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GRAND TOUR OUTER PLANET MISSIONS
DEFINITION PHASE

Report of the Imaging Science Team

February 1, 1972

PART 1: Quantitative Imaging of the Outer
Planets and Their Satellites

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*Dr. Bruce C. Murray (California Institute of Technology) resigned as a member of the team on December 2, 1971. We gratefully acknowledge his inputs to the work of the team especially in the areas of information return and data compression.

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1. INTRODUCTION

The OPGT Definition Phase Imaging Science Team was formed by NASA in April, 1971. In the interval of time between then and December 1971 the team has held 8 full meetings with numerous additional subcommittee meetings. A team plan was formulated in which it was decided to emphasize considerations of scientific rationale, science priorities, choice of sensor and optics, mission sequencing and problems of information return. Future considerations will center around a more detailed interaction with engineers at JPL on a narrower range of TV systems. Other areas which require intensive investigation concern on-board data compression and editing modes, tape recorder/buffer storage strategy, ground data handling requirements, in-flight calibration, environmental radiation problems, and navigation capability.

NASA has funded several outside technical studies at the request of the imaging team. The status of these studies is reported in Part 2 of this report.

The team would like to acknowledge the willing help and advice offered by R. Krauss of University of Wisconsin, G. Smith, L. Simmons, G. Root, G. Bailey, L. Synder and P. Penzo of JPL during all phases of this work.

2. SUMMARY AND MAJOR CONCLUSIONS

A. Recommended Imaging System and Fallback Position.

The recommended imaging system is outlined in the table below. In developing this system particular attention was given to the fraction of the science payload which can be justifiably allotted to imaging, thus the recommended system is not our first choice but represents a compromise system. The system is characterized by high angular resolution. This is required because of the large OPGT encounter distances and the demand for a reasonable amount of time coverage, at useful spacial resolution, for planetary studies.

RECOMMENDED CAMERA SYSTEM

Camera 1

Sensor	1" target Intensified Silicon Vidicon
Intensifier Stage Photocathode	S-20
Sensor resolution at 20% response	26 lp/mm (line pairs/mm)
Spectral response	0.35 - 0.70
Format in pixels	500 x 500
Encoding	8 bits per pixel (picture element)
Bits per frame	2×10^6
Focal length	2000 mm
Field of View	0.32° x 0.32°
System angular resolution at 10% system response	11.2 μrad
Estimated weight	43 lbs (20 kg)

Camera 2

Sensor	1" target silicon vidicon
Sensor resolution at 20% response	28 lp/mm
Spectral response	0.4 - 0.95
Format in pixel	500 x 500
Encoding	8 bits per pixel
Bits per Frame	2×10^6
Focal length	300 mm

Camera 2 (Cont)

Field of view	2°.2 x 2°.2
System angular resolution at 10% system response	73 μrad
Estimated weight	22 lbs (10 kg)

The total instrument weight is estimated to be 67 lbs (30 kg). The system should also include an optical switch, a half-frame data buffer, an editor-compressor device, and a tape recorder. The ancillary equipment in Section 7 should also be considered part of the imaging system with the exception of the satellite seeking-scan platform pointing device which should be considered part of the general spacecraft system.

Fallback Position: It is entirely possible that the capabilities and resources required for the recommended system will not be available. In that case the team proposes the following strategy in reducing the scope of the imaging experiment.

i. The Removal of a Sensor - The team is of the opinion that the performance level provided by the recommended optical system is already below optimum, although adequate, and that further reduction in this area will not provide any substantial relief in cost or power and only a minor adjustment in weight. The primary area in the system in which major savings can be accomplished is in the sensors themselves. The definition team therefore proposes that if further reductions are required, the Camera 2 sensor (silicon) and electronics should be removed. Performance and optical versatility is maintained (by means of the optical switch). However, reliability and spectral response are compromised.

ii. Add-On Line Scanner - The team is considering the possibility of a light weight, low resolution line scan add-on to alleviate problems introduced by a single sensor.

iii. Reduction in Scope of S/C Data Storage System - The team concludes from its sequencing exercises to date that a scientifically justifiable mission can be flown without the use of a tape recorder given the existing S/C data rate capability. The picture return is severely curtailed at Neptune and Pluto but nevertheless the imaging possibilities are far from negligible.

B. Scientific Justification and Objectives.

The team has conducted a broad survey of the scientific objectives of the OPGT imaging experiment and finds that it can achieve new and detailed knowledge in the following areas:

a. Scientific exploration and detection of novel physical phenomena
b. Atmospheric processes on the major planets
c. Surface characteristics of the satellites and Pluto
d. Fundamental data on the gross properties of outer solar system objects

We place a major emphasis on the performance of comparative studies of planets and of satellites. Major consideration should be given to the second planet and its satellites in a given mission in evaluating the performance of the imaging system.

If both JSP and JUN are to be flown we consider the priorities for the two missions to be equal; if only one is flown, we recommended it be a JUN.

C. Imaging Instrument.

i. Sensors - The principal requirements on the Grand Tour imaging sensors are for high resolution, efficiency, wide spectral response, long life, and compatibility with spacecraft and planetary environments. No device currently available is satisfactory in all five respects, and so additional sensor development is needed. The Imaging Team believes that the silicon vidicon and the silicon intensifier target (SIT) vidicon have the greatest potential for timely development to an acceptable state, and we endorse the effort to improve these devices. Areas in which studies should immediately be undertaken, or continued, are as follows: The effects of severe radiation environments on these sensors need immediate attention. The short term storage capability of these tubes must be extended. Both black and white reseau patterns should be made available. In their present form the silicon and SIT vidicons have a very limited scanning format - approximately 500 lines per picture. An effort should be made to enlarge the format without incurring a prohibitively large weight increase.

Several alternatives to the conventional slow scan television camera have been studied. One instrument, the dielectric tape camera (DTC), appears well suited to the Outer Planet Missions, although it is still in the early stages of development. The DTC offers adequate resolution, high sensitivity, and large format. In addition, the camera itself provides long term storage for several pictures, thereby eliminating the need for an auxiliary storage device such as a magnetic tape recorder. The team believes that the potential capabilities of the DTC are so great that a vigorous development program sponsored by NASA is justified.

ii. Optics - The very large encounter distances which characterize the OPGT flybys plus the limited sensor resolution and the low surface brightness of outer solar system objects demand that a reasonably fast, long focal length telescope be the primary optics for the OPGT imaging experiment. We conclude that a focal length of 4 m is possible and desirable. Focal lengths of 1 m and less seriously impair the scientific return from the imaging experiment. Estimates of the weight of systems including a 4 m telescope exceed that fraction of the weight of the science payload that can reasonably be allotted to the imaging experiment and we therefore recommend that a 2 m telescope be adopted for the system. A speed of f/10 appears adequate although further study is required in this area.

Both wide angle and narrow angle cameras are needed on the mission. The wide angle camera is primarily useful for planetary studies in which large areal coverage, rather than high resolution, is required.

The Imaging Team has sponsored an industry study which considers the problem of light weight telescope design, optical switching of telescopes and sensors and mechanical and optical design.

iii. Ancillary Equipment - The imaging system should include a selected set of broadband, narrow-band and polarizing filters. The team has sponsored a study to develop reliable filters for such uses. We anticipate that further support in this area will be required.

Some form of automatic exposure control using light from the instrument's optical path is essential in view of the unknown and varying albedos of most of the targets.

Finally, a device should be included which will point scan platform instruments at satellites. The large uncertainties in ephemerides may prevent adequate pre-programmed searches and such a device will improve the information transmission efficiency as well as assisting in the search for new satellites.

iv. On-Board Data System - For the extended Grand Tour missions the team is apprehensive about the reliability, cost, weight, and power consumption of the current OPGT tape recorder system. The imaging experiment should include a large data storage buffer. When such a buffer is used in conjunction with a data editor/compressor and a tape, a capacity equal to one half of an uncompressed picture is sufficient. With no tape a full frame buffer is desired.

Preliminary sequence studies indicate that while the bulk storage provided by a tape recorder is always desirable, particularly at Neptune and Pluto where the real time data rate is low, a satisfactory experiment can be performed without storage.* Therefore, we strongly urge that trade-off studies, in which all or part of the tape recorder weight and power are reallocated to other systems, particularly the science instruments and telemetry, be performed.

Data Compression - The Imaging Team strongly endorses the inclusion of data editors and compressors on the Outer Planet spacecraft. Editing/compression schemes should include black sky and partial frame editing, pixel editing, and compression by delta modulation or some similar algorithm. The compression schemes should be sufficiently simple that no major redesign of NASA's ground data system is required. The Imaging Team believes that this restriction will require the use of a fixed line length compressor.

Telemetry and ground systems should be developed which provide the low bit error rates ($\sim 10^{-5}$) required for compressed data.

D. Trajectories.

Trajectories should be chosen to provide favorable encounters with satellites of the second planet (Saturn or Uranus). Given a choice between a single close encounter and several more distant ones, it is reasonable to trade

*This assumes current telemetry data rates.

closeness for multiplicity. The longer the focal length of the narrow angle (NA) camera, the greater the potential for multiple encounters. The Imaging Team recommends several trajectories for further study in Section 4.

E. Ground Data Handling.

The total picture volume per planetary encounter is estimated as follows: Jupiter, 24,000; Saturn, 7,500; Uranus, 2,500; Neptune, 1,500; Pluto, 1,500. The frame rate may be as high as 540 per day or as low as 10 per day. The team has not ascertained whether this data can be handled by present systems available at the DSN and JPL. We anticipate the need for standard processing of all frames to provide raw, contrast enhanced, maximum discriminability, and geometrically corrected pictures. Selected processing of a sizeable fraction (~10%) is also anticipated.

F. Other Considerations.

The definition team wishes to make the following recommendations for studies in support of the OPGT missions.

(i) We recommend that NASA support ground-based astrometric studies of the satellites of the outer planets in order that the ephemerides of these objects will be improved to the degree required for navigating the Outer Planet Missions.

(ii) We recommend that NASA continue to support ground-based photometric studies of the objects in the outer solar system.

(iii) We recommend that NASA support ground-based photographic monitoring of Jupiter and Saturn for a period of months preceding and following the encounters of the OPGT spacecraft with these planets.

(iv) We recommend that NASA arrange for close interaction between the Jupiter Pioneer F & G flight team and the OPGT flight teams.

In addition, we also propose that the standard practice in the Scientific Data Release Policy be changed to extend the time for the preparation of a preliminary science report to at least 6 months after the encounter period.

3. THE SCIENTIFIC RATIONALE FOR A GRAND TOUR OUTER PLANET MISSION IMAGING EXPERIMENT

A. Introduction.

Most of the mass, angular momentum, diversity of physical properties, and clues to planetary origins lie in the solar system beyond Mars. There are five known outer planets, at least 29 satellites, and innumerable asteroids and comets. Information on these objects is at best fragmentary and sometimes contradictory and before sound decisions can be made as to which of these objects most requires intensive study in the future, an exploratory reconnaissance is required which provides a basic quantitative description of the entire outer solar system. One of the most powerful means of performing such a reconnaissance is provided by the Grand Tour Missions with a high resolution imaging experiment. Quantitative imaging can provide new and detailed knowledge in the general areas of:

(i) Exploration and detection of novel physical phenomena.

(ii) Atmospheric processes on the major planets.

(iii) Surface characteristics of the satellites and Pluto.

(iv) Fundamental data on the gross properties of outer solar system objects.

Most of the discussion of planets which follows is based on our knowledge of Jupiter and Saturn and not on the more enigmatic planets, Uranus Neptune and Pluto, since we know much more about the former.

Table 1 gives a brief guide to the types of objectives that we have identified for the imaging experiment.

B. Scientific Objectives for an Imaging Experiment.

i. Exploratory Imaging - One of the major capabilities of an imaging system is its registration of unexpected natural phenomena. For example, in Martian exploration, Mariner 4 imaging revealed a highly cratered planetary surface; while Mariners 6 and 7 discovered large regions apparently entirely devoid of craters. Mariner 9 has uncovered evidence of extraordinary meteorological phenomena, probably connected with windblown dust, including

Table 1. Brief Guide to Types of Science Objectives for OPGT Imaging Experiment

1. EXPLORATORY Imaging

   (a) Search for novel physical phenomena e.g., perhaps connected with atmospheric motions, satellite surface physics, the Io flux tube, aurorae, satellite shadows, etc.

   (b) Search for new solar system objects.

2. THE MAJOR PLANETS

   (a) Size; shape; gross rotation; spin axis; scattering properties; coarse polarimetry.

   (b) Large scale lateral and vertical cloud distribution; time development and scales of atmospheric motions; interaction of dynamical regimes (spots, etc.)

   (c) Effects of internal energy source; convection cell patterns.

   (d) Growth; dissipation; morphology and vertical structure of clouds.

   (e) Aurorae

3. THE SATELLITES AND PLUTO

   (a) Size; shape; rotation; spin axis; cartography; polar caps.

   (b) Major physiographic provinces; impact features; orogeny; volcanism; lineaments; secondary features.

   (c) Surface texture: colorimetry; scattering properties.

   (d) Detection of an atmosphere (past or present): polar caps; clouds; hazes; distribution and lifetime of frosts; vertical stratification of aerosols above limb.

   (e) Saturn's Rings; thickness; vertical and lateral distribution of material; microcharacteristics through gross scattering properties; stellar occultations.

4. OTHER OBJECTIVES

   (a) Improved satellite ephemerides.

   (b) Search for new satellites and asteroids

   (c) Targets of opportunity (comets; asteroids).

1,000-kilometer long time-variable wakes; spectacular photographs of the satellites Phobos and Deimos showing lumpy, irregular, and crater-pocked surfaces of remarkably low albedo; and signs of immense calderas within the dark markings on top of the high Amazonis ridge, among the most spectacular volcanic features known in the solar system.

The OPGT imaging experiment will examine five planets and at least twenty-nine satellites with much higher resolution than ever before possible. For the first time these objects will be observed in their terminator regions, on their night sides, and at large phase angles. There is a significant chance of discovering new satellites and asteroids.

Unlike all other planets, the rotational axis of Uranus is in its orbital plane and its meteorology should be unique in the solar system.

The apparent low density of many satellites indicates them to be members of a class of objects entirely different from Earth's moon. Other satellites have atmospheres or large light variations. Thus, the presence of novel and unanticipated phenomena is effectively guaranteed and the exploratory potential is immense.

ii. Imaging of Atmospheric Processes on the Major Planets - Here the key scientific objectives are to gain an understanding of atmospheric energetics, dynamics, and cloud physics at different spatial and temporal scales.

The atmospheres of the major planets differ significantly among themselves as well as in comparison with those of the terrestrial planets. In addition to differences in composition and scale some are heated from below. The orientation of the rotational axis of Uranus, which is approximately pointing sunward for the M'79 JUN Missions, provides a unique situation in atmospheric dynamics. Other differences which will effect the dynamics include a range of almost 3 in apparent surface gravity, 4-1/2 in rotational velocity, and 2-1/2 in effective temperature. These differences and the possibility of new information about the atmospheres of the terrestrial planets which will become available from ATS, Nimbus, Mariner '71, MVM'73 and Soviet space vehicles, indicate that a well executed imaging experiment on the OPGT missions could lay the observational basis for a wider and more profound understanding of planetary dynamical meteorology.

The specific objectives that the imaging experiment can contribute to the area of atmospheric processes are the following:

(a) Local and Global Energy Balance; Vertical Cloud Structure

We are dealing with deep atmospheres which not only receive energy from the sun but probably also transport large amounts of energy out from the interior. In order to understand the processes that are observed or are expected to occur in these atmospheres, it is necessary that we determine (i) where solar energy is deposited and (ii) the magnitude of the internal heat source and the primary modes in which it is transported outward through the atmosphere. The first objective concerns the altitude and vertical structure of the clouds. Earth-based spectroscopic information from the rocket UV through the photoelectric infrared unfortunately does not offer a clear picture of the structure with the exception of indicating the presence of a haze extended high into the atmosphere and the possibility of layering or very tenuous clouds. On theoretical grounds we expect a vertical layering in the composition of the clouds but it is not clear whether the cloud layers will be in a discrete or a continuous distribution.

Photography (Fig. 1) from the earth in the CH_4 bands at 8900 Å or 6200 Å indicate the presence of either altitude or tenuosity differences in the clouds between belts and zones (see Fig. 1) and the presence of polar hoods. High resolution photogtaphy in and out of absorption bands at 8900 Å and 6200 Å is possible with the silicon sensors that are being considered for this mission and should act as an excellent discriminator for different layers of clouds. In principle, altitude differences considerably less than a scale height can be determined in this way. Other techniques are based on observations of vertical shear and limb photography (cf. Fig. 2). The latter will probably only be useful for the higher altitude clouds (above the 50 mb level) because of the large slant path molecular optical depths encountered on these large planets.

As far as the global energy balance is concerned the imaging experiment cannot produce a complete answer. It can, however, provide a basic contribution in the area of total solar energy input, i.e., it can do roughly half the job.

The target in the silicon vidicon is responsive to light from a least 3500 Å out to 1 micron; this wavelength band covers 67% of the incident solar energy. What fraction of this energy is actually deposited in the planetary atmosphere depends on the planet's global scattering properties and these can be measured in several wavelength bands by means of relative photometry. It is anticipated that the types of imaging systems currently being considered can measure the gross properties of the planetary scattering function with a relative accuracy of 5% over a wide range of phase angles and with sufficient resolution to illustrate differences between belts and zones.

(b) Energy Redistribution on a Global Scale

Solar energy is preferentially deposited, in all but Uranus' atmosphere, near the equator, while radiative loss to space probably occurs with little contrast over the entire planet. This implies energy redistribution by means of motions. In the Earth's atmosphere the major lateral energy transport is believed to take place by means of large scale eddies. What are the dominant modes for such transport in the massive, deep, atmospheres of the major planets? High resolution imaging can contribute to the solution of this problem by defining the scales of motion in both time and space; and by determining the forms and lifetimes of large scale instabilities that are present.

The contrasting points of view that have been published* regarding these motions imply rather different motion fields in both their temporal and spacial characteristics. The theories are clearly in a very crude state and would benefit from high resolution imaging data on both the morphology of the motion field and the temperature field in the atmosphere. The imaging experiment can provide the former.

