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THE APPLICABILITY OF FRAME IMAGING FROM A SPINNING SPACECRAFT

VOLUME 1

SUMMARY REPORT

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SUMMARY REPORT

1.0 INTRODUCTION

This report presents the results of the "Study of the Applicability of Frame Imaging from a Spinning Spacecraft", performed by CBS Laboratories, Stamford, Connecticut, for the National Aeronautics and Space Administration, Ames Research Center, under Contract NAS2-7107. Volume 1 is a summary of the final report of the study. Volume 2 presents the detailed technical results. The study was performed over the 10-month period from July 1972 through May 1973.

2.0 DESCRIPTION AND SCOPE OF STUDY

The basic purpose of this work is to study the applicability of frame-type imaging systems for use on board a spin-stabilized spacecraft for outer planet applications. Two basic types of spacecraft platforms are presently being considered for these future missions. First is the familiar three-axis stabilized spacecraft, as typified by the Mariner and Viking vehicles. The second is a spin-stabilized system, as typified by Pioneer F and G. This study addresses the use of frame imagers on spinning platforms only. The distinction between frame imaging and spin-scan imaging should be noted, as only the former is treated in this study.

The major objectives of this study are to select the most feasible frame imaging systems for this class of mission and to prepare preliminary design information which defines the systems for a specific Jupiter orbiter mission. In addition, system performance levels and cost tradeoffs in terms of important system parameters are to be investigated.

The scope of the study includes only frame imagers on a spinning spacecraft, and the emphasis is placed on an orbiting mission of Jupiter with encounters with the Galilean satellites. However, the discussion is extended to include camera performance at the other outer planets.

All types of frame imagers having potential for this application have been considered, regardless of the current state of the art. Detailed sensor models of these systems are developed at the component level and used in the subsequent analyses. An overall assessment is then made of each of the candidate sensors, based upon the results of worst-case performance analyses, technology problem areas, foreseeable improvements, and the relative reliability and radiation tolerance of the systems. Special attention is directed at the constraints imposed by image motion and by the limitations of data transmission and storage.

Based upon the overall assessment of the potential sensors, the most promising systems are selected and examined in detail for the specified Jupiter orbiter mission. The three selected camera systems are the secondary electron conduction (SEC) vidicon, the electrostatic storage camera (ESC), and the intensified charge-coupled device (ICCD). The relative merits of each of these systems are then analyzed, and system design characteristics are presented using preliminary configurations, block diagrams, and tables of estimated weights, volumes and power consumption. Performance tradeoffs are then discussed. Finally, cost and development schedules are presented for the three selected frame imaging systems.

3.0 BASIC APPROACH

The work is initially divided into nine separate study tasks. Each of these study tasks is treated independently in the detailed technical discussion in Volume 2.

- Selection of the Candidate Systems
- Preparation of Computer Models
- Preparation of Computer Programs
- Radiation and Reliability Factors Study
- Image Motion Analysis
- Worst-Case Analysis, Comparison of Cameras and Selection
- Analysis for Jupiter Orbiter Mission
- Preliminary Design and Technological Assessment
- Cost and Development Schedules

4.0 SIGNIFICANT RESULTS OF THE STUDY

The significant results and assumptions applying to each of the major study tasks are now summarized.

4.1 SELECTION OF CANDIDATE SYSTEMS

The principal requirements for the ideal frame imager for planetary missions are high resolution, high quantum efficiency, reliability, and compatibility with the spacecraft and planetary mission environments. These requirements also include high radiation tolerance, light weight, low power consumption, low cost, and adaptability to a variety of outer planet missions. For spacecraft with limited data storage equipment, long target storage with a slow-scan capability is also essential. No currently available imaging system satisfies all of these requirements. At best, camera systems must be selected on the basis of compromise, accepting the shortcomings of the device as well as its merits and satisfying only the most important requirements for a particular mission.

Based on these and other imaging system requirements, several candidate camera systems have been selected for study. Both imaging systems which have been employed in previous space missions, and other systems offering many distinct advantages but still in the developmental stage, are among the candidates which have been considered. Included as candidates are the slow-scan vidicon, silicon vidicon, silicon intensifier target (SIT) vidicon, SEC vidicon, return beam vidicon, silicon dioxide vidicon, electrostatic storage camera, and charge-coupled imagers. The use of an intensifier stage coupled to the candidate sensors has been considered where applicable.

