effectiveness of the IMC is directly proportional to the number of active lines. For our application, approximately five accumulating lines will be used to increase the signal five-fold, with no loss of resolution. With the range of image motion velocities anticipated for this mission, 64 different charge transfer rates are needed to keep the mismatch between the optical and electronic image velocities below 3%. The runout mismatch depends on the number of IMC lines used. In this instance, the worst-case error would be 5 lines × 3% = 15% of one pixel overall error. Obviously, the larger the number of accumulation lines, the greater the demands on the CCD clock frequency generator.

The stepper motor is used with two stages of conventional gear reduction and a harmonic drive. The result is a step size of five pixels with an accuracy better than one pixel. The commandable look angles range from 10 to 185 degrees, but the instrument sees only the radio antenna at the low end of the scale.

Because of the large number of commands required to take a single picture, the imager will have a simple automatic sequencer. With this optional sequencer turned on, the camera will automatically take a series of pictures with a preselected look angle advance between frames.

The telescope focal length has been chosen to give an angular resolution of 100 μr per pixel. The optical aperture is limited to approximately 10 cm by weight restrictions.

The format of a full frame is 160 pixels × 640 lines. The short dimension is determined by the number of elements in the linear sensor. From a performance standpoint, it would be desirable to have a longer sensor, and linear CCDs many times this size have been built. However, the length of the sensor also determines the data rate out of the camera. (Recall that the line time is determined by the use of the IMC, and not by dark charge buildup or some other controllable factor.) With only 160 elements in the sensor, the maximum data rate is already 8 megabits per second. Rates higher than this would significantly increase power consumption in both the camera and the spacecraft data system.

The long dimension of the frame is determined by the capacity of the spacecraft data buffer. The imager could continue to sample the scene indefinitely, but when the buffer is filled, a pause of 2 - 8 minutes is required to relay the data to earth. Current projected capacity for a solid-state buffer on the Pioneer is 10^6 bits.

The camera can be commanded to record a quarter or half frame. The chief utility of this option is for multispectral work. The three sensors are arranged in the focal plane to permit recording of a quarter frame in three registered colors or a half frame in two registered colors.

The noise equivalent exposure is projected to be 2 $\mu J/m^2$ in 2854°K illumination, and about three times better than that in sunlight. The dynamic range should be several thousand. Digital encoding of 8 bits has been chosen to provide compatibility with existing data handling systems on the ground. Variable gain and offset values will permit assignment of the 256 grey levels to all or part of the camera's dynamic range.

III. AREA ARRAY CAMERA

The other instrument development effort is directed toward demonstrating the feasibility of an area array CCD camera for use on 1979 and later flights, such as the proposed Mariner Jupiter/Uranus mission. This camera will be compatible with the traditional Mariner spacecraft design, particularly the more recent versions (Mariner Venus/Mercury, Mariner Jupiter/Saturn). In addition to the broad requirements discussed above, specific constraints on camera design are imposed by Mariner-class missions in general, and by outer planet missions in particular.

For the present development effort, a maximum data rate of 250 kbps has been established. This corresponds to a frame readout time of approximately 6.5 seconds, which in turn requires sensor cooling to reduce dark current to an acceptable level. With dark current suppressed, the sensor itself must be capable of image storage to prevent degradation during the long readout, and to allow a pause between exposure and readout.

Unlike standard-rate television and the line scan imager, exposure (or integration) time for the area array camera is not simply the period between successive readouts. In this application, both exposure and readout times must be separately commandable from the ground. In keeping with recent practice, the camera will have variable readout rate to allow continued real-time operation as the communication channel rate falls off with distance.

Medium- and narrow-band optical filters have been an important part of past Mariner imaging experiments. CCD sensors for future missions should also maintain good image quality when narrow spectral filters are used.