(c) Other Objectives Concerned with Atmospheric Processes on the Major Planets

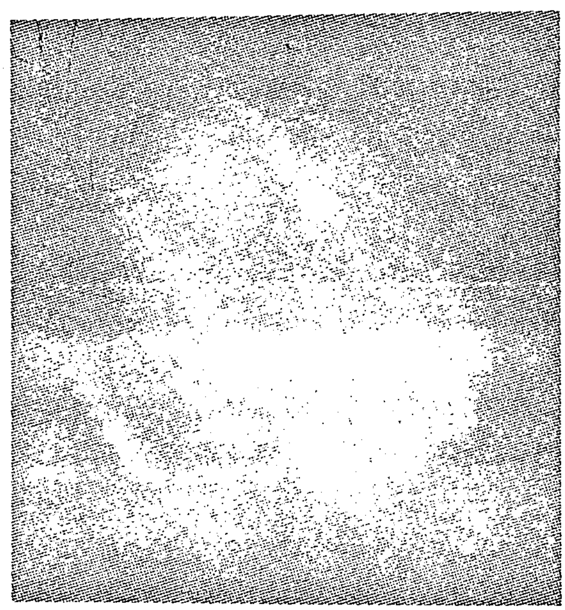
We have identified the following other areas in which an imaging experiment on the Grand Tour will also return valuable data concerning

*Stone, P. H. 1967, J. Atmos. Sci., 24, 642; Ingersol, A. P., and Cuzzi, J. N.; 1969, J. Atmos. Sci., 26, 981; Barcilon, A., and Gierasch, P. 1970, J. Atmos. Sci., 27, 550.

Figure 1. Methane band photography of Jupiter and Saturn

These three photographs illustrate the use of narrow band spectral filters to study the vertical distribution of methane and clouds in the atmospheres of the major planets. The top left photograph was taken of Saturn in the 7300Å methane absorption band and shows a prominent equatorial belt which is not obvious in the picture (right) taken near, but not in, the absorption band. The lower, Jupiter photograph, taken at McDonald Observatory, reveals a South polar hood (upper left) and bright belts in the 8900 Å absorption band.

G. Munch provided the Saturn photographs, taken at Palomar Observatory, for this figure.



atmospheric processes: The nature and interaction of weather centers, spots, etc.; convection patterns related to the outflow of internal energy; possible complex molecular synthesis; and auroral phenomena.

Jupiter and, to a lesser degree, Saturn are spotted planets. Some of the observed spots such as the Great Red Spot and the white ovals on Jupiter are extremely stable, long-lived features. The existence of such stable features in the otherwise very dynamic atmosphere of Jupiter is one of the major puzzles confronting planetary astronomy and for that reason such features deserve the closest possible scrutiny.

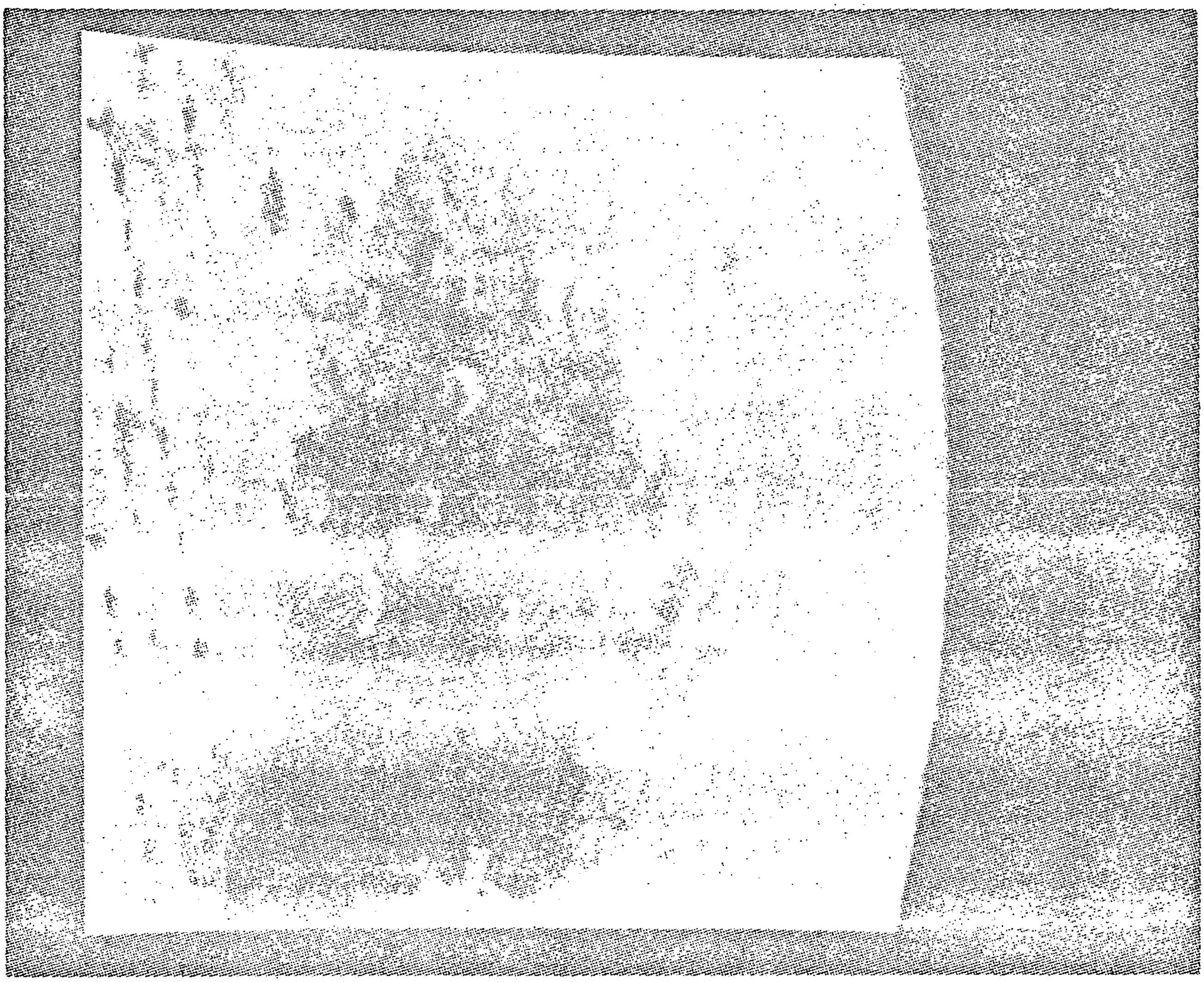
A review of published literature on the Jovian Great Red Spot (GRS) shows that different models lead to quite different predictions about the dynamics in and around the GRS. For example, the static Taylor column models predict no exchange of material between the GRS and its surroundings. All the models make specific predictions on the vorticity within the GRS. High resolution imaging with adequate time coverage of the GRS and related spots on Jupiter and other Jovian planets should provide the critical clues to the nature of such objects by measuring the state of their flow regimes.

Other spots or weather centers on Jupiter and Saturn are transitory in nature. They sometimes appear with surprising speed and can vanish just as rapidly. The development of one such weather center is shown in Fig. 3. In order to help understand the nature of these phenomena, which could be related to a dynamical instability in the zonal flow or to a long-lived disturbance deep in the atmosphere, the imaging experiment can provide information on the vertical location in the atmosphere and also provide an indication of the local flows. Fig. 4, which shows a cyclonic pattern in the Earth's atmosphere, demonstrates that flow patterns can, in fact, be determined by direct photography of thick clouds.

Jupiter and Saturn are the only planets for which we are reasonably sure that there exists a tremendous outflow of internal energy through the atmosphere. However, lesser fluxes are not entirely ruled out for the other planets. The presence and uniformity of this flux over the planet's surface may be directly indicated by the presence and distribution of convection cells (similar to the solar granulation) delineated by local cloud structure.

Figure 2. Mariner 7 limb haze photography

This Mariner 7 picture (7N5) reveals a haze layer beyond the Martian limb. Detailed photometric analysis indicates that three distinct layers are present in the picture.



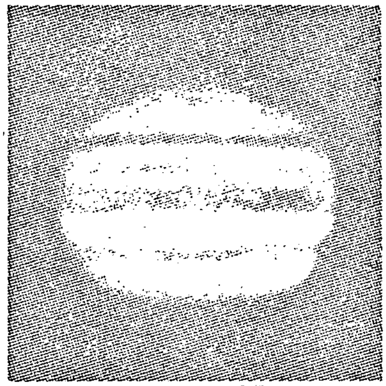
16-a

Auroral emissions on Jupiter have been the subject of many ground-based searches. The detection and location of auroral phenomena would be direct evidence of particle precipitation into the atmosphere. The morphology of the emission would contain information on magnetic field geometry although we expect that any inferences would always be highly controversial. We would expect to see dark side visual aurorae primarily in Balmer emission from hydrogen and perhaps also from helium. A rough calculation suggests that other molecular species will not be in sufficient supply at the relevant altitudes to provide appreciable emission rates. The present ground-based work places a limit on Hα emission at about 10 k Rayleighs - or a brightness of 3×10^{-2} ergs cm^{-2} sec^{-1} ster^{-1} which should be detectable with the proposed system. A special problem is associated with some models for the interaction of Io with the Jovian ionosphere. It is possible that enhanced auroral activity is present over the area of contact of the Io flux tube with the Jovian atmosphere. Any such localized source could be sought out on the dark side of the planet with much greater discriminability than we can manage from Earth, confined as we are to observations of the illuminated hemisphere.

Laboratory experiments on simulated Jovian atmospheres show that large scale production of organic molecules of considerable complexity should be expected on these planets. Such materials have a coloration reminiscent of the general coloration of Jupiter and a determination of the vertical distribution and motions of brightly colored material in the atmospheres of the Jovian planets should be of considerable importance in checking the hypothesis that the coloration is due to pre-biological organic chemistry, and in determining the energy sources for the production of these materials. It is possible, for example, that leakage of high energy charged particles at the mirror points of the Jovian radiation belts could produce such vividly colored organic molecules and specific searches for coloration at the mirror points of the Jovian atmosphere is another objective of the imaging experiment.

Figure 3. Jupiter: 1971 SEB Disturbance

The growth of a major disturbance in Jupiter's South Equatorial Belt is seen in these International Planetary Patrol ultraviolet photographs. Such spots occasionally appear with surprising speed and can vanish just as rapidly.



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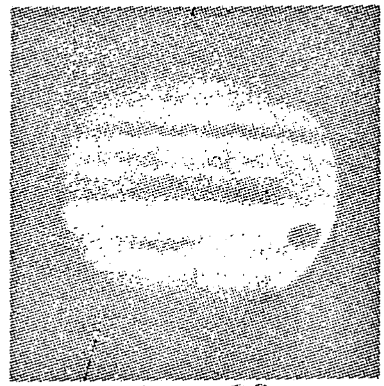

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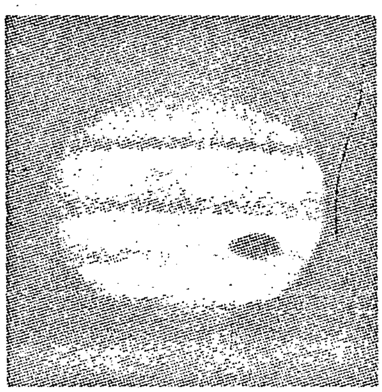

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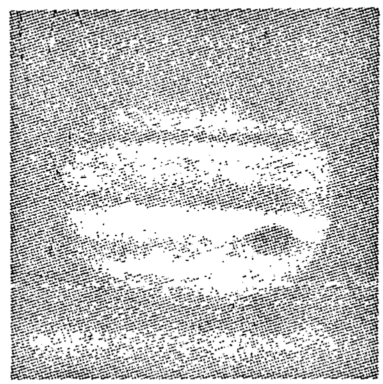

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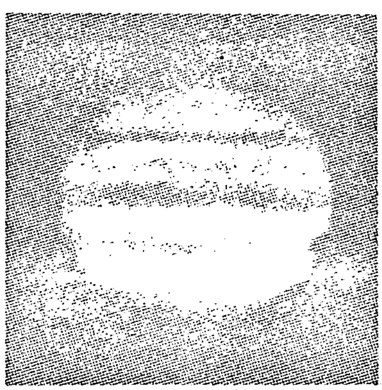

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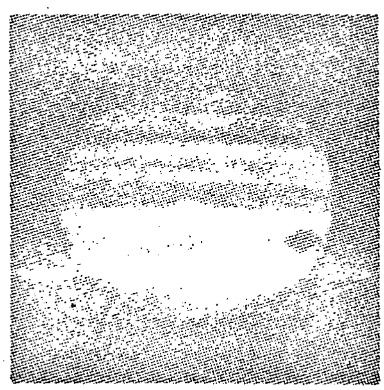


June 24

International Planetary Patrol

iii. Characteristics of the Satellites and Pluto

(a) The Satellites

Dynamically, the satellite systems of Jupiter, Saturn, and Uranus are miniature solar systems; their study and the study of the rings of Saturn should help in understanding the general problem of the origins of solar systems throughout the Galaxy.

The densities of the Jovian satellites decrease with increasing distance from the primary, in analogy with the trend of the mean densities of the inner planets. This trend is probably reversed for the inner satellites of Saturn. Furthermore, it appears that several of these bodies have densities below that of uncompressed rock. This has led a number of investigators to suggest that such satellites must be composed of mixtures of icy and rocky materials.

These objects are not all simply fragments of rock or bodies like our moon which are interesting only because they exist in the outer reaches of the solar system. They represent a distinctly new kind of aggregation of matter, one which has not yet been studied at close range.

Six satellites are of planetary size, some may be similar to the moon but some are probably cosmic snowballs; some are likely to have liquid interiors, all are probably impact counters, preserving a unique account of the debris in the outer solar system over geological time; some have atmospheres, clouds and surface frosts; the colors and albedos of others cannot be understood in terms of any known materials; some live within intense belts of trapped relativistic charged particles. Given a suitable high resolution imaging system, the extended Observatory Phase of the OPGT flybys permits detailed observations of many of these satellites to be made over a major fraction of their surfaces and comprehensive maps to be constructed which are superior to the best ground-based maps of Mars.

Figure 4. ATS Photographs

TOP

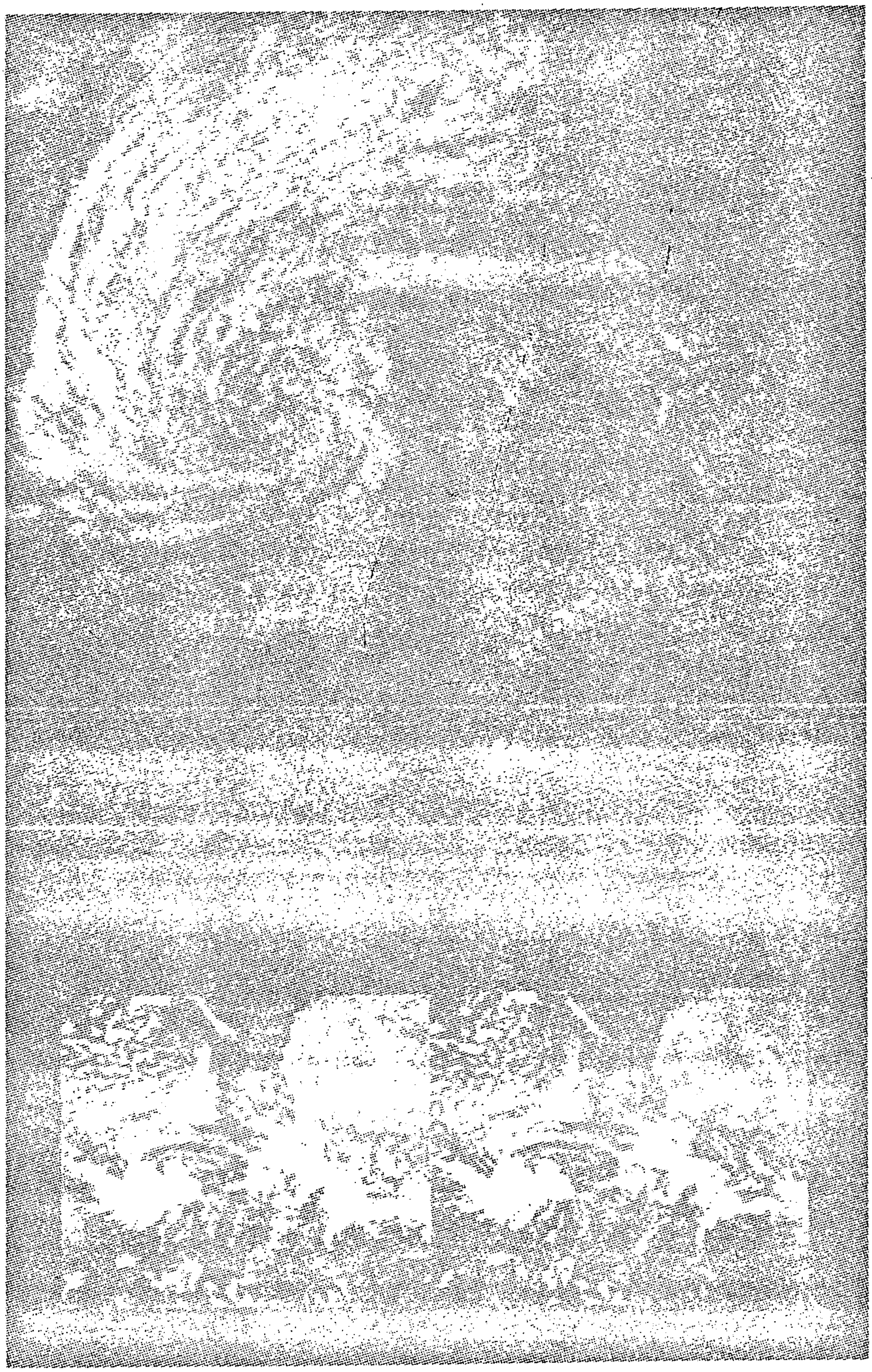
Upper Layer Cloud Structure

An ATS-3 picture of a large storm vortex near the terminator zone shows a surprising amount of upper level texture made visible by shadowing due to the low sun angle. At lower center, the sunlite edges of cloud layers are accentuated. This detail is completely lost in small phase angle images, where one sees primarily the cloud thickness variation expressed as changes in amount of backscattered sunlight.