4.2 CAMERA MODELING

In order to compare the performance of the candidate cameras, a detailed analytical model is developed for each system. These models describe the resolution (modulation transfer function) and peak-signal-to-RMS-noise characteristics of the frame imagers. They are used in subsequent analyses to predict the performance of the candidate systems.

As an example, Figure 1 illustrates the mathematical model used to characterize the signal-to-noise ratio of the electrostatic storage camera. The contributions due to the major noise sources are identified.

The analytical signal-to-noise-ratio models take into consideration the orbital relationships for an outer planets mission. Mission parameters such as the planetary irradiance, scene contrast, image smear due to the spacecraft spin rate, altitude, and phase angle, are included in the model. The models predict performance through the use of the aerial image modulation (AIM) concept and the threshold modulation method.

Computer programs were developed for the signal-to-noise-ratio models of the candidate imaging systems. These programs, written in FORTRAN IV, are used to perform the parametric analysis. A detailed presentation of these programs is given in Volume 2.

Figure 1

MATHEMATICAL SIGNAL-TO-NOISE RATIO MODEL
FOR ELECTROSTATIC STORAGE CAMERA

$$SNR = \frac{\frac{M_o \tau_s(K) G_M m\delta_t I_b C_t t_e t_L W_p S_p \cos\theta}{2C^* r^2 f^2} \int_0^\infty W_\lambda P_\lambda t_{o\lambda} \sigma_\lambda d\lambda}{\left[\frac{8eI_F B^3 C^2}{g_m^2} + \frac{4kTB}{R_L} + G_M^2 \left(2eI_b B\left(\frac{m\delta_t}{\delta_m - 1} + a^2\delta_t^2 + a^2[\kappa-\delta_t]\delta_t + a[1-a]\delta_t\right) + \left[\frac{m\delta_t I_b}{C^* A}\right]^2 \left(\frac{eI_b[1+(\kappa-2)\delta_t]}{2B} + \beta^2[G_t+1]\left[\frac{eG_t A t_e t_L W_p S_p \cos\theta}{4r^2 f^2} \int_0^\infty W_\lambda P_\lambda t_{o\lambda} \sigma_\lambda d\lambda\right]\right)\right)\right]^{1/2}}$$

Preamp FET Shot Noise; Load Impedance Thermal Noise; Read Beam Shot Noise; Electron Mult. Noise — Modified By: Mult. at Read-Out; Secondary Emission Noise of Dielectric; Energy Analyzer Partition Noise; Dielectric Charging Noise during Readout; Quantum (Image) Noise

LIST OF PARAMETERS

Symbol	Description	Units
k	Boltzmann's constant	joules/°Kelvin
T	Absolute temperature	°Kelvin
B	Bandwidth of video circuit	Hertz
R_L	Output load impedance	ohms
I_F	FET channel current	amps
C	Preamp input shunt capacitance	farads
g_m	Transconductance	amps/volt
G_M	Gain of electron multiplier	-
e	Electronic charge	couls
I_b	Readout beam current	amps
a	Fraction of return beam passing thru energy analyzer	-
M_o	Object modulation	-
$\tau_s(K)$	System MTF	-
r	Sun-planet distance	astronomical units
f	f number of optical system	-
θ	Phase angle	degrees
σ_λ	Relative spectral distribution of detector (S-20)	

Symbol	Description	Units
δ_t	Secondary emission of tape during readout	-
δ_m	Secondary emission yield of first dynode of electron multiplier	-
κ	Secondary emission noise factor	-
m	Slope of readout characteristic	amps/amp / volts
C^*	Tape capacitance/unit area	farads/meter^2
A	Area of element	meters^2
β	Noise bandwidth correction factor	-
G_t	Gain of storage tape	-
t_e	Exposure time	sec
t_L	Transmission of optical system	-
W_p	Peak spectral density of input flux	W/m^2/nm
W_λ	Relative spectral distribution of the input flux	-
$t_{o\lambda}$	Spectral transmission of sensor faceplate	-
S_p	Peak monochromatic responsivity of the detector (S-20)	amps/W

4.3 IMAGE MOTION ANALYSIS

It is concluded that an image motion compensation system is mandatory for operating frame imagers on spinning platforms. The performance of frame imagers is limited by the rotation of the spacecraft because of the excessive image motion which occurs during exposure. An image motion compensation system that provides compensation for approximately 90% of the relative motion between the sensor system and the planetary scene is required at nominal spin rates (5 rpm) to obtain acceptable performance levels. With image motion compensation (IMC), exposure times can be increased (to the 0.0005 sec to 0.001 sec range), increasing the signal-to-noise ratios of some sensors to acceptable levels.

