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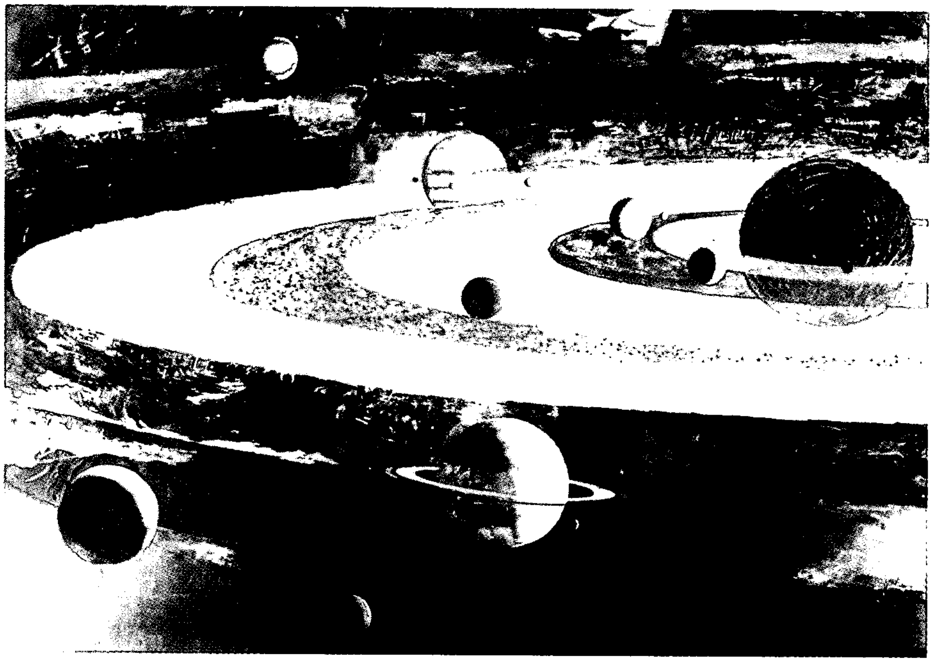

Remote Sensor Support Requirements For Planetary Missions

SUMMARY REPORT

SD 71-487

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Remote Sensor Support Requirements For Planetary Missions

SUMMARY REPORT

June 1971

Contract NAS2-5647

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Advanced Concepts and Missions Division
National Aeronautics and Space Administration

Space Division
North American Rockwell

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FOREWORD

This report summarizes the study approach, methods, results, and conclusions of a study of Remote Sensor Support Requirements for Planetary Missions. The study was performed by the Space Division (SD) of North American Rockwell Corporation (NR) for the Advanced Missions and Concepts Division, Office of Advanced Research and Technology, National Aeronautics and Space Administration, under Contract NAS2-5647.

A previous study of imaging sensor support requirements for orbital missions to the inner planets and Jupiter was performed by the Illinois Institute of Technology Research Institute (IITRI) under Contract NAS2-4494.

The present study was conducted in three phases: identification of observation objectives and requirements, development of sensor identification scaling laws, and evaluation of sensor support requirements. Detailed reports of the three phases have been published as SD 70-24, SD 70-361, and SD 70-375.

The study was managed by A. C. Jones for the NR SD Grand Tour Program Office. Dr. J. B. Weddell provided technical direction in Phases I and III, and W. F. McQuillan in Phase II. Other study participants were Dr. M. Blander, D. G. Brundige, Dr. J. C. Bryner, E. Flint, Dr. J. W. Haffner, Dr. G. M. Hidy, Dr. W. W. Ho, Dr. M. Lipeles, A. W. Love, C. D. Martin, R. P. Nagorski, L. S. Pearce, E. Vecchio, and A. E. Wheeler. Prof. R.E. Newell of Massachusetts Institute of Technology and Prof. G. de Vaucouleurs of the University of Texas served as consultants. The assistance of K. F. Sinclair, P. Swan, and B. A. Swenson of the Advanced Missions and Concepts Division is gratefully acknowledged.

This report was prepared by Dr. J. B. Weddell and A. E. Wheeler.