BOTTOM

Stereo Pair of ATS-3 Pictures Show Cloud Motion

Convective clouds in Atlantic tropical storm off west coast of Africa. (Relax eye muscles until pictures blend) False stereo effect arises from cloud displacements between pictures due to winds. Apparent heights are directly proportional to East-West wind component. When each picture is rotated 90° apparent heights are directly proportional to North-South wind components.



A major objective of Grand Tour satellite photography should therefore be to characterize the surface morphology at a sufficiently high resolution to allow a quantitative assessment of the nature and strength of the surface material, the age of the surface, the degree of internal activity, surface texture, soil homogenity and composition, and the presence of contemporary or past atmospheric activity. Emphasis should be placed on performing comparative studies of the satellites in a particular family as this will lead to a better understanding of uniqueness and order in the nature of the satellites.

(b) Pluto

We know little about Pluto. Even such basic parameters as its diameter or its mass are very poorly known. It is the remotest known planet in the solar system and as such, the surface may contain information about events reflecting the history of the outer part of the system, perhaps since very early times.

Pluto is unique among the outer planets in showing a substantial variation of reflectivity with rotation. This characteristic plus the long rotation period tend to support the commonly held hypothesis that this planet is actually an escaped satellite of Neptune. One obviously wishes to determine whether the variation in reflectivity is caused by an irregular distribution of "maria" and "terrae" as observed on the moon and possibly Mercury, or whether the reflectivity is controlled by condensed volatiles mixed with dust -- a giant version of the dirty snowball model for comet nuclei. High resolution (1-5 km) imagery should be able to establish this difference rather easily, especially if coupled with the spectral information provided by filters. The discovery of a satellite of Pluto would cause a major change in our current views on the origin of that planet.

(c) Saturn's Rings*

The system of Saturn's rings presents several outstanding problems: An understanding of the gaps and boundaries of the ring requires more precise measurements of the location, width and even existence of the gaps (or regions of rapid intensity change) than has been possible from the earth. One

*We acknowledge communications from F. A. Franklin regarding this topic.

would like to see imaging of both the sunlit side of the rings (where the gaps appear darker than the surrounding ring) and from the dark ring side where the gaps may, if they possess a sufficiently large amount of material, appear brighter than the adjacent ring. Scans, with a large dynamic range, should include regions both exterior and interior to the visual extent of the rings. Secondly, an understanding of the structure of the rings requires a better knowledge of the ring thickness and the average particle size -- in particular, are the rings a mono-layer of particles; and are they surrounded by an envelope of finer material?

The imaging experiment should endeavor to make precise measurements of the ring thickness either directly or, if sufficient resolution is not available (approximately 1 km is required), indirectly by measuring the surface brightness of the rings while passing through the ring plane. Also of interest are the presence and motion of clumps of material which have been detected not only in the rings but also in the gaps. The gross photometric properties of the particles will provide information on their microstructure, and the distribution and optical thickness of ring material near the gaps may indicate the degree of competition between perturbing and damping forces in the ring plane. Local occultations of bright stars can be helpful here.

iv. Fundamental Data and Special Topics - The preceding three sections are concerned with what, in the team's opinion, should be the primary goals of the Grand Tour Imaging Experiment. There are, however, many other subsidiary goals that we have identified:

(a) Fundamental data especially on the satellites, such as shape, diameters, figure, rotation rate and orientation of spin axis.

At present only the diameter of Io (from the β Sco occultation) is known with any precision; the remaining satellite radii have uncertainties on the order of 100 km or more, which lead to large imprecision in density estimates. It is usual to infer from their variation of brightness with orbital phase that some satellites are in synchronous rotation with respect to the parent planet and that the spin axis is normal to the orbital plane. No observational check (such as radar) is currently available for confirmation of these assumptions.

(b) Satellite Orbit Dynamics.

By imaging the satellites against the star background from a nearby spacecraft, it is possible to determine their positions in space far more accurately than by means of Earth-based observations. The high positional accuracy that is possible and the ability to observe satellite orbits through a wide range of angles makes imaging data of this kind a powerful tool for improving the orbits and ephemerides of the satellites.

Better ephemerides may in turn yield better determination of the masses of large neighboring satellites and the dynamical oblatenesses of the primaries, which factors cause large periodic and secular perturbations in the orbits of the inner groups of satellites of Jupiter, Saturn, and Uranus.

(c) Long Base Line Stellar Parallaxes*.

The escape trajectories of the Grand Tour missions offer a greatly extended baseline for measuring parallactic shifts of close stars by means of TV-photography. In practice, the finite data transmission capability and lifetime of the spacecraft will probably limit the baseline to downwards of 100 a.u. If we assume an Earth-based measurement accuracy of ±0.01'' and a baseline ratio of 1/50, we find that in order to compete the spacecraft-based measurements must be accurate to ±0.5''. Consequently, this experiment is not feasible unless a very-high resolution system is flown. However, even with high-resolution the concomitant reduction in sensitivity and field of view of the TV system will produce further difficulties.

(d) New Satellite Search.

The completeness of our knowledge of the solar system is not assured and every opportunity should be taken to survey the vicinity of the major planets for the presence of as yet undetected satellites and ring phenomena.

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*We are grateful to A. D. Code for an input on this topic.

(e) Targets of Opportunity.

These include imaging of comets and asteroids which may move into the vicinity of the spacecraft during the mission.

C. Mission Priorities.

i. Relative Priorities for Planet and Satellite Imaging - The OPGT missions may be our only opportunity for some decades to explore the solar system beyond Saturn. Our ignorance of the satellites and planets of the outer solar system is profound. Both the planets and the satellites of the outer solar system are of such extraordinary interest that it is impossible to make priority distinctions between them. Accordingly, we establish precisely equal priorities for Grand Tour Reconnaissance of the satellites and planets of the outer solar system. Acceptable imaging systems must provide high quality data on both the planets and their satellites.

ii. Relative Priorities for the Planets - Because of the uniqueness of the OPGT mission trajectories and the fact that we know least about those planets farthest from the Earth, it seems reasonable that OPGT should concentrate on the outermost objects of high scientific interest, i.e., the Uranus, Neptune and Pluto systems. For the closer planets, Jupiter and Saturn, it is very likely that there will be other non-OPGT opportunities in the next two decades, thus they rate a somewhat lower priority in the context of the OPGT missions. On the other hand, the practical difficulties of optimizing systems for the outermost objects are severe. Accordingly, taking the product of scientific desirability and engineering feasibility, we recommend that primary attention be focused on Saturn, Uranus, and if possible, Neptune and their satellites. This implies, for example, accepting a degradation in opportunities at the Jovian satellites in favor of optimizing the opportunities for Uranian satellites on a JUN mission.

iii. Relative Priorities for JSP and JUN Missions - We have considered the relative priorities of JSP vs. JUN missions and conclude that when there are opportunities to fly both JSP and JUN missions these two missions should have equal priorities. However, in the case that there is only a single opportunity available, for reasons discussed above, priority of the JUN mission is considered slightly higher than the priority of the JSP mission.

4. TRAJECTORIES

A. General Characteristics.

The Grand Tour flyby trajectories are characterized by extremely large encounter distances and very long flyby times. They are entirely different in character from previous Mariner flybys of the terrestrial planets as the following comparisons show: Grand Tour encounters are generally measured in hundreds of thousands of kilometers rather than thousands and flyby times are measured in days and hours rather than hours and minutes.

B. Factors Determining Choice of Trajectories and Imaging Strategy at Jupiter.

Planetary encounter conditions vary only slightly for a given mission throughout the range of arrival dates. The primary criteria therefore, for selection of arrival date should be favorable satellite encounter conditions. Favorable satellite encounters at more than one planet per trajectory may not be possible* and it is important to make some decision on the relative priorities placed on the different planetary systems. In Section 3 we recommended a lower priority for the satellites of Jupiter. A study of the trajectories reinforces this recommendation because relatively close encounters with Jovian satellites will occur regardless of the arrival date.

C. Favorable and Multiple Satellite Encounters.

As a general rule the closer the spacecraft approaches a satellite, the better. However, if more than one satellite can be encountered along the same trajectory it may be reasonable to trade closeness for multiplicity. The imaging system directly affects this tradeoff. If a high resolution system is available, useful data can be obtained at greater distance, and multiple encounters are favored. If the system resolution is low, we propose trading multiplicity in favor of high resolution at one satellite. It must be remembered, however, that the spacecraft may not approach arbitrarily close to a satellite on account of ephemeris uncertainty (ranging from, perhaps, 1,000 km for the Galilean

*This problem will not be resolved until accurate trajectories are available.

satellites to 20,000 km for Neptune's satellites) and the unknown perturbative effect introduced by the uncertainty in the satellite's mass. This latter effect is believed to preclude flyby distances smaller than 25,000 km for the most massive satellites.

D. Available Mission Sets and Recommended Trajectories.

Three basic sets of four missions each have been recommended for study by the OPGT Science Steering Group (SSG):

(a) JSP 77; JSUN 77; JUN 79 (2)

(b) JSP 77; JSUN 78 (2); JUN 79

(c) JSP 77 (2); JUN 79 (2)

From the point of view of imaging science there appears to be little difference between the options although option (b) is slightly preferred to the others. JSUN 78 gives a better pass at Saturn than a JSP, a larger number of observable satellites, and slightly better viewing conditions for Saturn's rings.

The best JSP 77 and JUN 79 trajectories, in terms of favorable encounters with the satellites of Saturn, and Uranus have been identified below in terms of their periapsis times subject to the constraints given in the following table:

Constraint/Mission	JSP 77	JUN 79
Launch energy (C_3)	$\leq$ 109 km^2/sec^2	$\leq$ 109 km^2/sec^2
Launch window	8/20/77-9/14/77	10/24/79/-11/17/79
Jupiter arrival window	2/20/79-5/1/79	5/12/81-7/31/81
Saturn (Ura.) arrival window	10/20/80-3/20/81	9/30/85-4/30/87
Pluto (Nep.) arrival window	6/30/86-5/20/88	2/25/89-11/1/91

Although these times are likely to undergo small changes later, they are sufficiently accurate for identification purposes. The trajectories for each mission are listed according to their preference. The bodies appear in the order of their encounter, the numbers in parenthesis giving the approximate encounter distances in thousands of kilometers. More detailed encounter data, such as slant range, phase angle, and smear velocity, have been prepared but are not included here. More accurate, integrated trajectories are required to connect the satellite encounters at one planet with those at another means of a single trajectory. Arrival dates and the flyby geometry at the last planets can then also be determined.

Recommended Trajectories

JSP 77 Saturn

(S = Saturn, T = Titan, H = Hyperion, I = Iapetus)

1. 13.70 Nov. - 80 T(428), S(566), I(50)

2. 31.94 Jan. - 81 T(670), S(740), H(601), I(350)

3. 29.40 Nov. - 80 T(444), S(598), H(371)

4. 20.72 Dec. - 80 S(643), T(476), H(424)

JUN 79 Uranus

(Ur = Uranus, M = Miranda, A = Ariel, U = Umbriel, T = Titania, O = Oberon)

1. 30.56 April - 87 Ur(80), M(30), A(90), T(340), O(500)

2. 20.44 June - 87 Ur(90), M(20), A(170), U(150), T(340), O(490)

3. 29.03 Aug. - 86 Ur(50), M(60), A(130), T(360), O(510)

4. 15.34 April - 86 Ur(40), M(70), A(160), U(210), O(540)

E. Comparison with OPGT Project "Standard" Trajectories.

For the JSP and JUN missions the OPGT Project has selected four "standard" trajectories which coincide with the Imaging Team's first choices above, except that the OPGT Project picked the Team's second choice at Jupiter for JSP 77. The reason for this is that for each of the two missions, the Project targeted one launch for Jupiter, contrary to the Team's philosophy, and the second launch for encounter at the second planet.

5. IMAGING SYSTEMS AND THEIR SCIENTIFIC CAPABILITY

A. Types of Systems Available.

Three camera types have been identified as reasonable candidates for Grand Tour missions: slow scan television, line scan imaging radiometer, and dielectric tape camera. The merits and shortcomings of these devices are summarized below.

i. Slow Scan Television - Television cameras have been used successfully on a number of near-earth and planetary space flights. The sensors require no moving parts or irreversible chemical reactions to record an image, and this gives them a reliability advantage over some other devices. Television has many applications other than space photography, and so new and improved sensors are being developed continuously.

Television cameras normally generate data much faster than a spacecraft telemetry system can return it to earth. To minimize this problem the selection is constrained to sensors with slow scan capability.

The requirements for high sensitivity, good resolution, large format, long life, radiation resistance, reasonable weight, low power consumption and slow scan performance reduce the choice of television sensor to three types: selenium target, silicon target, and silicon intensifier target (SIT) vidicons. The key parameters of these sensors are listed in Table 2.

The Selenium Vidicon used in the Mariner series, offers good resolution, acceptable format, low weight, and excellent slow scan characteristics. Unfortunately, its sensitivity is low; it lacks response in the red and near infrared, (Fig. 5) and there is some question about its reliability and radiation resistance.

The Silicon Vidicon is more sensitive than the selenium, but still requires a relatively fast optical system at the further planets. This type of tube has excellent red response and the potential for long life. On the other hand the resolution is modest and the format small. The short term storage of the silicon vidicon is poor, and target cooling may be needed to achieve slow scan performance.

Table 2. Vidicon Characteristics

	Selenium 1 inch	Silicon 1 inch	Silicon 1-1/2 inch	SIT 1 inch	SIT 1-1/2 inch
Relative Sensitivity	1	8		25 - 125	
Resolution at 20% Response - lp/mm	47	28		26	
Spectral Range at 15% of Peak Response - nm	300 - 625	350 - 980		380 - 730	
Scanning Format - lines x pixels	700 x 832 (Mariner 9)	500 x 500	800 x 800	500 x 500	800 x 800
Estimated Camera Head Weight - lbs	8	12	21	18	29

The SIT consists of a silicon vidicon preceeded by an electrostatic image intensifier. The gain provided by the intensifier gives the SIT adequate sensitivity for use with long focal length telescopes. The spectral range, determined by the S-20 intensifier photocathode, does not have the extended red response characteristic of the silicon tube but is considerably better than the Selenium Sensor. The slow scan and small format problems of the silicon vidicon also exist in the SIT. Because it is more complex and requires a high voltage supply, the SIT should be slightly less reliable than the silicon vidicon.

ii. Line Scan Imaging Radiometer - The line scan camera consists of a small number of point sensors located at the focus of a telescope. The two-dimensional image is formed by sweeping the telescope field of view over the scene in a pattern of contiguous straight lines. The scanning operation is achieved by spacecraft motion, by moving mirrors, or by some combination of these. The scanning format and exposure (dwell) time are not fixed, but can be varied to suit the circumstances of a particular picture.

A major advantage of the line scan camera is the freedom available in choosing the sensor(s). With the proper combination of detectors, the spectral range is almost unlimited. The dynamic range is large, a large format is

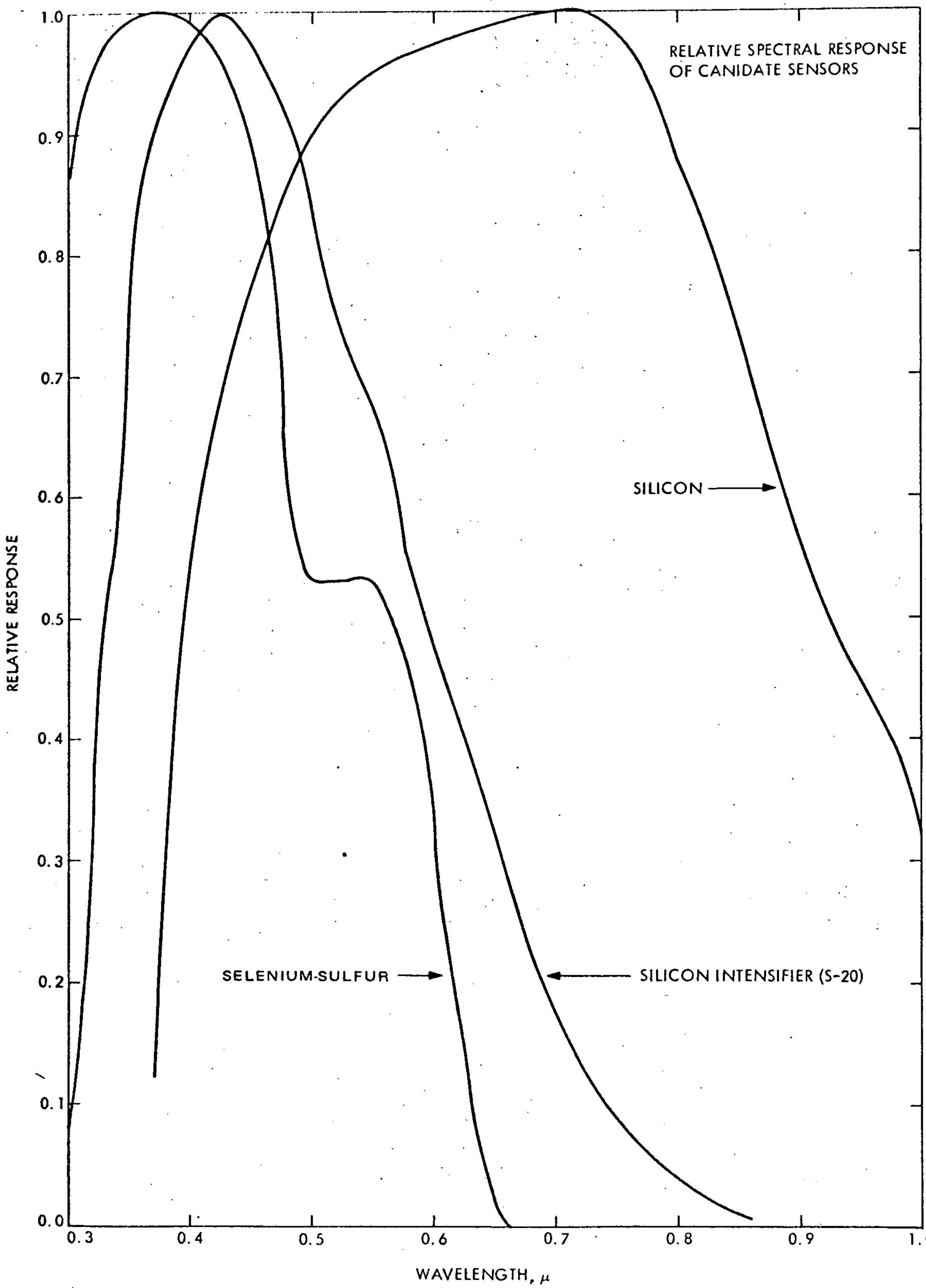


Figure 5. Normalized Spectral Response of Candidate Imaging Tubes

available, and the photometric accuracy is excellent. In comparison with other imaging systems, the line scan camera offers the additional advantage of low weight.