An electronic IMC system in which corrections are applied within the image section of the frame imager is desirable particularly when the exposure time is short. Electronic IMC will be simpler, lighter, and more reliable than its mechanical counterpart. Two-direction compensation, which is needed when the viewing angle of the camera is not normal to the spacecraft spin axis, will also be easier to implement using electronic IMC.

Among the several types of image motion present,the linear motion caused by the spacecraft spin rate is clearly dominant for short exposure times. The motion of the spacecraft relative to the planet, as well as random vibrations of the sensor mounting platforms, are not significant until the effects of spacecraft spin motion have been corrected.

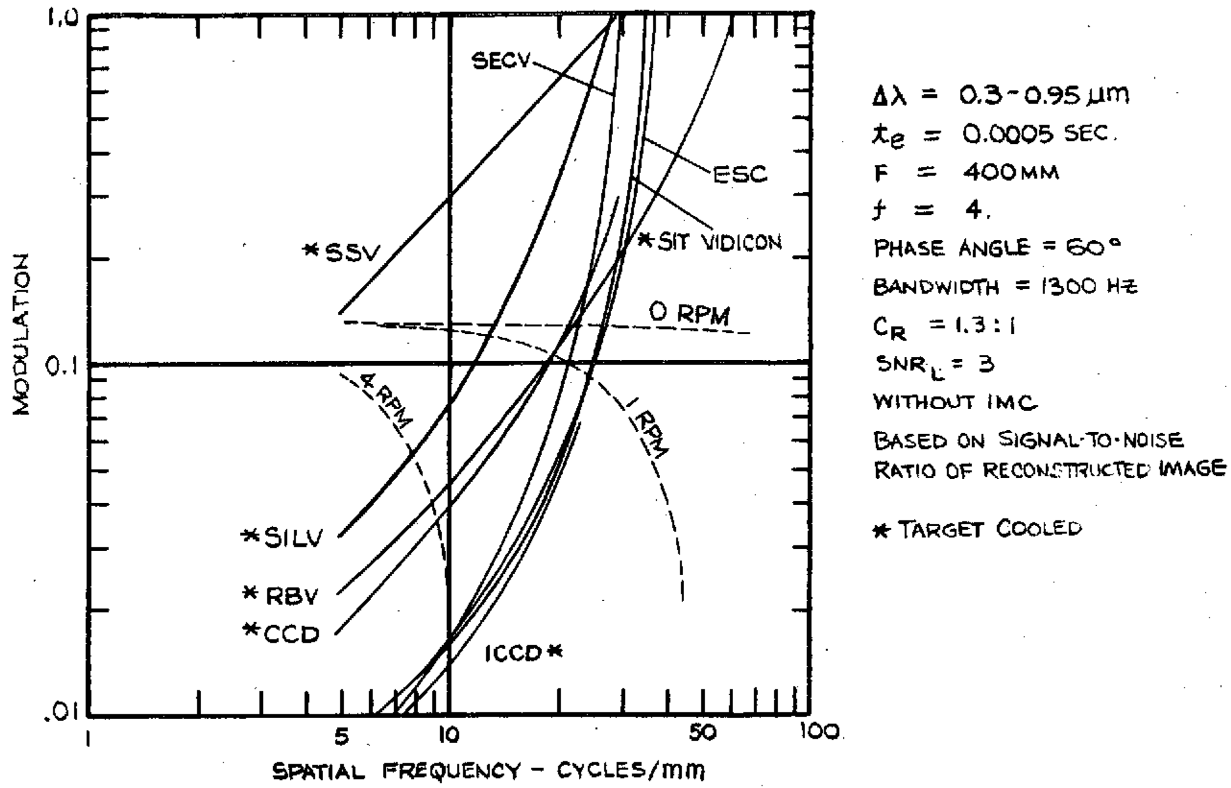
4.4 WORST-CASE ANALYSIS AND SELECTION OF BEST SYSTEMS

The analytical models of the candidate systems were used in a worst-case parametric analysis in order to select the most promising frame imaging systems to be used on spinning spacecraft. Based on the results of this analysis and on an overall assessment of all potential frame imagers, three satisfactory systems were found:

- SEC Vidicon
- Electrostatic Storage Camera
- Intensified Charge-Coupled Device.