Radiation tolerance is an important consideration for outer planet spacecraft, particularly for missions involving Jupiter. The cameras and other hardware must continue to operate predictably after exposure to the radiation dose integrated over the life of the mission. Allowance must be made for the possibility that the radiation flux at Jupiter will temporarily saturate the sensor, precluding any imaging during that period.

To demonstrate that these requirements can be met with a CCD imager, a feasibility model of the camera is being developed in three stages. First, a 500-element line array camera was constructed, using a Fairchild sensor (CCD-101). This camera served primarily as a learning tool, providing familiarization with general CCD operating characteristics and constraints.

The second phase of development is a breadboard area array camera, to be followed by the feasibility model itself. The feasibility model camera will be designed to use a 400 × 400 element sensor being developed for JPL by Texas Instruments. This will be a thinned, backside illuminated device for maximum quantum efficiency, particularly in the blue and near-ultraviolet. The sensor will also be a buried-channel type, which is expected to provide higher transfer efficiency, lower noise, and improved radiation tolerance compared to a surface-channel device. This is accomplished with the penalty of increased dark current and lower saturation level.

The breadboard camera will initially use a high-performance version of the recently announced RCA 320 × 512 element sensor. This is a surface-channel, front illuminated device developed primarily for standard-rate television applications. It does not, in its present form, offer all of the performance advantages projected for the Texas Instruments sensors but has the distinct advantage of being currently available. Most of the operational characteristics and circuitry requirements are similar to those of the Texas Instruments sensor.

The feasibility model camera will be a single package comprising test optics, electromechanical shutter, CCD sensor with cooling mechanism, and signal processing electronics. External optical filters will be used to demonstrate the camera properties for specific spectral bands. Table 2 summarizes the characteristics of the area array camera, including some parameters specific to the Mariner Jupiter/Uranus application. Figure 3 is a functional block diagram of the camera. A brief description of the various blocks is given in the following paragraphs.

The sensor housing contains the optics, shutter, sensor, cold plate, and cooling radiator. For an acceptable dark signal at the longer frame times, it is anticipated that a sensor temperature of -40°C will be required. This must be accomplished with the surrounding structure at -30°C to +50°C, and while maintaining the position of the sensor relative to the optical focal plane within ~50 μm.

The cooling radiator will provide cooling of the sensor in a simulated space environment, with additional cooling hardware required for bench operation. Also in bench operation, the sensor housing will be purged with dry nitrogen to prevent condensation of moisture.

The signal processor performs dc restoration and filtering of the raw sensor output signal prior to conversion to a serial digital data stream by the analog/digital converter. The sensor uses the standard "gated-charge" preamplifier, and one of the primary functions of the signal processor is minimization of the reset noise associated with this type of device. The performance of the signal processor is expected to be independent of the sample frequency (sensor clock frequency), thus simplifying the implementation of variable-rate operation. The analog/digital converter is a commercial 10-bit unit. CCD cameras are expected to have a larger dynamic range than can be encoded in 10 bits, so the signal processor will have adjustable gain.

The balance of the circuitry provides timing and control and bias to the sensor and shutter, and multiplexes the digital video with camera status data to create the composite serial data.

Table 3 lists the projected performance specifications for the camera. The camera performance will be highly dependent on the sensor characteristics, and is therefore somewhat speculative. (One goal of the program is to provide a test vehicle for assessment of sensor performance in a typical spacecraft application.)

The feasibility model camera will be subjected to a test program designed to verify and demonstrate the suitability of a CCD camera for a Mariner-type mission, including performance and environmental considerations. This testing will include characterization of the performance parameters listed in Table 3: temperature, thermal-vacuum (space simulator), vibration, and radiation.

The emphasis will be on identifying and solving problems. Specific areas of concern are sensor cooling and mounting, gradients in the sensor, focal plane shifts, and radiation compatibility (both damage and interference effects).

IV. CONCLUSIONS

We have described the general constraints placed on camera design for a planetary spacecraft, the potential advantages of CCDs in meeting these constraints, and two specific camera implementations. Success of these camera development efforts will be largely dependent upon progress in sensor development.