Two major difficulties make a line scanner alone less than ideal for the highest resolution requirements of the Grand Tour. The short dwell time per pixel yields a poorer signal to noise ratio than a SIT vidicon. A second difficulty is caused by spacecraft attitude drift. At encounter both the spacecraft and the planet are in motion so that both ground resolution and the scene can change during a single frame. A three axis stabilized spacecraft like OPGT drifts in an unpredictable manner within narrow preset limits and this motion would seriously perturb the pattern of scan lines at high resolutions. As resolution is reduced both difficulties become less important, especially with accurate monitoring of spacecraft drift rates.

Some of the imaging science objectives do not require high resolution. The possibility of combining a SIT vidicon and a simple line scanner into a hybrid system using the same optics was briefly considered as shown in the Appendix. Even though it has some very attractive features, the committee did not have the opportunity to pursue this option with detailed studies. The opportunity to add a simple, low cost, light weight, long life imaging system to improve the probability of mission success and to enhance the science return would seem to deserve additional careful study.

iii. Dielectric Tape Camera - The dielectric tape camera (DTC) consists of an image intensifier followed by a silicon dioxide storage target. The target is capable of long term storage and can be read out non-destructively. Several targets can be made available inside the sensor providing the DTC with its own long term bulk storage. The DTC and SIT have similar sensitivity and spectral response. However, the format of the DTC can be as large as a few thousand lines per picture with higher sensor resolution than the SIT.

The DTC would be an ideal choice for the Grand Tour missions except that it is not a fully developed instrument. Although most of the components exist, a working DTC has never been built and considerable time and money will be required to develop the DTC into a reliable flight configuration.

B. Optical Systems.

i. The Choice of Focal Length* - Mechanical and Thermal Tolerances - Engineering complexity and reliability appears to rule out any provision for active focusing. The telescope is therefore constrained to operate within close mechanical and thermal tolerances if it is to maintain performance. These tolerances become extreme when reasonably compact telescopes with focal lengths of 4m and longer are considered.

Spacecraft/Scan Platform Pointing Accuracy - In order to operate the imaging system efficiently, the angular field of view should be considerably in excess of the incremental pointing capability of the scan platform which is presented quoted at 0°.1. The imaging team feels that a field of view of less than 3 times this would be unwise. Thus, a 500 x 500 pixel sensor format implies a focal length no greater than 2 meters.

ii. Choice of Aperture - The weight of a telescope is strongly dependent on its aperture, roughly varying as the third power. For this reason, no apertures greater than about 200 mm ($\approx$ 25 lbs) are being considered.

iii. Necessity for a Wide Angle/Narrow Angle Combination - The need for wide angle optics is based on the following requirements:

(a) Wide Coverage of planetary terminator region during flyby.

(b) To extend the time-base for global coverage of planets on approach.

(c) To provide an adequate basis for the interpretation of the nested high resolution narrow angle frames.

iv. Optical Switch - The ability to operate either sensor through either optical system can be provided by a suitable optical switch. The switching can be done in the traditional manner with a simple flip mirror or beam splitter, (Fig. 6).

The team has included this valuable concept in their first three imaging system options in Table 3.

*In this discussion we assume a system resolution of 22.5 lp/mm.

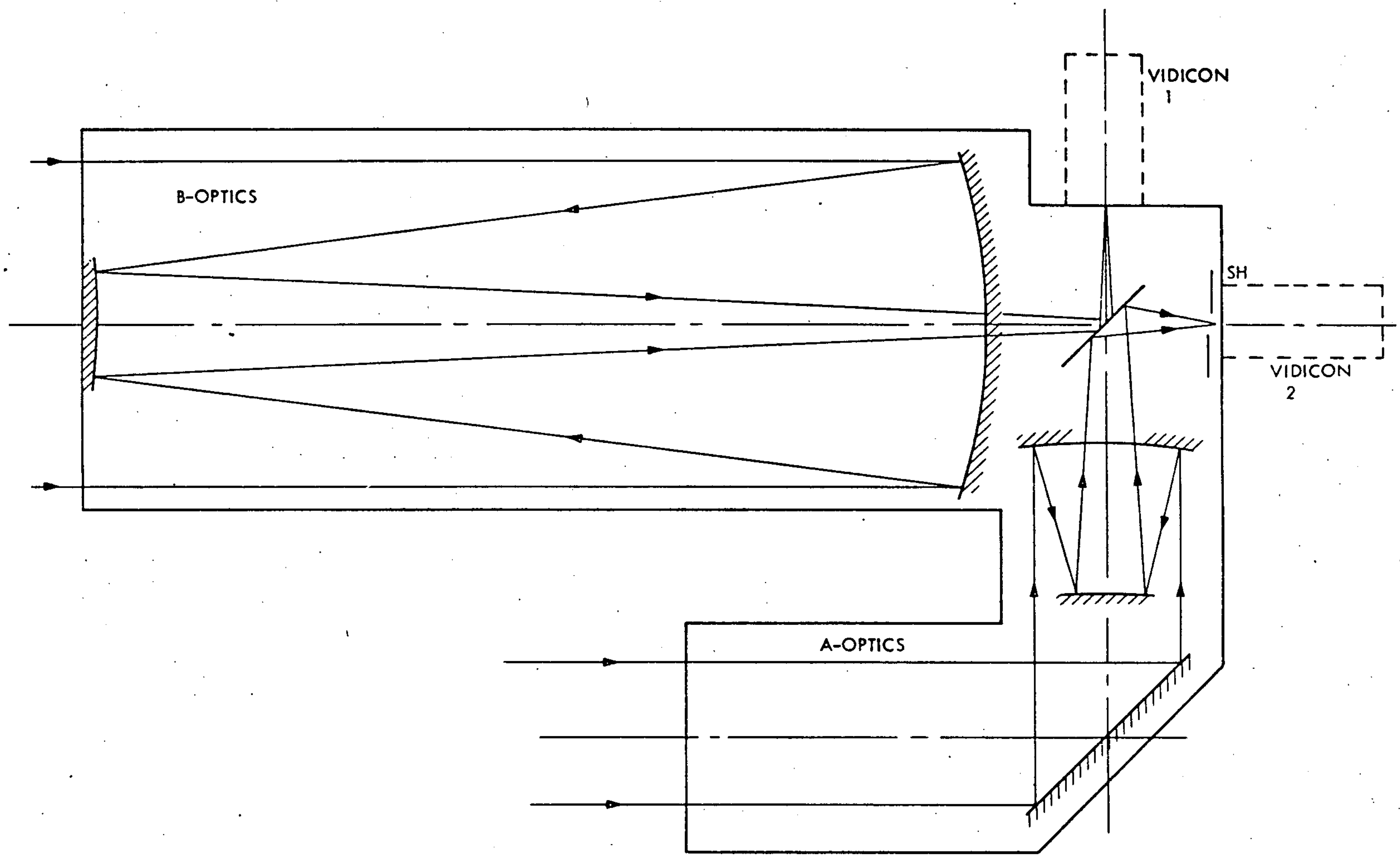


Figure 6. Optical Configuration

v. Optional Configuration - Clear aperture optical systems, as well as more traditional configurations, are being considered because of their apparent versatility.

The team decided that a separately funded outside optics study was desirable. The objectives and status of this study are described in Part 2 of this report.

C. Choice of Imaging System.

i. Options - The final selection of an imaging system must be based on weight and reliability considerations, as well as performance. As of this date, an exact weight allocation for the imaging system has not been established, although the question has been thoroughly discussed. Therefore, the Imaging Team has chosen to present several alternative systems (see Table 3) which represent a wide range in performance, cost and weight.

The first point to recognize in Table 3 is that all the systems are slow scan television cameras. The choice of one-inch vidicons, rather than the 1-1/2 inch version, results from a realistic assessment of the eventual weight allocation for imaging (See Table 2). If additional weight should become available, the Imaging Team would strongly endorse the use of larger format sensors. Selenium Sensors were excluded because of their poor sensitivity, limited spectral response, and doubts about their long term reliability. Optical switching is included on the assumption that it can be reliably mechanized, and will weigh only a few pounds. The clear aperture telescope has not been specifically included because the practicality of this configuration will not be known until the Itek study has been concluded.

Systems A, B, and D incorporate a SIT vidicon for sensitivity and a silicon vidicon for red response. The redundant aspect of having two sensors is an added benefit. System C is included to demonstrate the capabilities of a high resolution, low weight system. The reliability implications of flying a single sensor have not been fully assessed by the Project but an effort to understand the possibilities of providing a light-weight, backup line scan system in this case are included in the Appendix to this report.

Table 3. Candidate Imaging Systems

System Letter	Sensor Type	Focal Length Meters	Aperture Diameter cm	f/#	Field of View, °	μrad / Line	Approx Resol, μrad	Optical Switching	Estimated Weight, lbs
A	SIT	4.0	22.9	17.4	0.16°	5.6	12.9	Yes	90
	Silicon	0.5	12.7	3.9	1.30°	44.8	89.6		
B	SIT	2.0	17.8	11.3	0.32°	11.2	25.8	Yes	67
	Silicon	0.3	7.6	4.0	2.20°	73.7	149.4		
C	SIT	2.0	15.2	13.1	0.32°	11.2	25.8	Yes	46
		0.3	7.6	4.0	2.20°	75.0	171.8		
D	SIT	1.0	17.8	5.6	0.65°	22.4	51.5	No	63
	Silicon	0.3	7.6	4.0	2.20°	73.7	149.4		
E	Silicon	0.5	12.7	3.9	1.30°	44.8	89.6	No	52
	Silicon	0.5	12.7	3.9	1.30°	44.8	89.6		

NOTES:
1. All sensors are nominal one inch tubes.
2. Scanning format for all systems is 500 lines x 500 pixels.
3. Digital encoding is at eight bits per picture element.
4. All optical systems are catopteric or catadiopteric.
5. Accessories such as automatic exposure control, in-flight calibration equipment, and camera pointing devices are not included in the weight estimates. The preliminary nature of these weight estimates should be emphasized.
6. System C could include a lightweight, low resolution line scan backup mode in order to provide redundancy and extended red response.

ii. Science Requirements on System Performance - Performance requirements for imaging the major planets are distinct from those for imaging their satellites. For planets we observe dynamic phenomena which exhibit coherency over extremely varied, and often large, scales in time and space. Therefore there is a need for extended time and areal coverage as well as resolution. Surface studies of satellites and Pluto, on the other hand, tend to strongly emphasize the need for very high resolution, although the need for maximum surface coverage at the highest resolution is important also.

The extremely large encounter distances that characterize the OPGT missions, combined with demands for high resolution capability and extended time coverage, underline the need for a high resolution system; and in light of the available sensor resolution this implies long focal length optics.

Planets: The requirements here are very stringent. A large format is required (approximately the scale of the belts or $\approx$10,000 km) with a spatial resolution capable of reaching the smallest scales of geostropic motions ($\approx$100 km for the major planets). Observations at this resolution should extend over a time scale of at least 2 days. A 10 μR/TV line system is needed for such performance. The format of a 1" tube is marginally adequate for the areal coverage requirement. Planetary limb photography requires resolution of the order of, or better than, a scale height ($\approx$ 20 km). At Jupiter and Saturn this implies a 10 μR/TV line system. Figure 7 illustrates the importance of focal length in one aspect of atmospheric studies.

Satellites: Experience with lunar and Martian photography suggests that the value of imaging of surfaces does not increase linearly with resolution. For example, a great advance was made in understanding the lunar regolith when resolution of about 100 m was reached and Shoemaker and his associates were able to analyse saturation bombardment by secondary ejecta. On Mars, the bend in the crater diameter distribution, revealed when resolution reached about 5 to 10 km, evidenced erosive activity and has been analyzed by Öpik and others. On the other hand, increasing lunar resolution from about 100 m to 1 m did not apparently result in great advances in lunar knowledge because the regolith surface at that scale is simply an amalgam of overlapping, eroded ejecta and secondary craters with little detail containing structural information. Generally a rapid growth in the value of imaging occurs between resolutions

Figure 7. Simulated Earth views by candidate systems

These pictures are typical of the views which would be obtained by the three candidate systems during most planetary encounters. The upper left frame (11.2 μrad/line) represents a 2 meter focal length and the lower two frames illustrate focal lengths of 1 meter and .5 meters. The remaining two upper pictures are enlargements of the 1 meter and .5 meter images.

The series shows the loss of detail in pictures of convective and stratus cloud structure near the terminator zone on the earth. In the highest resolution photo cloud shadows of individual convective cells are clearly visible thus allowing the heights of these elements to be determined. In the lowest resolution picture it is not possible to separate convective clouds from stratus clouds and the cloud vortex at the right edge is lost completely.

of several tens of kilometers to some tens of meters and it is, therefore, important to maintain this range of resolution on the primary satellites in a system. Because of the large ranges encountered in these Grand Tour missions this indicates a system performance of at least 20 μR/TV line. Figures 8 and 9 illustrate the importance of focal length in surface studies.

iii. Recommended System - Although System A has the preferred performance it is unrealistically heavy. The imaging team therefore recommends system B, with its reduced performance, as the prime candidate. System D maintains the advantage of reliability but reduces weight by chopping the performance in half. This has a serious impact on the quality of the imaging experiment and is considered a marginal system by the team. System E, which the team does not recommend, takes this strategy to an unacceptable limit. System C represents the teams recommended fallback position if B is beyond available resources. Here redundancy is sacrificed rather than performance. This imposes extra risk in the system, however, the team is of the opinion that it is not excessive. This position is supported by the sequencing analysis which follows.

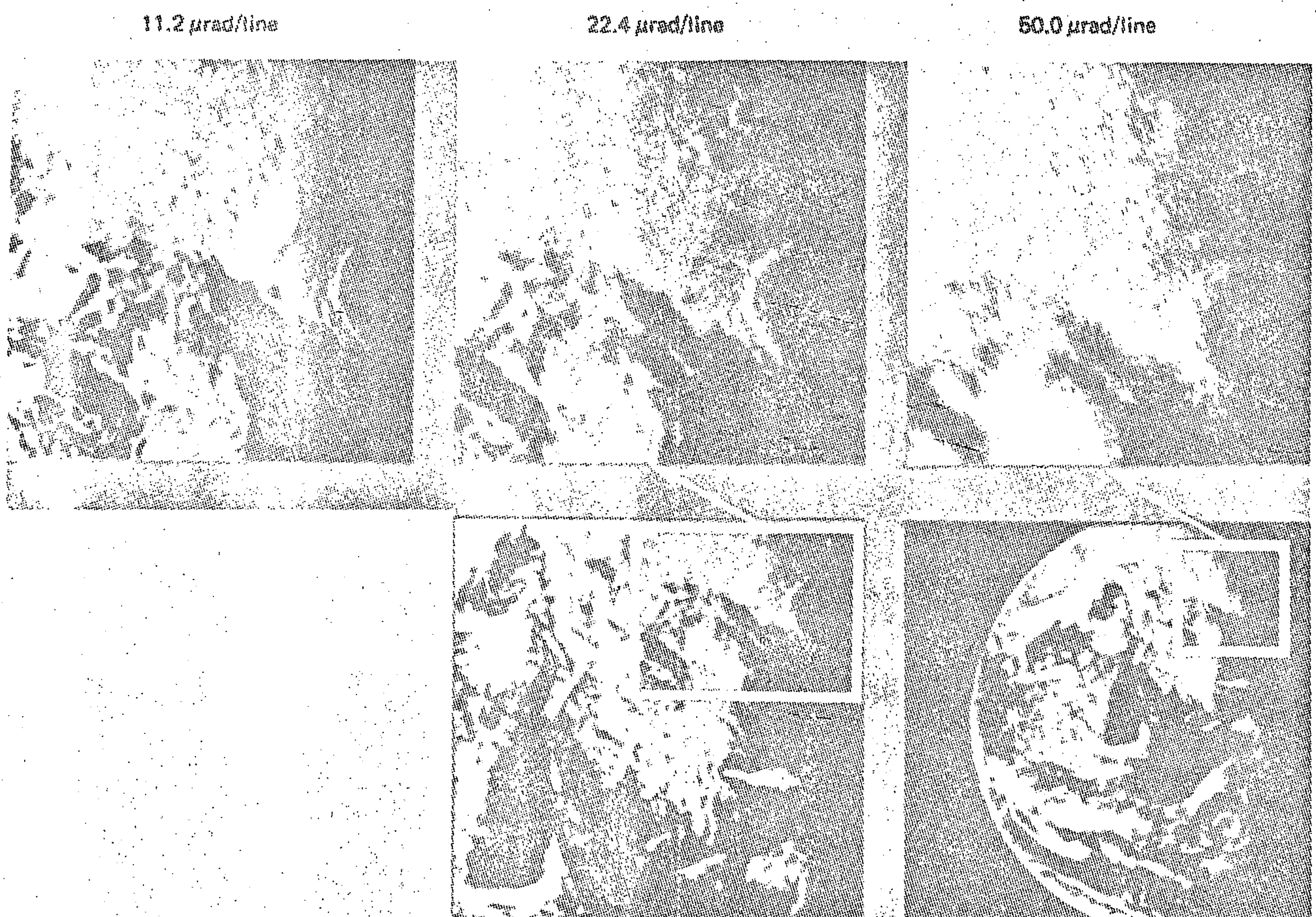
Having identified the silicon and the SIT vidicons as the most promising candidate sensors, the Imaging Team recommends the continued development of these tubes. Radiation resistance, slow scan capability, and white reseau patterns should be emphasized. Finally, cost and payload guidelines are urgently needed so that detailed work on the functional design of one of these systems can begin in earnest.