The preliminary screening analysis used to select the best camera systems was based on a number of constraints. The analysis was limited to the planet Jupiter at a worst-case phase angle of 60 degrees and a contrast ratio of 1.3:1. The weight of the complete imaging system was limited to 18 kg. Spin rates of 2 to 32 rpm were considered for a spin-stabilized system as typified by Pioneer F and G. A 3-year mission duration was assumed. Imaging systems with long target storage were considered most desirable so that the data could be transmitted back to Earth without ancillary data storage equipment. Telemetry rates between 2,048 and 83,220 bits/sec were considered, but a nominal value of 16,384 bits/sec was used for most of the analysis.

Typical threshold modulation curves for the candidate sensors based on the signal-to-noise ratio of the reconstructed images are shown in Figure 2 with available aerial image modulation curves for several spin rates superimposed. Threshold curves are based on a constant signal-to-RMS-noise ratio of 3, an exposure time of 0.0005 sec, and a video bandwidth of 1300 Hz which corresponds closely to an average data rate of 16,384 bits/sec. The sensors preceded by asterisks must be cooled to temperatures ranging to $-60^{\circ}C$ to reduce the dark current of the targets sufficiently to operate at slow-scan rates. This gives a good indication of why many frame imagers were rejected. Devices such as the slow-scan vidicon (SSV), silicon vidicon (SILV), and return beam vidicon (RBV) are not sensitive enough to perform adequately at the worst-case conditions.



THRESHOLD MODULATION CURVES

Figure 2

Table 1 summarizes the selection factors used in determining the best camera systems. Characteristics identified by a "Y" rating represent desirable features, while a "N" rating indicates an undesirable feature. Camera systems with a single major or several minor negative characteristics were rejected. Characteristics that were considerations for rejection are circled in the table.

TABLE 1

SUMMARY SENSOR SELECTION MATRIX

SENSOR	SLOW-SCAN CAPABILITY (W/O COOLING)	LONG TERM STORAGE (W/O COOLING)	PRE-STORAGE TARGET GAIN	HIGH SENSITIVITY	HIGH TARGET CAPACITANCE	DEVELOPED & SPACE QUALIFIED	ADEQUATE WORST CASE PERFORMANCE	GOOD RADIATION RESISTANCE	SELECTION
	CHARACTERISTIC								
SEC VIDICON	Y	Y	Y	Y	N	Y	Y	Y	Yes
ESC	Y	Y	Y	Y	Y	N	Y	Y	Yes
ICCD	(N)	N	Y	Y	N	N	Y	-	Yes
CCD	(N)	N	N	N	N	N	(N)	-	No
SIT VIDICON	(N)	N	Y	Y	Y	Y	Y	-	No
SILICON VIDICON	(N)	N	N	(N)	Y	Y	(N)	-	No
RBV	(N)	N	N	(N)	Y	Y	(N)	-	No
SiO_2 VIDICON	Y	Y	Y	Y	Y	(N)	Y	Y	No
SSV-SELENIUM	Y	Y	N	(N)	N	Y	(N)	-	No
SSV-ASOS	(N)	N	N	(N)	Y	Y	(N)	-	No