Current sensors exhibit a high degree of spatial nonuniformity of response. Significant improvement in this area will be required to meet the stated instrument performance goals.

Another concern is temporal stability. While CCD sensors are ultimately expected to have the inherent stability of a silicon device, this has not been realized in current devices.

Perhaps the most difficult problem is the development of sensor thinning technology to achieve high quantum efficiency and blue/UV response. Potential problems are warping and distortion of the sensor due to thermal gradients and other effects, and mounting and cooling problems.

Finally, radiation tolerance is an important problem for most projected planetary missions. Devices must be developed which minimize radiation effects, and those effects must be well understood to allow appropriate shielding and other precautions.

For future camera development, expansion to larger formats will be the primary goal. If this is to be accomplished with larger monolithic arrays, improvements in dark current and transfer efficiency will be required. Also, larger arrays will aggravate the thinning problem. An alternate implementation of the larger format involves the use of multiple sensor mosaicking, either by mounting the sensors side by side in the image plane, or by the use of optical image splitting. Neither method is completely satisfactory, the first leaving gaps in the image and the second resulting in greater optical system complexity and sensor mounting problems.

In summary, it appears that CCD cameras can play an important role in future planetary explorations, and that the potential performance advantages justify continued intensive development effort.

Table 1. Line scan imager characteristics

Sensors	Three 160 × 5 CCDs, buried-channel, backside illuminated, three-phase, double-level aluminum gates
IMC	Compensates for spacecraft roll
Multispectral	Three bands
Telescope	Focal length 229 mm, f/2.3
Stepper	Five-line increments through 165 deg
Sequencer	Automatic stepping in look angle
Size	0.25 × 0.25 × 0.50 m
Weight	7 kg
Power	10 W
Angular resolution	100 μr/pixel
Frame format	160 × 640 pixels, quarter and half frame allowed
Field of view	1 × 4 deg full frame
Noise equivalent exposure	2 $\mu J/m^2$ in 2854°K illumination
Encoding	8 bits/pixel
Data rates	Sixty-four rates from 0.5 to 8 Mbps

Table 2. Area array camera characteristics

Sensor	Texas Instruments, buried, backside
Image (raster) format	400 × 400 elements
Pixel pitch	23 μm
Image size	9.2 × 9.2 mm
Signal processing	Baseband, filtered, dc restored
Signal encoding	10 bits/pixel
Spectral filters	External to camera
Exposure times	2 - 2048 ms, 2× steps
Serial data rates	7.81 - 250 kbps, 2× steps
Frame readout times	210 - 6.56 s, 2× steps
Operating modes	1. Expose and read 2. Expose and hold 3. Read without exposing 4. Inhibit
Optics*	Focal length 1500 mm, f/8.5
Angular resolution*	15.3 μr/pixel
Shutter*	Two-blade electromechanical
Sensor cooling*	Nominal -40°C, external radiator
Size*	3000 cm^3
Weight*	4 kg (plus optics weight)
Power*	12 W

*Mariner Jupiter/Uranus application.

Table 3. Area array camera performance specifications

Saturation charge	$\sim 5 \times 10^5$ electrons
Saturation exposure	$< 10^4$ $\mu J/m^2$ at 2854°K
Noise equivalent exposure	< 2 $\mu J/m^2$ at 2854°K
Dynamic range	$> 2 \times 10^3$
Dark charge	< 5% of saturation at 13 s, -40°C
Squarewave response	> 30% at 22 lp/mm
Quantum efficiency	> 20% at 400 nm > 50% at 600 nm > 50% at 800 nm > 5% at 1000 nm