D. Sequencing: Typical Mission Profiles.

i. Immediate Aims of Sequencing Study and Ground Rules - To date the team has performed only a partial study of the incredibly complicated job of planning mission profiles for each of the three flybys of the 4 projected missions. However, considerable insight has been gained by concentrating our efforts on two particular flybys:

SIMULATED VIEWS BY CANDIDATE OUTER PLANETS IMAGING SYSTEMS

EARTH AS VIEWED FROM 500,000 km BY A 1-in. SILICON VIDICON AND OPTICAL SYSTEMS
SELECTED TO YIELD THE INDICATED RESOLUTION/TV LINE:



41-a

Figure 8. Simulated Lunar views by candidate systems

These pictures are typical of the views which would be obtained by the three candidate systems for all satellite encounters except the specifically targeted close encounters, such as those considered in Section 4 for Iapetus, Miranda and Triton. Scientific results can be categorized as follows:

50.0 μrad/line (.5 meter focal length): Detection of broad dark markings (already detected from Earth in some cases)

22.4 μrad/line (1 meter focal length): Determine existence of large craters. Some data on topographic character of surface. No data on physical geology.

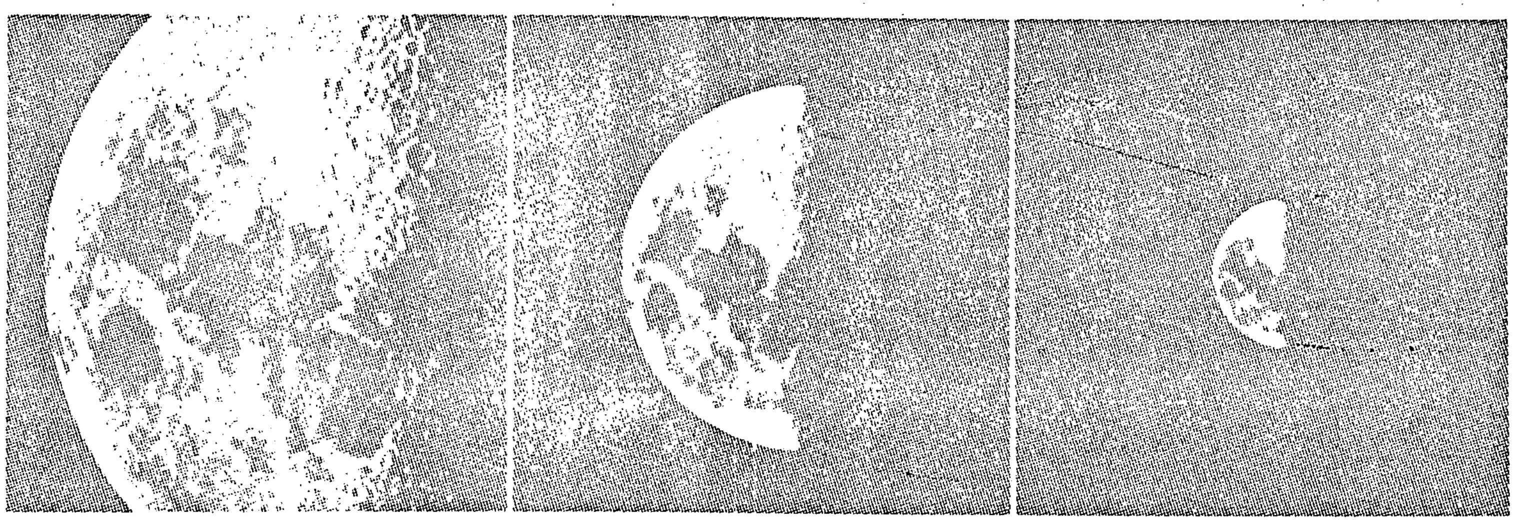
11.2 μrad/line (2 meter focal length): Sufficient resolution for statistical analysis of craters. Data on topographic character of surface. Some data on physical geologic structure, such as uncratered smooth regions, large faults, mountains, etc.

42-a

SIMULATED VIEWS BY CANDIDATE OUTER PLANETS IMAGING SYSTEMS

MOON AS VIEWED FROM 500,000 km BY A 1-IN. SILICON VIDICON AND OPTICAL SYSTEMS SELECTED TO YIELD THE INDICATED RESOLUTION/TV LINE:

11.2μrad/line | 22.4μrad/line | 50.0μrad/line



a. JSP '77 - November 13, 1980 Saturn flyby

b. JUN '79 - September 5, 1989 Neptune flyby

An idea of the intricacy of OPGT flybys can be gained from Figure 10 which shows a time-range plot through the Saturn system.

The immediate aims were to compare the performance of the 5 candidate imaging systems described in Table 3 in order to check:

a. The influence of focal length on science capability

b. The usage of wide angle camera

c. The importance of on-board mass data storage

d. The importance of data compression

e. Size the data handling problem

f. To compare the imaging system performance requirements for the JUN and JSP missions.

This latter topic could be of importance if different payloads for the two missions are to be considered. Some ground rules had to be set regarding available data rates and our assumptions are included in Table 4. This table also includes frame rates per day. The mass data storage problem was investigated only for system C.

ii. Sequencing Saturn (JSP'77 - Nov. 13, 1980) - No attempt is made here to include all the details of the sequences that have been generated. In particular we omit a detailed exposition of precisely where and how the science objectives are accomplished in the sequence. Such data has been generated but is too bulky for inclusion in this report.

Table 5 compares the time coverage at better than a specified resolution on approach to the planet and Table 6 the maximum ground resolution attainable as well as a measure of the maximum image size relative to the camera FOV.

Figure 9. Simulated Lunar views by candidate systems

These are typical of the views that can be obtained in the best satellite encounters discussed in Section 4. Iapetus, Miranda, Ariel, Triton, and probably at least one Galilean satellite can be imaged with resolution somewhat better than in these views; other satellites are imaged with considerably poorer resolution (see companion illustration). Scientific results can be categorized as follows:

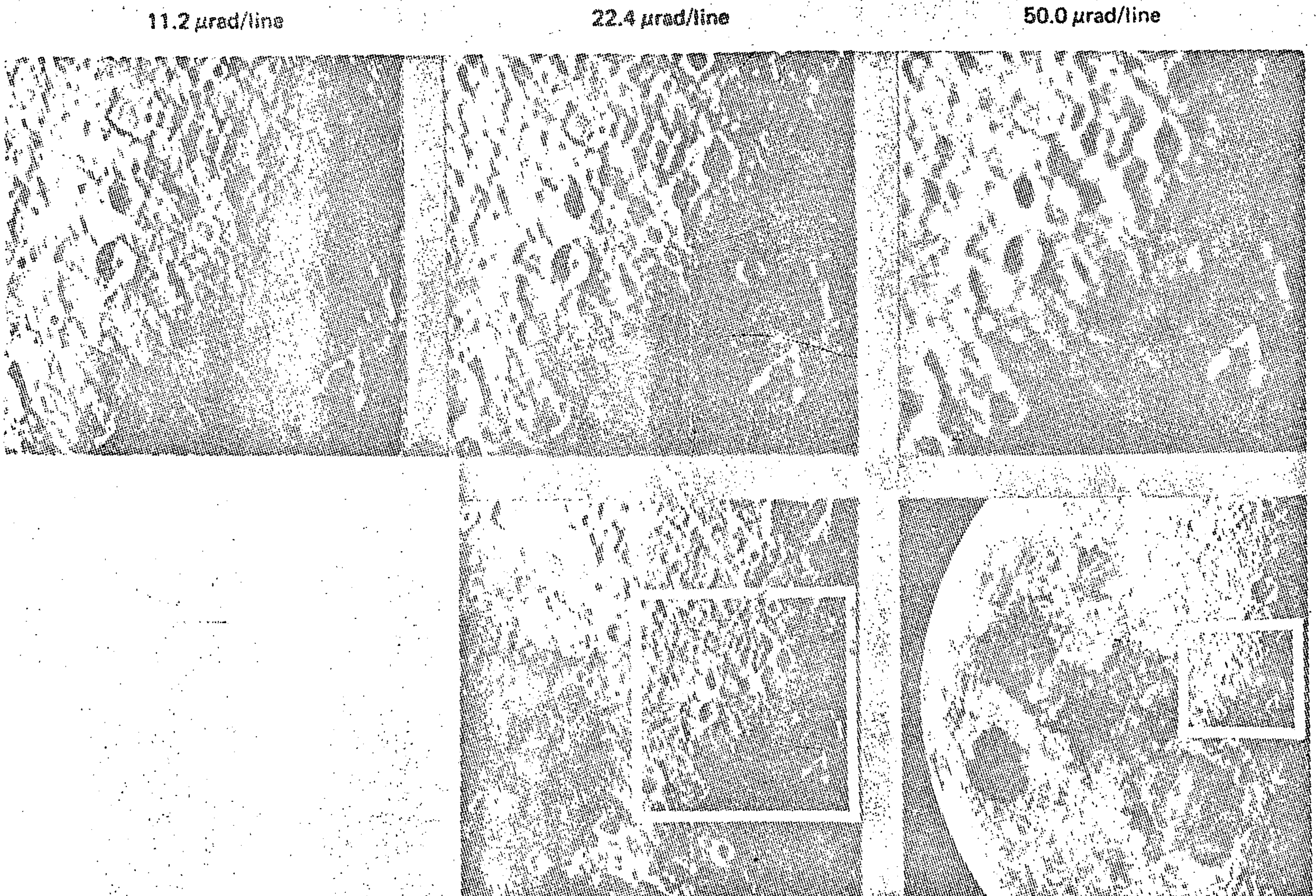
50.0 μrad/line (.5 meter focal length): Statistical analysis and detection of craters down to 5-10 km diameter. Data on topographic character of surface. Detection of major geologic structure such as faults, systematic lineament trends, mountains, etc.

22.4 μrad/line (1 meter focal length): Detection of volcanic/tectonic structures at scales typical of structure on earth, e.g., graben, crater chains. Some data on geologic provinces such as ejecta blankets, volcanic fields, flow units. Extension of crater statistics to about 2-5 km diameter.

11.2 μrad/line (2 meter focal length): Structural and geometric data on profiles of rilles, mountains, etc. Detection of flow units, secondary craters, volcanic constructional features, etc. Extension of crater statistics to about 1-3 km diameter.

SIMULATED VIEWS BY CANDIDATE OUTER PLANETS IMAGING SYSTEMS

MOON AS VIEWED FROM 100,000 km BY A 1-in. SILICON VIDICON AND OPTICAL SYSTEMS SELECTED TO YIELD THE INDICATED RESOLUTION/TV LINE



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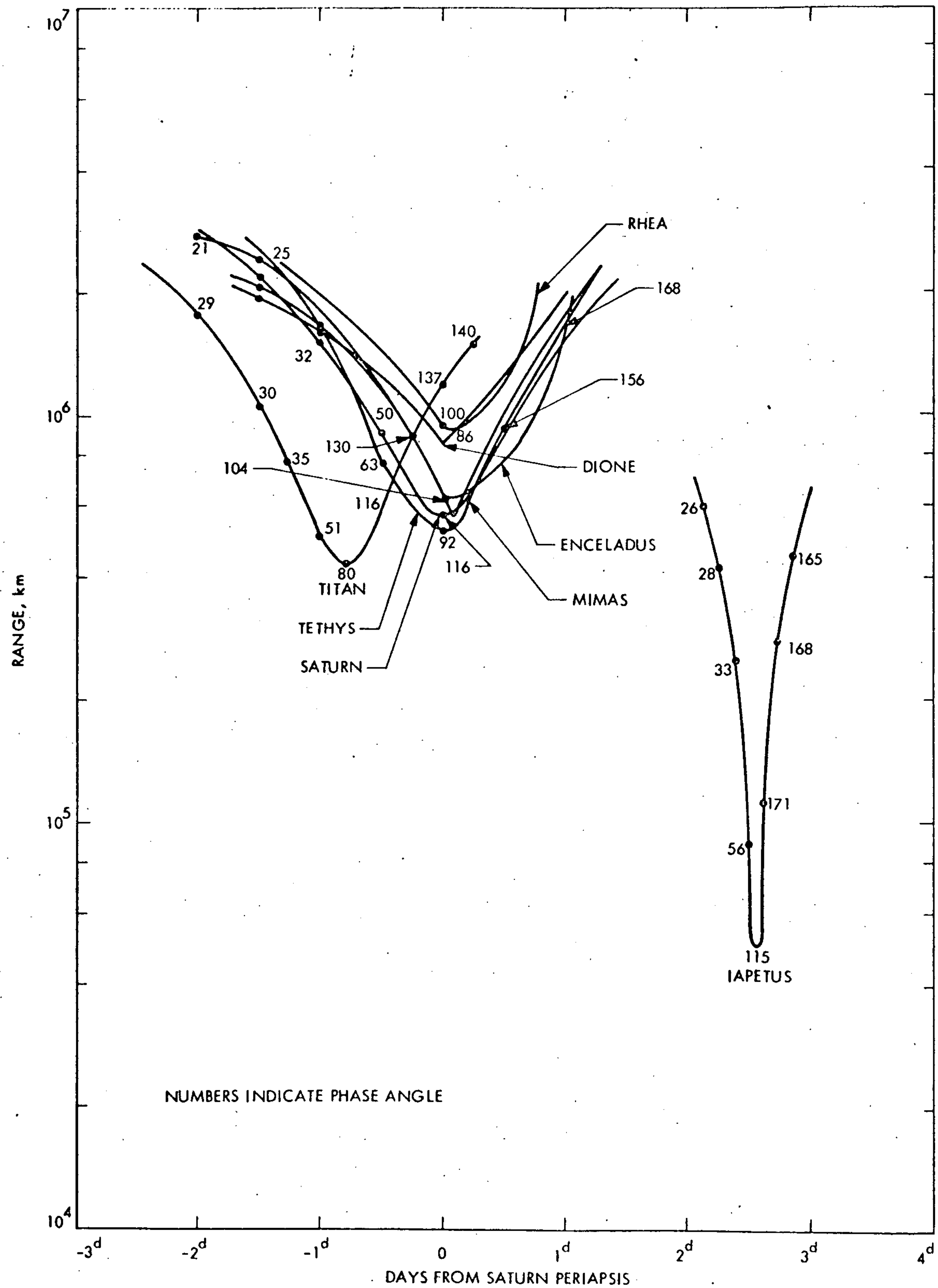

Figure 10. Saturn flyby - range vs. time

Table 4. OPGT Data Rate Sheet

Planet	Total Data Rate (bits/sec)	Imaging Data Rate (bits/sec)	8-bit Encoding NO COMPRESSION	
			Transmission Time/Frame (sec)	Full Frames per Day
JUPITER	16,384	12,534	160 (2-2/3 min)	540
SATURN	2,896	2,215	903 (~15 min)	95
URANUS	724	554	3610 (~1 hour)	24
NEPTUNE	362	227	8811 (~2-1/2 hour)	9.8
PLUTO	362	227	8811 (~2-1/2 hour)	9.8

Table 5. Saturn - JSP'77 - November 13.70, 1980

Focal length (meters) Sensor	Days Before Encounter				
	0.3m SIT	0.5m SiV	1m SIT	2m SIT	4m SIT
3000 - km Resolution	13	25	44	88	176
Saturn fills 0.4 FOV (field of view)	6	10	21	41	80
Saturn fills 0.8 FOV	3	5	10	21	40
Saturn fills field	2.5	4	8	16	33
500-km Resolution	2	4	7	14	29
Saturn fills 1.6 FOV	1.5	2.5	5	10	20
300-km Resolution	1.1	2.3	4	8.5	17
100-km Resolution	0.08	0.67	1.3	2.75	5.5

Table 6. Saturn Encounter JSP'77 - November 13, 1980

	Optics	Saturn	Mimas	Enceladus	Tethys	Dione	Rhea	Titan	Hyperion	Iapetus
Maximum Resolution (km)	2 M	14.6	15.1	16.5	13.4	21.9	24	11.0	44	1.3
	1 M	29.1	30.1	33.0	26.8	43.7	48	22.0	88	2.6
	0.5 M	50.7	52.4	57.3	46.6	76.0	84	38	153	4.5
	0.3 M	97.2	100	110	89.3	146	160	74	294	8.7
Max. Ang. Dia./FOV	2 M	36.9	0.1	0.2	0.37	0.19	0.25	2	0.06	4.6
	1 M	18.2	0.05	0.1	0.18	0.1	0.12	1	-	2.3
	0.5 M	9.1	-	0.05	0.09	0.05	0.06	0.5	-	1.2
	0.3 M	5.9	-	-	-	-	-	0.3	-	0.6

Comparison of Systems - Saturn Encounter

(a) Wide-Angle Optics

Analysis of System B shows that deletion of the wide-angle optics adversely affects the Saturn encounter in three areas:

(1) The period over which full-disk, single-frame pictures of Saturn can be obtained is diminished by 13.5 days, adversely affecting study of atmospheric circulation on Saturn.

(2) The ability to obtain nested wide angle and narrow angle terminator pictures at closest approach to Saturn is lost, which seriously hinders study of cloud structure.

(3) Finally, "global" coverage of Saturn's terminator region is lost, further impacting circulation studies.

(b) Tape Recorders

Analysis of system C reveals that deletion of tape recorders affects the Saturn encounter in two places:

(1) The number of frames of Saturn taken within ±4.5 hours of closest approach drops from 122 to 24.

(2) The number of frames obtained during the entire Iapetus encounter falls from 160 to 60. Nevertheless extensive coverage of Iapetus at high resolution is obtained.

(c) Focal Length

Comparison of systems B, D and E illustrates primarily the impact of focal length on the science accomplished during the mission. A summary of these comparisons is shown in Table 7 and in Figure 11.

(d) Summary

For studies of satellites the longest possible focal length is desirable. A focal length shorter than 1m has essentially no capability for comparative studies.