CODE: Y YES

N NO

\- INSUFFICIENT DATA

◯ CONSIDERATION FOR REJECTION

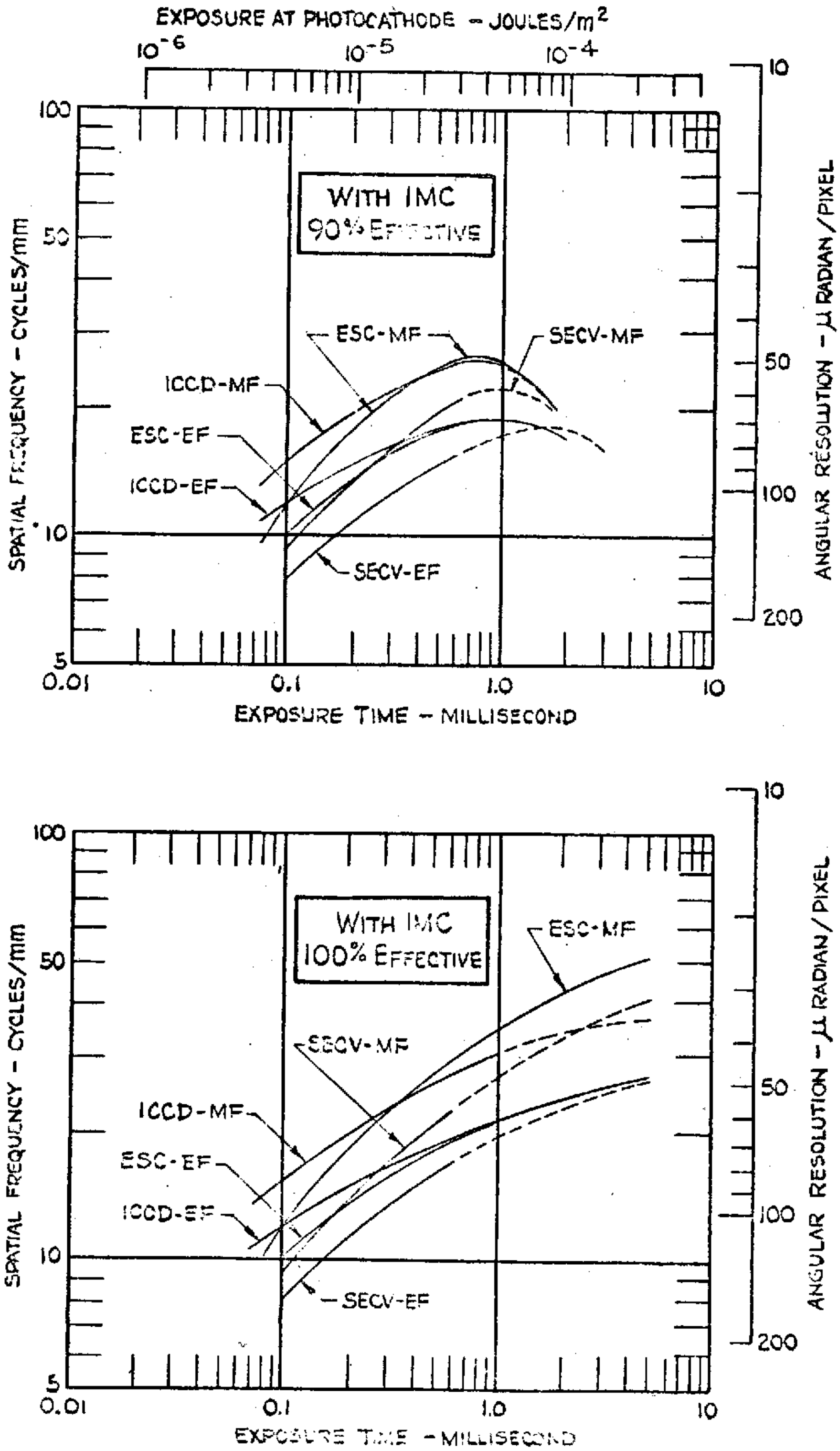
Devices such as the slow-scan vidicon, silicon vidicon, and return beam vidicon were rejected on the basis of inadequate worst-case performance due to low sensitivity. The charge-coupled device was rejected for inadequate performance because of the excess readout noise that occurs at slow-scan rates. The SIT vidicon was eliminated because of the cooling required to achieve slow-scan operation. The SiO_2 vidicon was dropped because there is insufficient justification to develop the sensor when similar sensors already perform as well.

The electrostatic storage camera was selected, even though it requires additional development, because of its multi-frame capability and excellent overall performance. The intensified charge-coupled device was selected despite a requirement for cooling because of its potential for excellent performance at low power and low weight. The pre-target gain reduces the readout noise at slow-scan rates to an acceptable level. The ICCD is more sensitive than the other camera systems. It does not require an electron beam for readout, and is easier to cool than a vidicon tube because of its small size and low-power consumption. The SEC vidicon was also selected, primarily because of its slow-scan capability, good performance and off-the-shelf availability.

Performance curves for various configurations of the three selected camera systems are presented in Figure 3 showing the resolution as a function of exposure time at Jupiter. Electromagnetically-focused (MF) configurations are included, as well as the electrostatically-focused (EF) versions. Nominal system parameters were selected. Currently available IMC subsystems which provide compensation for ninety percent of the motion due to the spacecraft spin are used in the upper graph. As the exposure time is increased, each sensor reaches a point of maximum performance. The resolution then begins to drop off as the smear due to image motion increases. Since IMC systems can probably be developed for this mission which would compensate for more than 90% of the relative motion, the lower graph of Figure 3 shows the ideal 100%-effective-IMC case for comparison. Note that as the IMC system is made more effective, exposure times can be lengthened. The shutter mechansim and optics diameter requirements can thus be relaxed accordingly.