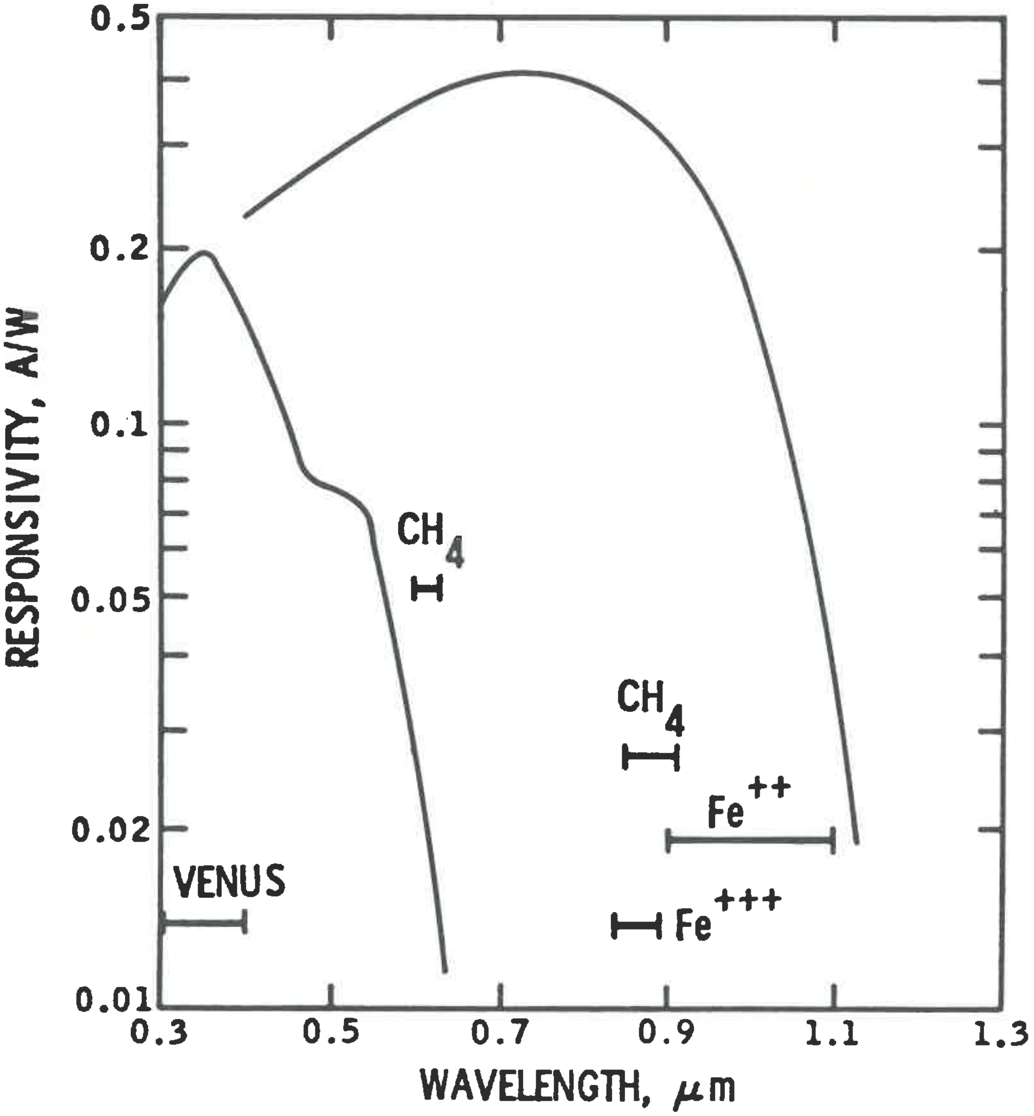

Figure 1. Typical spectral bands of interest to planetary scientists (Response curves for selenium-sulfur vidicon and CCD are superimposed.)