Table 7. Performance of OPGT Optical Systems

Focal Length:		A 4m	B & C 2m	D 1m	E 0.5m
Planetary Performance					
Days with resolution better than earth-based	Saturn	204d	102d	51d	29d
	Neptune	560	280	140	70
Days with resolution better than 100 km	Saturn	5.5d	2.8d	1.3d	0.7d
	Neptune	4.4	2.7	1.3	0.8
Planetary rotations with planet filling 0.8 to 1.0 FOV	Saturn	16	12	5	2
	Neptune	4	2	1	0.5
Best resolution	Saturn	7 km	15 km	29 km	51 km
	Neptune	2	4	8	14
Satellite Performance					
Number satellites at better than 30 km resolution (Sat.)		8	7	3	1
Number satellites at better than 3 km resolution (Sat.)		1	1	1	0
Examples of best resolution	Triton	0.4 km	0.7 km	1.5 km	2.6 km
	Iapetus	0.6	1.3	2.6	4.5
	Titan	5	11	22	38
	Tethys	7	13	27	47
	Rhea	12	24	48	87
	Hyperion	22	44	88	153
Percent of rotation observed at better than 100 km res. (Phase 0 to 140°)	Dione	100%	100%	66%	15%
	Triton	100	46	17	5
	Titan	50	22	12	8
	Hyperion	22	10	3	0
	Iapetun	5	3	2	1
Percent of rotation observed at better than 30 km res. (Phase 0 to 140°)	Mimas	100%	64%	20%	0%
	Enceladus	98	49	1	0
	Tethys	80	40	26	0
	Rhea	34	17	0	0
	Triton	30	15	8	4
	Titan	18	9	4	2
	Iapetus	2	1	1	0
	Hyperion	0	0	0	0

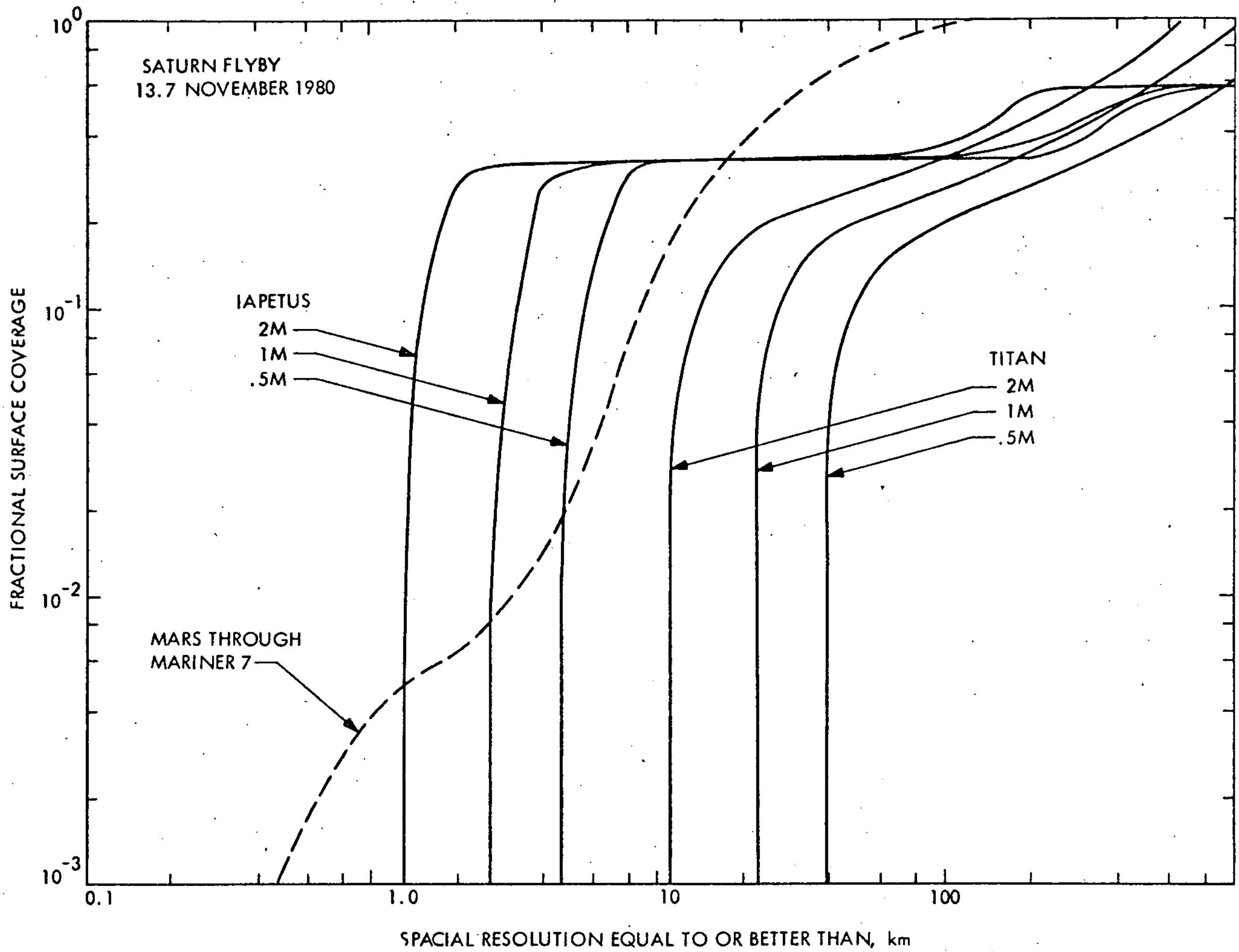

Figure 11. Satellite Science: Coverage vs. resolution

A comparison of the performance of Systems B, D, and E at Saturn's satellites. To indicate the information obtained by these systems, the cumulative Martian data through Mariner 7 has been plotted.

In the case of the planets, format is as important as focal length. However, long focal length is preferred for planet studies since it leads to a proportional increase in the time base over which studies of rotation and atmospheric circulation can be carried out.

The wide-angle camera is needed primarily for studies of planets.

Tape recorders are useful in that they allow a very significant increase in the number of pictures taken at two critical junctures during the Saturn encounter. However, it is apparent that an excellent imaging experiment could be carried out at Saturn without use of the tape recorders.

iii. Sequences - Neptune (JUN 79 - September 5, 1989) - Tables 8 and 9 give quantitative information on time coverage, maximum resolution and image size.

Comparison of Systems - Neptune Encounter

(a) Wide Angle Optics

Deletion of the wide-angle optics adversely affects the Neptune encounter in the same ways as it did in the Saturn encounter. Nesting of wide angle and narrow angle pictures will be desirable during the potentially close encounter with Triton.

Table 8. Neptune - JUN 79 - September 5, 1989

	Days Before Encounter				
	0.3 m SIT	0.5 m SiV	1 m SIT	2 m SIT	4 m SIT
6000-km resolution	~21	~35	~70	~140	~280
3000-km resolution	10	20	35	~70	~140
500-km resolution	2	3.3	7	11	~70
Neptune fills field	0.8	1.3	2.5	5	10
300-km resolution	1.2	2	3.5	7	14
100-km resolution	0.4	0.75	1.3	2.7	4.4

Table 9. Neptune - JUN 79 - September 5, 1989

Maximum Resolution and Image Size Data			
	Optics	Neptune	Triton
Maximum Resolution (km)	2 m	4.0	0.7
	1 m	7.9	1.5
	0.5 m	13.8	2.6
	0.3 m	26	5
Max. Ang. Dia. / FOV	2 m	45	23.5
	1 m	22	11.6
	0.5 m	11	5.8
	0.3 m	7.3	3.8

(b) Tape Recorder

Deletion of the tape recorders has far more serious implications at Neptune than is the case at Saturn. If the tape recorder is deleted, the total number of pictures of Neptune and Triton combined during near encounter falls from about 115 to about 10.

(c) Focal Length

The impact of focal length on the science accomplished in the case of Neptune is essentially the same as for Saturn (cf. Table 7 and Figure 12). The low communication rates at Neptune, make long focal lengths with the consequent lengthening of the observing period highly desirable.

In the case of Triton, the argument for long focal length is somewhat different from the case of the satellites of Saturn. Triton overflows the FOV of all the systems at closest approach*, and the argument for longer focal length is then solely to increase the observing period available below the resolution threshold.

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*We have assumed a 25,000 km pass at Triton.

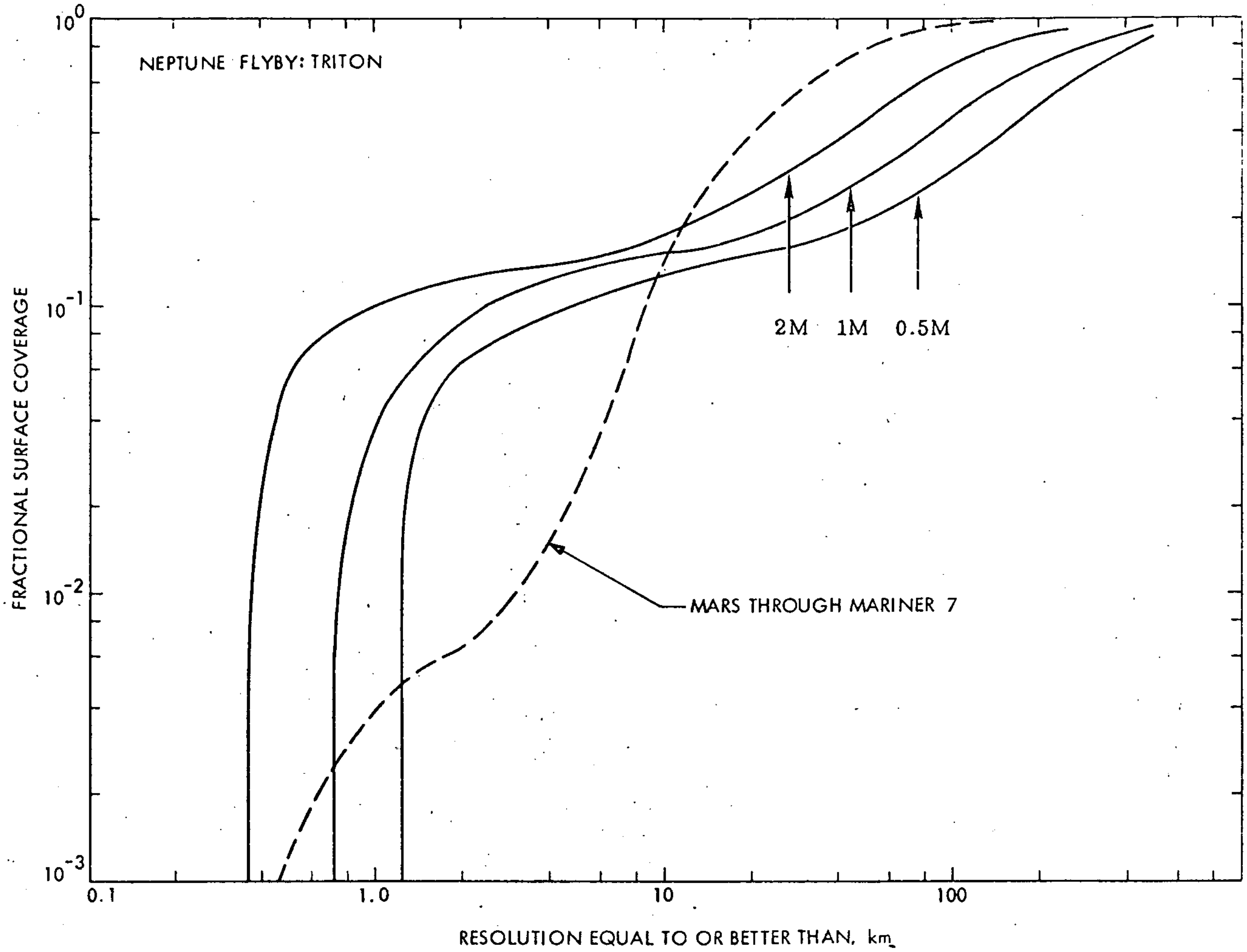


Figure 12. Satellite Science: Coverage vs. resolution

6. DATA HANDLING

A. The Spacecraft Data System

The function of the spacecraft data system is to process, store, and return to earth the digital data generated by the science instruments. Since the data system is essential to the success of the imaging investigation, the Imaging Team is concerned that it be highly reliable and well suited to the experiments it will support. The requirements on the data system differ considerably for the various science instruments and for the several phases of a long mission, and so flexibility is a major design goal. Unfortunately, high performance can be equated with additional weight/cost, and the pounds/dollars consumed by the data system will not be available for the science payload. Therefore, the Imaging Team is also concerned that the data system not be overdesigned at the expense of the camera system.

B. Discussion of Data System Components

The telemetry system is the portion of a data system which transmits information from the spacecraft to the ground stations. Generally, the data is not transmitted in a simple stream as produced by the science instruments, but is "coded" to minimize the effect of noise in the telemetry channel. Since the data stream is digital, the signal-to-noise ratio of the telemetry channel has an equivalent in bit error rate. The data rate of the telemetry system depends on the earth-spacecraft range, but for most of a Grand Tour flight, the telemetry rate will be lower than the minimum data rate of the imaging system. Therefore, an auxiliary device is needed to match the camera rate to the telemetry rate.

The data storage system (DSS) accumulates the high rate data generated by the cameras and plays it back at a lower rate to the telemetry system. Since the DSS can store information indefinitely, the playback sequences can be planned to optimize science and/or minimize ground station costs. On previous planetary missions, the DSS has consisted of a magnetic tape recorder. With such a recorder, the data rate reduction is accomplished by some combination of (1) different tape speeds for record and playback, (2) recording in parallel on several tape tracks and playing back one track at a time, and (3) small rate buffers at the input/output of the recorder. Recorders of reasonable size and weight can store several tens of pictures. Although experience with recorders has so far been good, the potential for wear and failure of the moving parts is a cause for concern on a ten year mission.

An alternative to the tape recorder is the large static memory or storage buffer. Because there are no moving parts, a buffer has the potential for high reliability. Most single-point failures would disable only a fraction of the storage capacity, not the entire device. Unlike the motor in a tape recorder, the critical components of a buffer are small, and could therefore be highly redundant. Because the various storage addresses can be interrogated in random sequence, the static memory is more flexible than the tape recorder. The buffer read rate can be adjusted to match the telemetry rate at all points in the mission. The major shortcoming which limits the utility of storage buffers is lack of capacity. A device with weight comparable to two tape recorders could store at most a few frames.

The processing function of the spacecraft data system is less well defined than the telemetry and storage functions. Processing can be used to enhance or suppress selected aspects of the picture, e.g., enhancement of high frequency detail. On recent missions, such processing on the spacecraft has been little used, probably because the introduction of digital data systems makes it possible to do this processing almost as well after the data has been returned to earth.

Another type of processing, data editing and compression, has been investigated by the Imaging Team, and appears to offer several advantages for the Grand Tour missions. Editing is the systematic elimination of data from an image without regard for the type of information contained in a particular picture. Compression is similar to editing, the difference being that an effort is made to minimize the information loss by taking into account the nature of the data contained in a particular image. In the limiting case, a data compressor removes only redundant data, and the device is said to be information preserving. The distinction between editing and compression is somewhat blurred, and the term compression is used generically to describe both. Since compressed pictures contain fewer data bits, the telemetry system can transmit more such frames in a given time interval. Equally important, pictures containing fewer bits require less storage capacity on the spacecraft. Thus, the limited capacity of a storage buffer is a less serious problem if data compression can be used.

Data compressors are not without problems. Before employing a compressor, the investigator must be reasonably sure that the resulting pictures will have adequate quality for the intended use. However, we cannot predict in detail the types of information the planetary pictures will contain, and so we can never be certain as to what constitutes adequate quality. In an effort to develop some information on this problem, the Imaging Team sponsored the preparation of simulated photographs showing the effect of some simple editor/compressors on typical planetary images. Some details of this study will be given below. From these pictures, the Team concluded that compression to reduce the data content of a picture by a factor of two resulted in images which were useful for many purposes. Compression by a factor of four caused substantial loss of image quality, and the Team considered these pictures acceptable only in extreme situations, such as a partial failure of the spacecraft data system.

The telemetry and ground data handling systems used for previous missions are not optimum for the transmission of compressed picture data. However, it appears that these systems can be made compatible with simple compression schemes. As presently structured, the ground data system relies heavily on the fact that every television line contains the same number of bits. The Imaging Team believes that a departure from fixed line length would make the system unnecessarily complex and risky. Therefore, the data compressors considered here are all constrained to operate at a fixed compression ratio, so that every line of a compressed picture will look like every other line (to the data system). With this restriction, the addition of a data decompressor at the ground stations should be a simple matter.

The use of data compressors also places a constraint on the bit error rate (BER) of the telemetry system. Without compression, acceptable pictures can be returned when the BER is as large as 5×10^{-3}. The simulation study indicates that 5×10^{-3} is too high for compressed pictures, but 10^{-5} is more than adequate. Thus, the maximum allowable BER will lie somewhere in this range. The problem lies in modifying the telemetry channel so as to guarantee an acceptable BER without substantially reducing the telemetry data rate. The Imaging Team understands that this can be accomplished through convolutional coding and sequential decoding of the telemetry, and we recommend the implementation of such a coding scheme.

C. Choice of Spacecraft Data System

The ideal data system would have the storage capacity of a tape recorder and the reliability of a storage buffer. Data compression would be available, but would not be mandatory, thereby allowing the return of either full or partial quality pictures. The weight of the system would not be so great as to force reductions in the science instruments or the telemetry system. In view of these considerations, the Imaging Team believes that the data system should consist of a single magnetic tape recorder storing approximately 50 frames, a static memory with capacity for one half of an uncompressed picture, and a small number of editing/compression algorithms, each with a compression factor of two. The data system proposed here is estimated to weigh 71 pounds as compared with 83 pounds for two tape recorders. Since all of the candidate television cameras have the same data format, only one data system need be considered.

With this data system operating normally, full quality pictures would be stored in the recorder. The half frame buffer would allow us to take, compress, and store a single picture without interrupting a playback sequence of the recorder. The compressor could be used to effectively double the telemetry rate whenever pictures of slightly reduced quality are sufficient. Should the recorder fail, the buffer would permit the return of compressed pictures one at a time.

The Imaging Team has also considered the practicality of an even lighter data system, one consisting of a single tape recorder (56 pounds) or a full frame buffer (25 pounds). The risk associated with flying a single recorder was thought to be unacceptably high. Although it is a very serious handicap, the one frame capacity of the buffer still permits an acceptable experiment to be carried out. Under extreme circumstances, the Team would recommend reduction of the data system to a single full frame buffer rather than reduction of the imaging system to sub-minimal performance.