4.5 ANALYSIS FOR SPECIFIED JUPITER ORBITER MISSION USING SELECTED CAMERA SYSTEMS

The mission selected for study by the National Aeronautics and Space Administration is a Jupiter orbiter which encounters three satellites. The selected 1976 orbit is equatorial with a 2.29 R_J periapsis, a 45.13 R_J apoapsis and a period of 14.22 days. From an interaction-region orbit (2.29 x 100 R_J), the spacecraft is deboosted into the selected orbit, where repeated close encounters with the satellites occur for about three to five orbits.



SPIN RATE = 5 RPM
PLANET JUPITER
$C_R = 3.1:1$
F = 400 mm $f = 4$
$SNR_L = 10$ $\theta = 60°$
BANDWIDTH = 1300 Hz
BASED ON SNR OF RECONSTRUCTED IMAGE.
$\Delta\lambda = 0.3 - 0.95\ \mu m$

RESOLVING POWER VERSUS EXPOSURE

FIGURE 3

The spin axis of the spacecraft, which is common to the antenna system, is normally directed towards Earth during the orbit so that information can be transmitted to the receiving station. Accordingly, a pointable camera is employed in order to view Jupiter from various portions of the orbit. This also allows the camera to follow the satellites during satellite encounters. For purposes of this analysis, the orientation of the camera viewing direction is assumed to be normal to the spacecraft spin axis.

Both the ICCD and ESC perform better than the SEC vidicon due to their higher modulation transfer functions (MTFs). The electromagnetically-focused configurations perform better than their electrostatically-focused counterparts because of the higher image section MTFs involved, however, additional weight and possibly power will also be a factor in their selection.

The data in Figure 3 show that system performance is limited more by image smear rather than by the sensor parameters, particularly for the high-performance electromagnetic configurations. If the smear could be completely compensated, high-performance cameras could be constructed. Such systems are not required for this particular Jupiter orbiter mission,however.

When photographing the satellites of Jupiter, the three selected camera systems all perform satisfactorily. However, if multispectral photographs of the satellite surfaces are to be taken, the electrostatic storage camera (ESC) offers an advantage. Because of its unique bulk storage capability, it can expose a sequence of pictures in rapid succession, each at a different spectral band, and transmit them back to Earth at a later time. Contiguous ground coverage over several spectral bands can be achieved in this manner over a wide resolution range from close-up shots to full-disk photographs. The ICCD and SEC vidicon, which must transmit each picture before another is taken, would require a tape recorder to obtain similar coverage over several different spectral bands.

The selected cameras appear suitable for missions to Saturn and Uranus without any major design change. The resolution of the sensors deteriorates due to the low available illumination when missions to Uranus are considered. For example, when a resolution of about 20 cycles/mm is obtained at Jupiter for a contrast ratio of 1.3:1,using an electrostatically-focused SEC vidicon, at Saturn and Uranus the resolution decreases to about 6 and 14 cycles/mm respectively. This decrease is particularly noticeable with the SEC vidicon because its MTF is lower than the other sensors (primarily because of its target thickness). The ESC is considered the best sensor for both the outer planet missions and for flybys when tape recorders cannot be used.

4.6 RADIATION AND RELIABILITY FACTORS

There is a need for additional radiation studies, as there is insufficient experimental evidence available to completely categorize the susceptibility of the various camera systems to radiation damage. However, a general grouping of these devices in order of increasing susceptibility has been made.

The SEC and SiO_2 vidicons and the electrostatic storage camera should be the least susceptible. These devices use an insulating film to store the image until readout, so the only degradation expected is due to the discharge of the target during storage periods or in peak radiation environments. The SIT vidicon and ICCD are probably more susceptible due to the increased dark current of the silicon targets.

There are insufficient data on the performance of other devices. However, the RBV and CCD both have photoconducting targets which may be susceptible to increased dark current and loss of quantum efficiency. This effect has been reported in other vidicons with photoconductive targets (e.g., the slow-scan vidicon and the silicon vidicon).

Only a qualitative assessment relating the comparative reliability of the candidate sensors is possible until specific auxiliary hardware is selected. Items such as tape recorders, special thermal control, image-motion-compensation mechanisms, and mechanical shutters will have a great impact on reliability figures. From a combined radiation and reliability standpoint, the SEC tube, silicon dioxide vidicon, and charge-coupled imagers should rank the highest. The SIT vidicon and ESC systems should have good reliability. The reliability of the RBV, silicon vidicon and slow-scan vidicon systems will range from good to fair depending on the auxiliary equipment requirements and the amount of shielding provided.

4.7 PRELIMINARY DESIGN

Preliminary design information has been compiled for the three camera systems chosen for the Jupiter orbiter mission. Sketches of each system with estimated dimensions are given in the detailed technical discussion. A functional block diagram of each system has been prepared showing the interrelationship between the various subsystems. The weight and power requirements of each system are presented as a function of several available performance options.