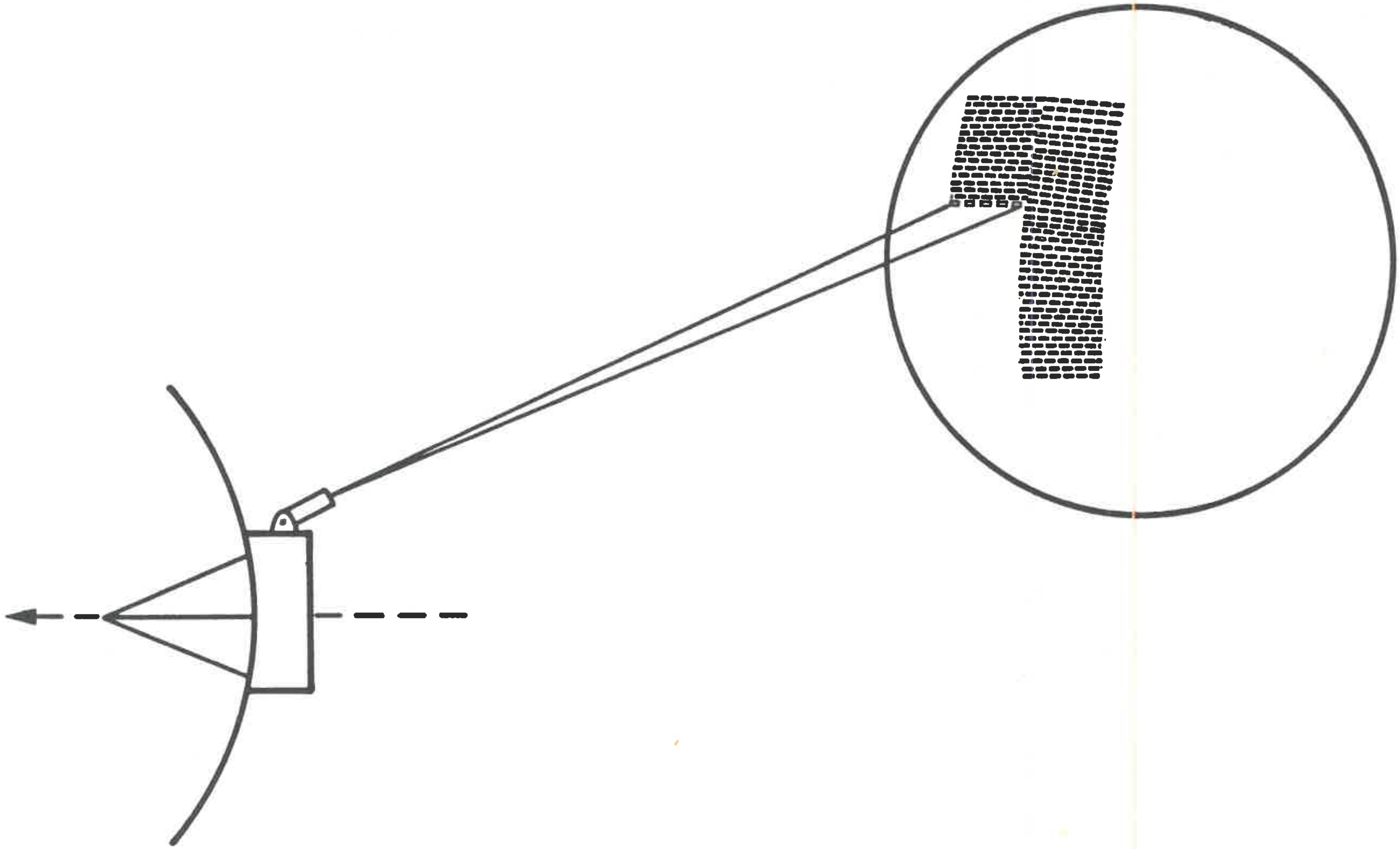

Figure 2. Method of image formation by line scan camera (Scan is from top to bottom.)