D. Discussion of Editing and Compression Schemes

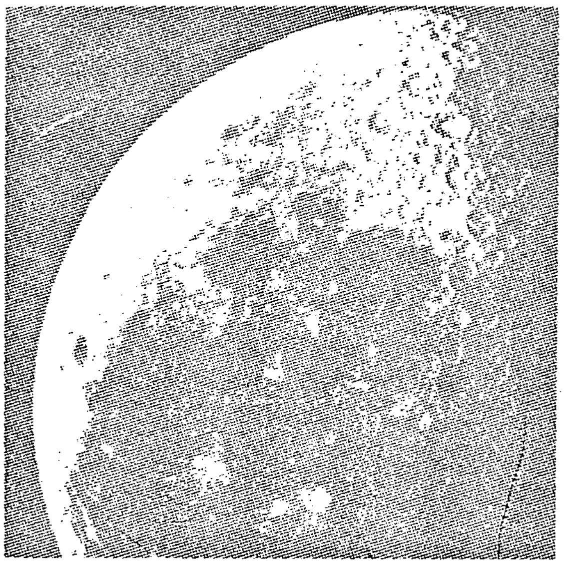
Three types of editing can be used effectively with the imaging system. The black sky or partial frame editor simply eliminates a portion of the frame and transmits the remainder. This scheme is particularly useful when the planet does not fill the entire field of view. The pixel editor eliminates some fraction of the picture elements in a preselected pattern. By editing out every second pixel in a checkerboard arrangement, the data content is reduced by two, but the resolution is reduced by $\sqrt{2}$. The bit editor reduces the number of bits used to encode each picture. This method is used when the number of resolvable grey levels in the picture has been reduced by noise in the camera.

All of the compressors considered have been variations on the delta modulator. This device uses the brightness of the first picture element as a reference, and then sends only differences (deltas) for the subsequent pixels. The brightness difference between adjacent pixels is assumed to be small, so fewer bits are needed to transmit the deltas than are needed to transmit the absolute brightnesses. Whenever the assumption of small brightness differences breaks down, as for example at a bright limb, the compressor can be expected to distort the image. Also, as the number of bits used to transmit each delta is reduced, the compressed picture becomes less faithful to the original.

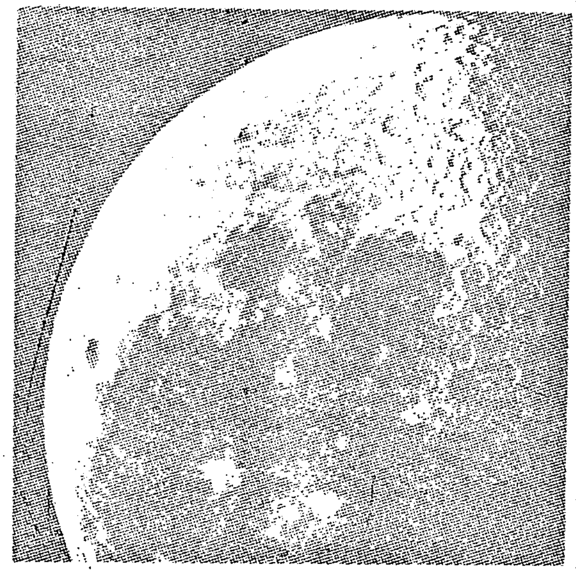
Compressors of this type are vulnerable to noise in the telemetry system. To reconstruct the brightness of a pixel, the decompressor must apply the delta for that pixel to the brightness value of the preceeding pixel. If a bit error occurs in the telemetry, an erroneous delta will be received, and the brightness reconstruction of that pixel will be incorrect. Moreover, since that pixel serves as the reference for the next, the error will propagate along the line until the next reference pixel is reached. For this reason, compressors require a lower bit error rate than would otherwise be needed. The team has concluded that the bit error rate must be considerably better than 5×10^{-3} if compressed data is to be transmitted.

Figure 13. Data Compression Effects

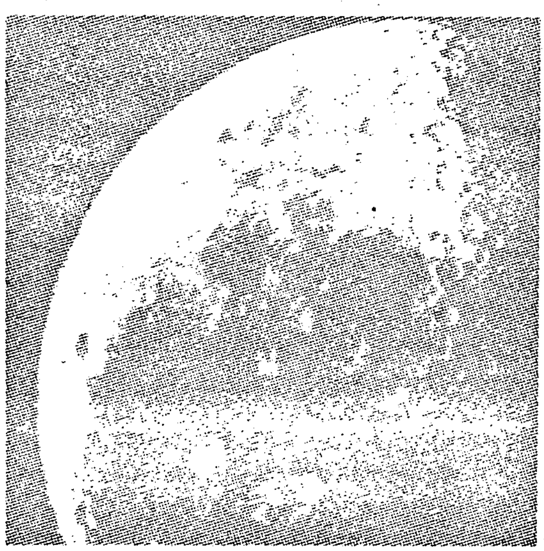
Figure 13. Compressed pictures: (a) Original image at 8 bits per pixel; (B) Compression by delta modulation to 4 bits per pixel; (C) Compression by delta modulation to 2 bits per pixel; (D) Removal of every other pixel by editing, compression of remaining pixels by delta modulation to 4 bits per pixel. The overall data reduction in the image is by a factor of 4. Ground processing replaces each missing pixel with the average of the four adjacent pixels.



A



B

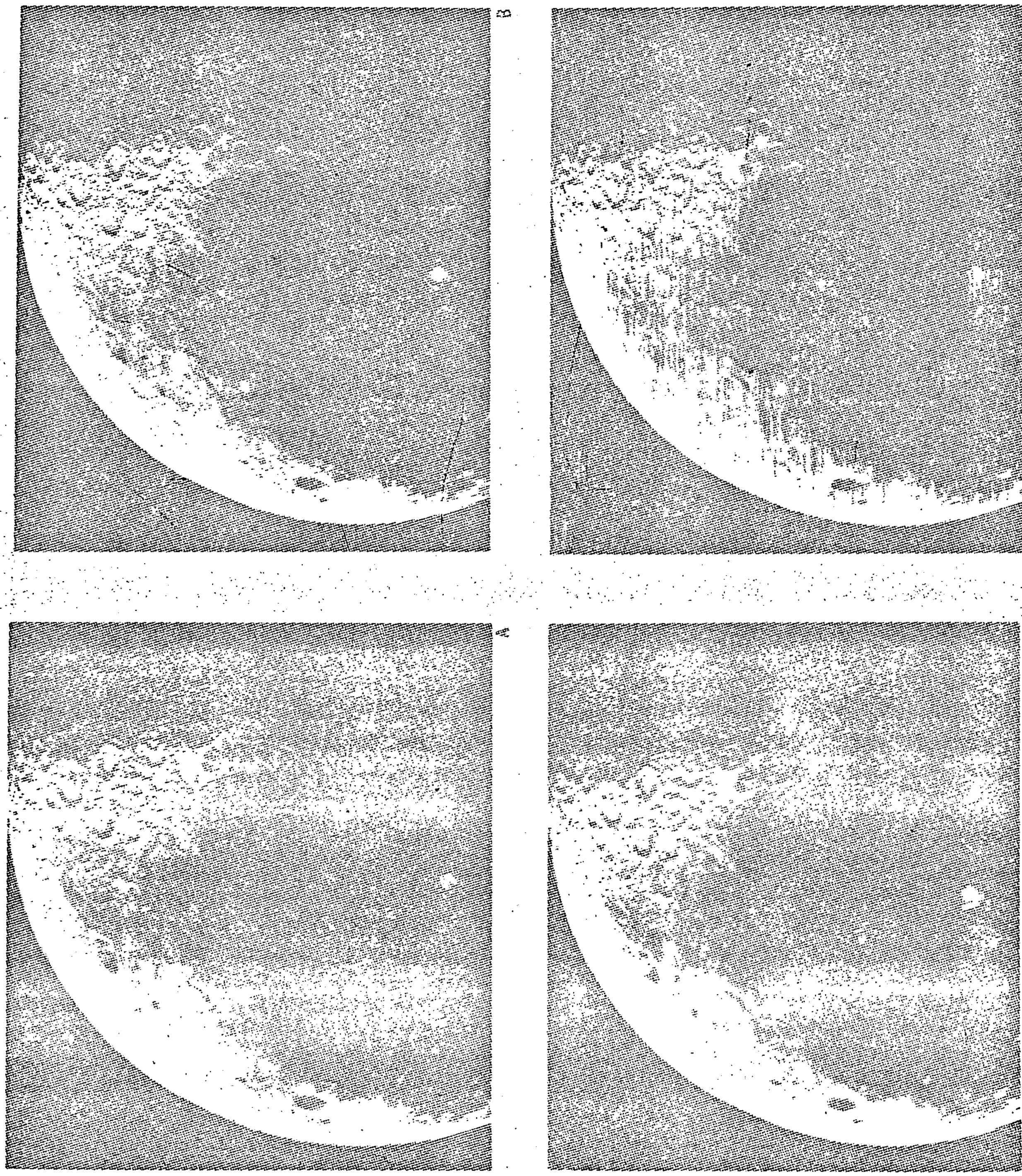


C

D

Figure 14. Telemetry Error Effects on Compressed Data

Figure 14 illustrates the effect of noise on a compressed image containing fine detail. The compressor used requires four bits to transmit each delta, so the compression ratio is two for a camera system with eight bit encoding. The frequency of reference pixels is one in fifty. Picture A is the original uncompressed image; B shows the effect of the compressor. Pictures C and D show the compressed picture with telemetry noise added. The bit error rate is 10^{-5} in frame C and 5×10^{-3} in frame D. Note in D that the errors are cancelled every fifty pixels when a new reference point is reached.



7. ANCILLARY EQUIPMENT

A. Filters.

The addition of filters to the basic camera system will enhance performance in at least three ways: Improvement in contrast allowing greater visibility of detail, development of physical information such as definition of provinces and elucidation of cloud structure, and determination of elementary compositional information such as detection of tenuous methane atmospheres. It is worth pointing out that in each case, the benefit pertains both to bodies with atmospheres and those without.

Based on these considerations, we can define a basic set of pass band filters:

Broad Band: 3650 Å, 5500 Å, 8500 Å

Narrow Band: 6200 Å, 8900 Å

Additions to this basic set can be expected as the science requirements become more refined. The wavelengths given are values of peak transmission; broad band filters are considered to have a full bandwidth at 1/2 peak transmission of about 1000 Å, narrow band of about 200 Å.

The broad band filters suggested provide color discrimination over a broad range of wavelengths which will enhance detail, provide some colorimetric information for use in determining the identity of chromophores in clouds and give some first order data on vertical cloud structure. The narrow band filters, being centered on methane absorption bands, offer the potential of much improved cloud structure determinations. The 8900 Å band will be useful for Jupiter and Saturn, the 6200 Å band for Uranus and Neptune. Finally, the 8900 Å filter in combination with the 8500 Å broad band filter provides a first order test for the presence of tenuous methane atmospheres on satellites and for the presence of the ferrous ion in minerals exposed on the surfaces of the satellites. Indexing and manipulation of filter positions should include ability for both pre-programmed sequences and a near real time override capability. An "open" position containing a quartz disk of the same optical thickness as the filters must be included and it is probable that some type of clear field lens will be necessary for inflight calibration.

B. Polarizers.

The opportunity afforded by the Grand Tour Missions to view the planets and satellites through a wide range of phase angles permits the maximum advantage to be taken of polarimetric observations. Discrimination between frosts and opaque particles, tests of atmospheric models, composition - independent searches for tenuous atmospheres and enhancement of cloud height and limb haze information by discriminating against the molecular scattered component of the total light are some of the areas in which polarimetric observations may be expected to contribute.

Image tubes are not recommended sensors for polarimetric observations because of the difficulties in making a reliable photometric calibration. Consequently, we do not propose building in a sophisticated polarimetric mode. Accuracy in quantitative polarization measurements will be limited to a few percent, thus polarizers should be used basically as discriminators.

C. Far Encounter Satellite Sensor.

The scan platform must be able to automatically locate satellites, whose ephemerides are poorly known, and center them in the field of view. In this way black sky is minimized and the information-carrying bits transmitted to ground are maximized. The imaging team has recommended to the SSG that the project look at the possibility of updating satellite ephemerides on approach as a solution to the above problem.

D. Exposure Control.

In many cases, we do not know the dimensions, reflectivities, and scattering properties of Grand Tour targets and total reliance on pre-set exposures will be extremely risky, since there will not usually be an opportunity to make exposure corrections after receiving the pictures.

As a result, some form of onboard exposure control using light that has passed through the optical system is mandatory and should be included in the imaging system design at the outset. Onboard real time compensation for the reduction in intensity caused by filters and polarizers should also be considered for the same reason.

8. SCIENTIFIC DATA RELEASE POLICY

Fundamental differences between the Grand Tour Mission flybys and those performed in earlier missions past the terrestrial planets require modification in the present concepts of scientific data release and reporting to NASA. This is particularly true in the imaging experiment, where the encounter period can extend over periods of months (e.g., 5 months for Saturn) and picture frame rates can be as high as 500 per day. In addition there will be a multiplicity of objects studied in each encounter.

This tremendous volume of highly varied data coupled with realistic assessments of a team's capability of interpreting the pictures requires a substantial change in the current 30 day requirement for the production of a preliminary science report. In the context of these missions such a short period can only lead to questionable interpretation, mistakes and generally bad science.

We recommend that the period for preparation of a preliminary report should extend for at least six months after the encounter period.

The Imaging Science definition team recognizes the need for the rapid release of suitably processed selected pictures for public information purposes and believes that this problem can be resolved separately from NASA's requirements on the flight team's scientific reports.

9. APPENDIX

USE OF A BACK-UP LINE SCAN IMAGER ON THE GRAND TOUR*

A number of unique properties of a line scan or point sensor imaging device suggest that its use as an add-on or back-up to a high resolution TV system on the outer planets missions may significantly increase versatility, reliability, and science return.

1. Light weight, simplicity, and low cost add-on features make a line scanner very attractive if TV system redundancy must be sacrificed for weight.
2. A line scanner with several sensors, redundant in both number and type has a high probability of returning at least some imaging data, and can operate without tape memory or even without a buffer if need be.
3. The use of individual point sensors with different spectral ranges, in conjunction with possible use of cold all-reflective optics, could make possible new experiments and further unify the mission by forming a bridge between imaging science and UV and IR spectrophotometry and radiometry.

The beautifully complementary line scanner/SIT combination, for example, could be a very worthwhile compromise of weight and performance -- a minimum mission which satisfies all imaging science requirements and actually enhances science return.

*This section was prepared by V. E. Suomi and R. J. Krauss

WHAT IS A LINE SCANNER?

The first line scan device used in orbit was the Spin Scan Cloud Camera on the spinning spacecraft ATS-1. It consists of a 5 inch telescope with a photomultiplier sensor and a 100 μr aperture. The spacecraft spin provides the scan along a line while the telescope is stepped from line to line once each revolution to provide the wide format 2000 line raster. The camera is still in regular daily use after 5 years of continuous operation in orbit. A multicolor spin scan camera on ATS-3 was launched a year later and is also still in operation. Other types of scans are possible as well. The ITOS and NIMBUS series are earth oriented satellites using a rotating mirror for the scan and the motion of the earth past the low orbiting satellite to generate a continuous strip raster. The Synchronous Meteorological Satellite, to be launched in late 1972 will use spacecraft spin plus a stepping mirror to obtain 25 μr/line resolution. The ERTS imager uses a large oscillating mirror and motion of the spacecraft, while the Imaging Photopolarimeter on the Pioneer mission uses spacecraft spin and telescope stepping.

Many other scan methods can be used to generate a raster, even a focal plane scan using a moving mirror on torsion springs, or a moving aperture. The rather obvious principle is that any spacecraft or telescope motion at right angles to a fast scan direction will generate a raster of fairly high geometric precision. The spacecraft motion can be used to great advantage in the right way. Other, undesired spacecraft motions do surprisingly little to distort the raster, as Figure 1 shows. These residual distortions can be removed on the ground in a computer mapping process using monitored spacecraft attitude drift rates. The OPGT optical system will already exist for the vidicons, so a separate optical system is not needed for introduction of a line scanner. It will be an add-on feature as shown schematically in Figure 2, with the sensors weighing under a pound, and electronics consisting mainly of detector amplifiers and necessary low bandwidth switching and multiplexing -- probably 5-10 pounds at most. The Imaging Photopolarimeter on Pioneer weighs about 11 pounds including optics.

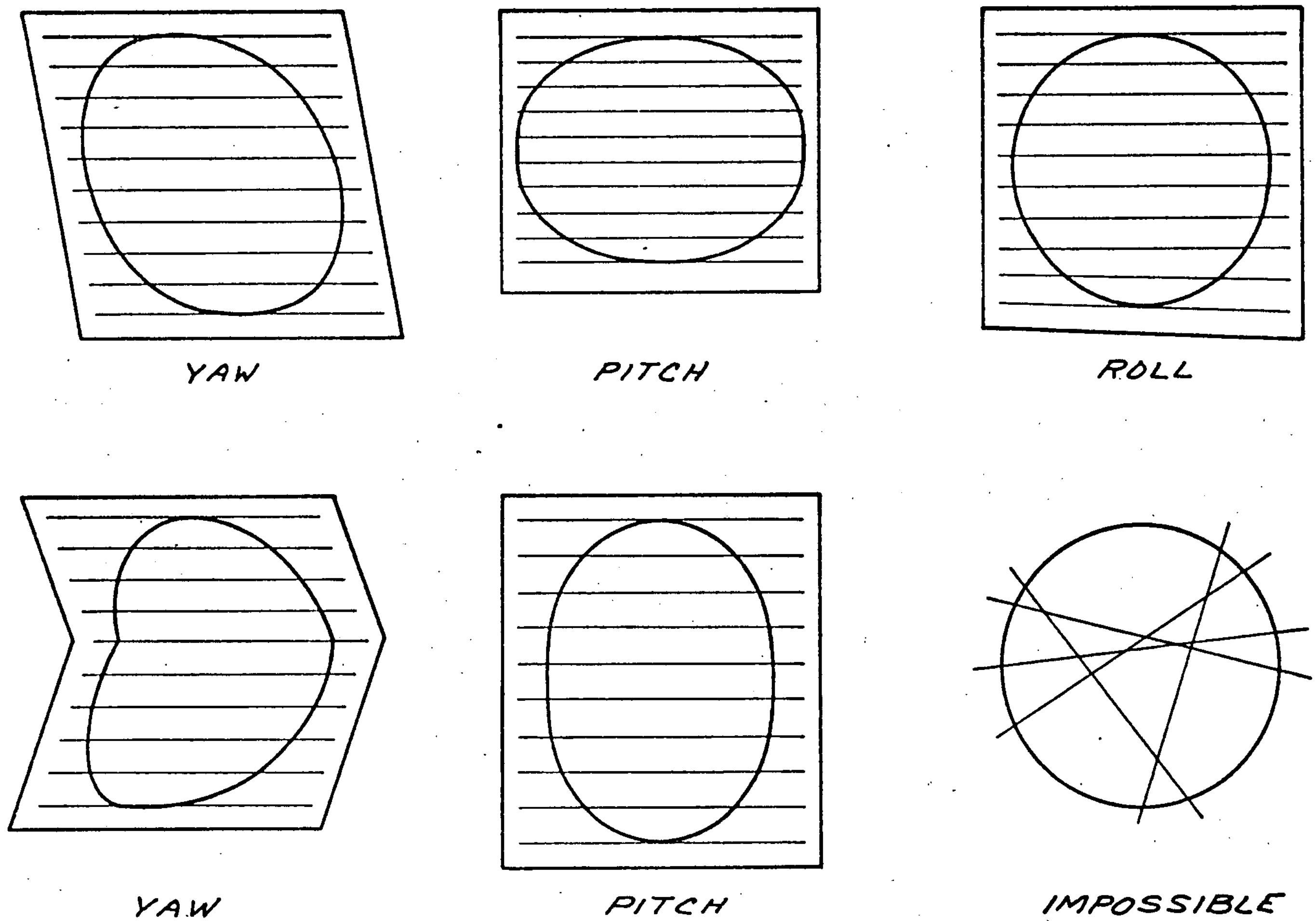


Figure 1. The effect of yaw, pitch, and roll on a line scan raster is shown here, greatly exaggerated. The distortion can be largely removed on the ground in a mapping process using measured spacecraft drift rates. Data loss between lines is virtually nonexistent, as drift is much less than one pixel per line. The "impossible" case would never occur unless spacecraft stabilization fails.