Weight and power design data for the systems are summarized in Table 2 to illustrate possible performance tradeoffs. System options necessary to photograph Jupiter and its major satellites are given in the upper table. Options more appropriate for other outer planet missions, where long transmission periods are required or when multispectral coverage is needed, are shown in the bottom table. These system options include a multiple-frame storage capacity so that they can return adequate data. The ESC system utilizes an internal storage drum, while the other systems depend on a tape recorder, to obtain the necessary photographic coverage.

4.8 COST AND DEVELOPMENT SCHEDULES

Both engineering cost estimates and two mathematical cost models developed by NASA were used to estimate the cost of the camera systems. Costs of mission operations and data processing were not included in the study.

TABLE 2

PERFORMANCE TRADEOFFS FOR SELECTED JUPITER ORBITER MISSION

CAMERA	FOCUS	SYSTEM RESOLUTION* (μrad/pixel)	WEIGHT (kg)	POWER (W)
ESC (30 frames available)	Electrostatic (ES)	72	16.2	24.8
	Electromagnetic (EM)	46	18.0	26.2
	Permanent Magnet (PM)	46	17.4	24.8
SEC	ES	76	12.8	16.2
	EM	59	14.6	17.6
	PM	59	14.0	16.2
ICCD	ES	68	12.1	11.2
	EM	50	13.9	12.4
	PM	50	13.3	11.2

PERFORMANCE TRADEOFFS FOR OTHER OUTER PLANET MISSIONS REQUIRING MULTIFRAME STORAGE

CAMERA	FOCUS	SYSTEM RESOLUTION* (μrad/pixel)	WEIGHT (kg)	POWER (W)
ESC (30 Frames available)	Electrostatic (ES)	72	16.2	24.8
	Electromagnetic (EM)	46	18.0	26.2
	Permanent Magnet (PM)	46	17.4	24.8
SEC (With Recorder)	ES	76	17.3	26.2
	EM	59	19.1	27.6
	PM	59	18.5	26.2
ICCD (With Recorder)	ES	68	16.6	21.2
	EM	50	18.4	22.4
	PM	50	17.8	21.2

*For 150-mm lens diameter, 400-mm focal length, 0.25-msec exposure, SNR = 10, 60° phase angle, 1.3:1 contrast, 5-RPM spin rate with 90%-IMC, 1300-Hz bandwidth.

The engineering cost estimates appear to be the most accurate both in terms of total cost and relative cost differences between the three systems. A summary of these estimates is presented in Table 3 for the three selected camera systems ranked according to an overall assessment.

TABLE 3

CAMERA SYSTEM COST ESTIMATES

ESC	$ 5.64 M
SECv	$ 2.95 M
ICCD	$ 4.8 M

Development schedules for the three best systems were prepared in detail. The overall period from the initial contract date to the delivery of the flight model to the spacecraft contractor is summarized in Table 4.

TABLE 4

DEVELOPMENT SCHEDULE

Camera Type	1st Flight System
SEC Vidicon System	21 Months
ESC System	36 Months
ICCD System	36 Months

5.0 CONCLUSIONS

The major conclusions of the study are summarized below:

- The use of frame imaging systems from a spinning spacecraft typified by Pioneer F and G is feasible. However, an image motion compensation system is required at all but the slowest spin rates to limit image smear during exposure and thereby maintain the resolution capability of the camera.

- Only a short exposure time (generally less than one millisecond) can be used at nominal spin rates - even when image motion compensation is provided - because of the residual image smear. This precludes the use of many frame imagers having insufficient sensitivity,such as the slow-scan vidicon, silicon vidicon, and return beam vidicon. Several other frame imagers are quantum noise limited and perform satisfactorily at these exposure levels.

- Sensors with image sections afford convenient low power, low weight methods of electronically implementing image motion compensation and shuttering.

- It is desirable to have a camera system that can store an image, without using an ancillary storage system such as a tape recorder, until the data handling and communications system can transmit the data to Earth. Emphasis was therefore placed on those camera systems capable of slow-scan operation. The SEC vidicon and electrostatic storage camera meet this and other criteria, and they are accordingly considered acceptable for a Jupiter orbiter mission.

- Almost all frame imagers are capable of slow-scan operation and long-term storage if sufficiently cooled. The SIT vidicon can provide integration times of several hours when it is cooled to $-60^{\circ}C$. Implementing thermal control, however, can involve the use of considerable weight and power and other practical difficulties. The SIT vidicon, for instance, is more applicable to missions using on-board storage at higher video bandwidths, and it was therefore rejected for this study.