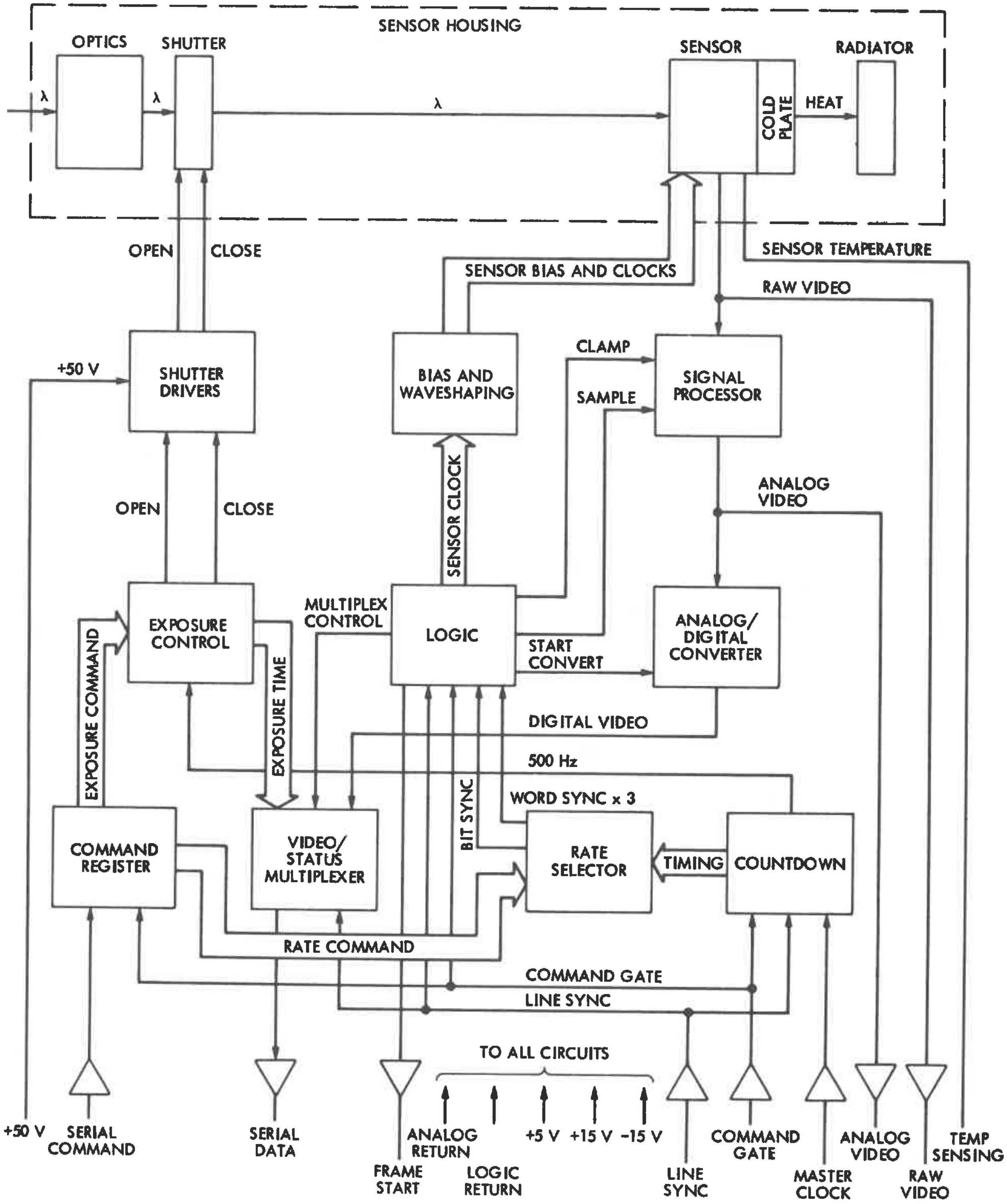

Figure 3. Functional block diagram for feasibility model area array camera