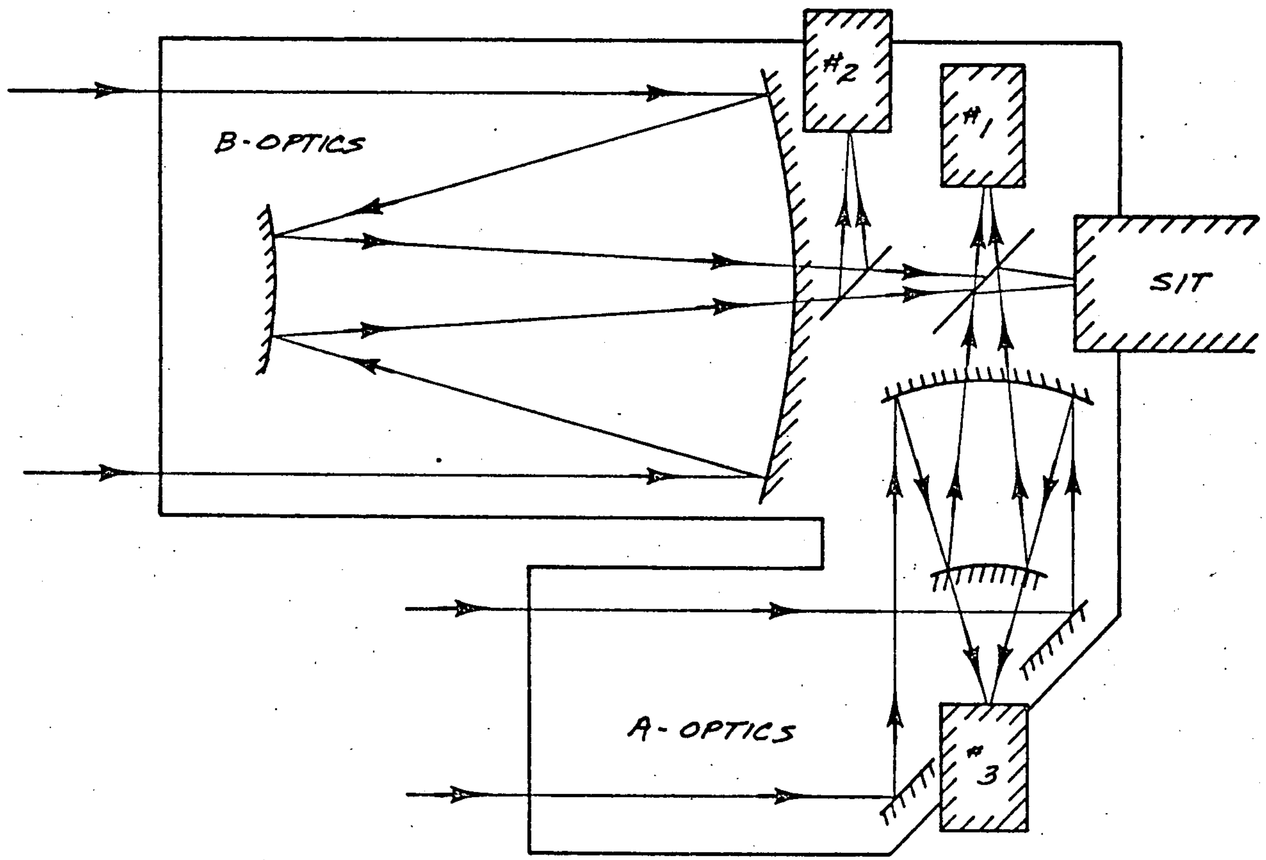


Figure 2. An optical system used for the Grand Tour would require maximum redundancy to increase probability of success. Flat mirrors inserted in the optical train at 45° angles allow either sensor to be used with either optics. A silicon intensifier vidicon (SIT) will probably be one of the sensors. The other may be a redundant SIT or a silicon vidicon at position #1. Line scan sensors could be placed at any of the numbered locations or others as well, as space permits.

POINT SENSORS

Many different types of sensors could be used, lending great versatility to any line scanner.

1. Radiometric accuracy. Point sensors are linear devices of extremely wide dynamic range. They are easy to calibrate. Instead of having a surface of N^2 individual sensors of slightly differing characteristics, only a single sensor is used. This sensor can be optimally chosen to have highest sensitivity in the spectral region of interest.
2. Long life. Line scan systems, as mentioned earlier, are still functioning in orbit after 5 years.
3. Spectral range. The selection of several sensors of different types would permit a spectral range for a line scanner considerably greater than any given sensor.
4. High resolution and high signal to noise. Both of these properties must be considered together, for they are inversely related for any given telescope aperture and sampling bandwidth. A reasonable frame time limits a point sensor to a few milliseconds dwell time, while framing sensors are generally smear limited or saturated at exposures of about a few hundred milliseconds. This $\sqrt{t}$ or 10:1 advantage of framing sensors makes a point sensor a poor choice if high resolution is the major criterion.
5. Image geometry. Mechanical line scan systems with 10 μr accuracy are difficult to build, while a 50-100 μr resolution, as existing systems show, is within the state of the art. With monitoring of spacecraft attitude drift rates, image reconstruction is no harder than generating a Mercator projection of Mariner TV frames. Data loss between lines is no problem for a reasonably stable platform. The drift rates would add up to just a fraction of a pixel per line in any direction.

IMAGING SYSTEM REQUIREMENTS

The imaging science team has set several important requirements and is considering tradeoffs between imaging systems (see section 5).

1. High resolution. The great flyby distances and the desirability of long time base observations make a high resolution imaging system mandatory. The line scanner as the primary imager was rejected by the team in spite of its other advantages because it failed to satisfy the high resolution requirement.
2. Sensor redundancy. The line scanner exceeds all other camera systems in the number and type of sensors which can be accommodated in a small package.
3. Data volume. If weight limitations required operation of an imaging mission without tape recorders, any camera will be limited in data return. A line scanner can match sample rate and resolution to bandwidth (see Figure 3). With a tape recorder, parallel operating multiple detectors can increase data output.
4. Spectral range. A line scanner with multiple detectors permits imaging over a larger spectral range than any single sensor.

Several other characteristics unique to line scanners are of interest as well:

5. Wide format. A 500 x 500 format is marginally adequate for planetary studies. The 500:1 ratio barely covers the relevant scales of interaction in the atmosphere. Mosaicking is a difficult and time consuming alternative. An optimum approach would be to make nearly simultaneous wide format 2000 x 2000 pixel frames with the line scanner at lower resolution and nest the high resolution frames within.
6. Perfect registration. Several detectors operating simultaneously in different spectral ranges will permit point by point comparison of images with identical geometry.
7. Ease of calibration. Simple 2-point calibration on the ground and in flight is possible because of the linearity of the detectors. The mission and subsequent data processing will be simplified.

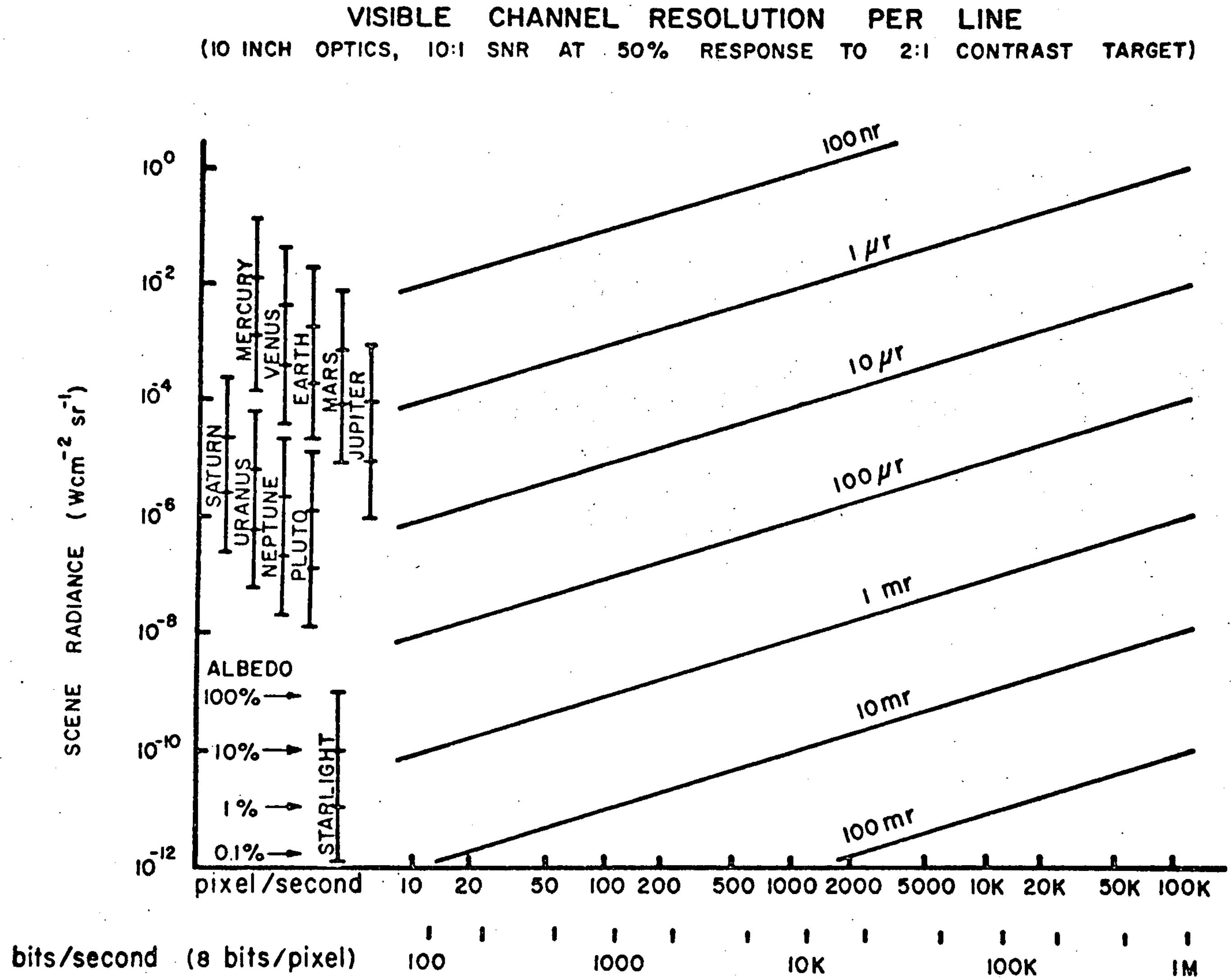


Figure 3. The imaging communications bandwidth for the outer planets mission will vary from 200 bps at Pluto to 15,000 bps at Jupiter, conveniently matching the single sensor sampling rates for a 50-100 μr resolution photomultiplier line scanner. Thus, real time transmission matched to the sample rate, without use of a buffer or tape recorder is possible. The data return is increased with on-board storage by operating more detectors simultaneously. Less than 1% reflected sunlight will produce a very good image.

SCIENCE PRIORITIES

Many of the Imaging Science objectives can be satisfied by a line scanner using a 50-100 μr/line resolution. Figure 4 shows two additional experiments which could enhance imaging science return.

Thus, while neither a 500 x 500 pixel high resolution SIT nor a line scanner can completely satisfy all the mission objectives, they serve to complement each other extremely well. In circumstances where the type A and B systems recommended by the imaging team will in all probability be too heavy, while the type D and E lightweight systems sacrifice too much performance, the type C option -- a single high resolution SIT with small format, and a line scanner backup to provide the wide angle capability -- may prove to be a most rewarding alternative.

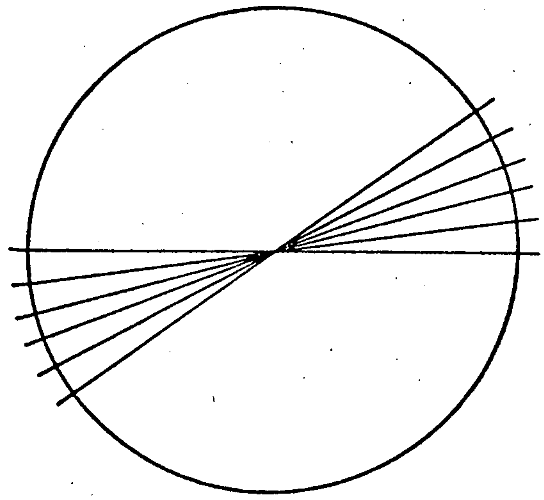


Figure 4a. With 50 μr resolution, an accurate line scan measurement of the figure of a planet to < 0.05% can be made at approach by pointing the telescope in the direction of spacecraft trajectory and rolling 180°. At 10 diameters distance, the planet width is 100 mr or 2000 pixels. At 5 diameters the planet is 4000 pixels across. Several thousand diameters are measureable in one roll.

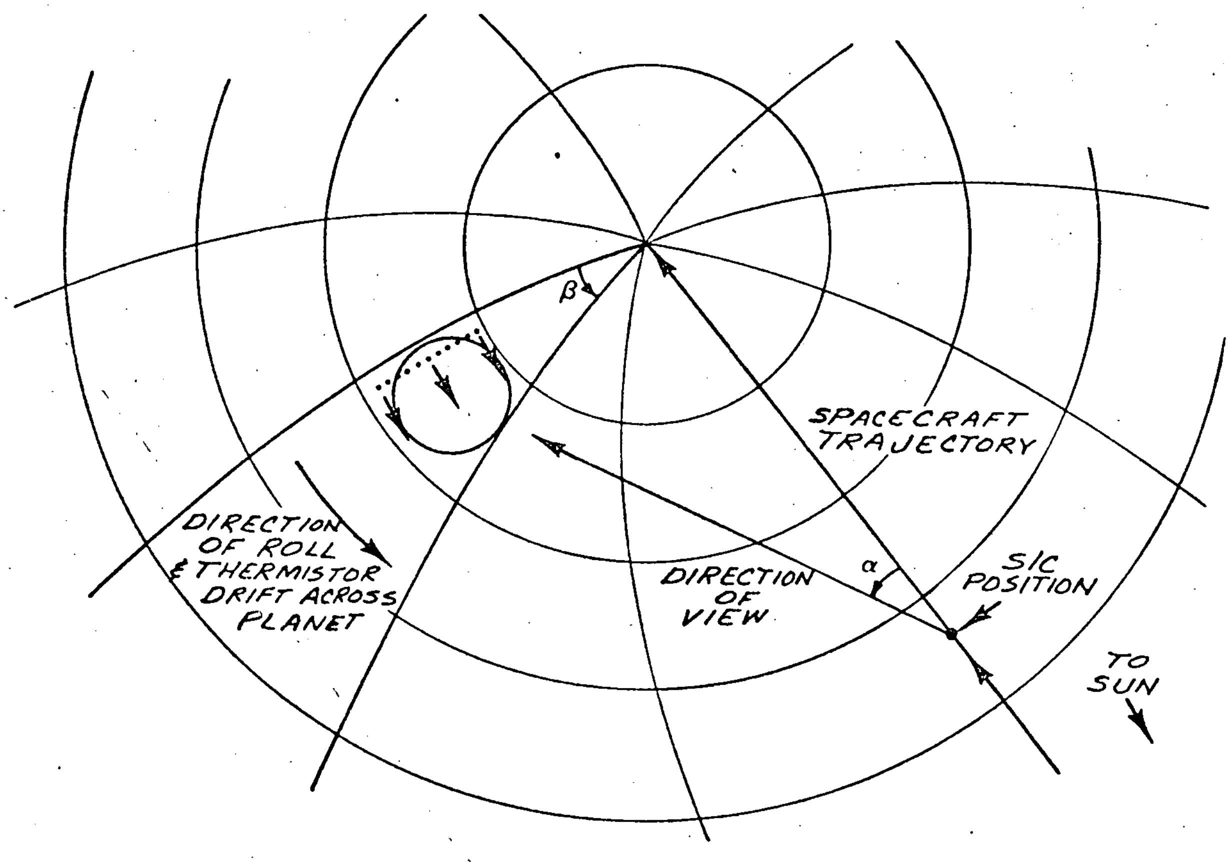


Figure 4b. Against the background of the celestial sphere, the telescope is aimed at an angle α away from the trajectory. The spacecraft makes a slow roll through angle β, causing an array of ~ 20 thermistors to drift across the planet, making a precise measurement of total radiation output as a function of latitude and longitude.