- The charge-coupled imager requires cooling to achieve a slow-scan capability. However, charge coupling is a significant new concept in imaging which has attracted much interest. The potential attributes of excellent performance at low power, low weight, and good reliability are very appealing. The low-noise properties obtained by integrating the amplifier on the CCD chip, used in conjunction with a high prestorage target gain, results in a system with excellent overall sensitivity. For these reasons, a charge-coupled imager was one of the systems selected for the Jupiter mission. An intensified charge-coupled device was selected as it contains an image section which makes electronic shuttering and electronic image motion compensation feasible. Unlike the basic charge-coupled device, its performance is less sensitive to readout noise at low clock rates.

- Based on a worst-case parametric analysis and an overall assessment of all potential frame imagers, the SEC vidicon, the electrostatic storage camera, and the intensified charge-coupled device were found to be the best systems for the class of missions studied.

- The three selected camera systems all perform satisfactorily using the parameters for the 2.29 x 45.1 R_J Jupiter orbiter mission. Ground resolution of 5 to 8 km at the surface of Jupiter can be achieved near periapsis with these systems. Less than 1 km ground resolution can be achieved at the surface of the satellite Io. Full-disk photographs of Jupiter would have a surface resolution of 200 km.

- Performance appears to be limited more by other system parameters than the sensors, particularly for the high-performance electromagnetically-focused camera configurations. If the camera parameters were not dominated by factors such as image smear, even higher-performance versions could be constructed. However, such systems are not required for this particular Jupiter orbiter mission.

- When photographing the satellites of Jupiter, the three selected camera systems all perform satisfactorily. However, if multispectral pictures are to be taken with filters over several color bands, then the ESC offers an advantage because of its multiframe storage capability. Several frames of a surface feature may be exposed,using different spectral bands, before the sequence of pictures is transmitted to Earth.

- The selected camera system appears suitable for missions to Saturn and Uranus without major sensor design changes. However, due to the low available illumination at Uranus, the resolution of all the sensors deteriorates, the SEC vidicon more than the others. The ESC is considered the best sensor for outer planet missions and flybys when weight and power limitations exclude tape recorders.

6.0 SUGGESTIONS FOR FURTHER WORK

Based on the results of this study, a number of suggestions are tendered for further work associated with the camera system.

- New camera concepts are now being actively investigated by industry. The electrostatic storage camera and charge-coupled imagers are two systems that should be adapted to future outer planet missions. NASA support in funding the development of the ESC and ICCD is clearly indicated by this study. Active support by NASA is recommended in order to speed up the availability of these systems.

- There is a need for additional radiation studies, especially involving low-energy protons, at irradiation levels approximating those expected at Jupiter. There is insufficient experimental evidence available on the susceptibility of the various camera systems to radiation damage.

- Even existing camera systems may require additional development work to function adequately on a Jupiter orbiter mission. In particular, the development of new shutters may be required in order to achieve the short exposure times necessary to limit image smear. The need for shutter design improvement will depend on the type of shuttering used, the effectiveness of the IMC system, the type of sensor and other factors. Existing mechanical shutters do not operate well in the required range of 0.0005 to 0.002 seconds and will have to be improved if they are to be used. An electronic shutter incorporated into the image section of the sensor is recommended from a reliability viewpoint. While electronic shutters have been satisfactorily applied to electrostatically-focused sensors, additional work will be required to implement electronic shuttering in electromagnetic image sections.

- An image motion compensation system is mandatory. Although presently available mechanical image motion compensation systems and angular velocity sensors are satisfactory, they are heavy.

Alternative mehtods of IMC should be investigated, particularly electronic IMC where compensation takes place within the image section of the tube. In the case when the viewing angle between the spacecraft spin axis and camera pointing direction is less than 90^{o}, it should be easier to implement two-axis compensation using electronic IMC rather than mechanical IMC. Alternative methods of sensing the required amount of angular compensation, including pre-programming fixed amounts of correction, should be analyzed.

7.0 BASIC DATA GENERATED APPLICABLE FOR GENERAL USE

A major portion of this study was devoted to the development of the analytical models of the various frame imagers and the computer programs used in the analyses. This work has been documented in considerable detail in Volume 2 so that it is available for general use. The camera models and associated computer programs may be readily modified to obtain comparative performance results for the various frame imagers on this and other deep-space missions.