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1.0 INTRODUCTION

1.1 PROGRAM OBJECTIVES

Unmanned missions utilizing remote sensing systems provide an effective means of exploring the planets. One of the major tasks in planning planetary missions is the definition of experiment payloads and the determination of the support requirements for transport and operation of these payloads. To determine the payloads and their support requirements, it is necessary to have an understanding of the scientific and engineering objectives pertinent to a given target, the observation requirements associated with these objectives, knowledge of the operational conditions for a particular encounter, and flexible models of candidate remote sensors capable of meeting all or part of the observation requirements on specific missions.

The overall goals of this program were to (1) establish the scientific and engineering knowledge and observation requirements for planetary exploration in the 1975 to 1985 period; (2) define the state of the art and expected development of instrument systems appropriate for remote sensing of planetary environments; (3) establish scaling laws relating performance and support requirements of candidate remote sensor systems; (4) establish fundamental remote sensor system capabilities, limitations, and support requirements during encounter and other dynamical conditions for specific missions; and (5) construct families of candidate remote sensors compatible with selected missions.

This study followed a related study conducted by IITRI (Reference 1) under Contract NAS2-4494. In the IITRI study, exploration objectives and observation requirements were established for the inner planets (Mercury, Venus, and Mars) and Jupiter. Scaling laws were developed for imaging sensors appropriate to these observation requirements and were applied to calculate sensor support requirements for orbital missions to these planets. Finally, a compatible family grouping of imaging sensors was established for each mission.

The NR study is a logical continuation of the IITRI program. It was concerned with (1) exploration objectives and observation requirements at Saturn, Uranus, and Neptune; (2) development of nonimaging sensor scaling laws; (3) application of imaging sensor scaling laws to flyby missions to Saturn, Uranus, and Neptune; (4) application of nonimaging sensor scaling laws to inner- and outer-planet flyby missions and to inner-planet and Jupiter orbiter missions; (5) definition of compatible imaging, nonimaging, and integrated sensor families for selected missions.

1.2 STUDY PHASES

To divide the program into logical units and to permit early documentation and review of intermediate results, this study was conducted in three phases.

1.2.1 Phase I

A specific objective of the first phase was to define the scientific and engineering objectives for exploration of Saturn, Uranus, and Neptune. Another objective of this phase was to identify observable phenomena and parameters that are compatible with remote sensing by imaging and nonimaging techniques and that will contribute significant information toward satisfying the exploration goals and objectives. A third objective was to define nonimaging remote observation requirements for the inner planets and Jupiter.

The observation requirements were formulated as quantitative specifications of the range, precision, and worth or importance of each observable property or observation parameter. The requirements were stated at two levels: the optimal level desired for the maximum foreseeable information return, and the marginal level representing minimal improvement of existing knowledge. The methodology and results of Phase I are reported in Reference 2.

1.2.2 Phase II

Specific objectives of the second phase were to (1) define remote sensor types compatible with the observation objectives previously determined; (2) develop scaling laws depicting design and performance versus support requirements; (3) develop a computer program for application of these scaling laws; (4) develop trajectory parameters for selected outer-planet missions; and (5) define future sensor development requirements for improved fulfillment of the observation objectives previously defined.

The scaling laws represent sensor models that provide a basis upon which sensor systems may be developed to meet the specific requirements of a given mission after the mission trajectory parameters and other physical constraints have been established. In developing scaling laws for sensor systems, the primary consideration was to establish procedures for estimation of sensor support requirements to meet specific scientific objectives. The scaling laws are then a means of establishing first-order characteristics of sensor systems and the associated support requirements. The scaling law is not intended to be a complete design procedure for each sensor type, but rather a means of establishing sensor system characteristics that have significant impact on support requirements. Application of the scaling law results in the establishment of overall sensor system operational characteristics and capabilities, as well as the gross physical properties. The methods and results of Phase II are reported in Reference 3.

1.2.3 Phase III

The specific objectives of the third phase were to (1) calculate flyby and orbiter trajectory parameter data required for evaluation of sensor support requirements; (2) apply sensor scaling laws relating measurement requirements to sensor design characteristics and support requirements; (3) establish compatible imaging, non-imaging, and integrated sensor families for selected flyby and orbiter missions; and (4) establish support requirements for sensors included in these families. The methods and results of Phase III are reported in Reference 4.

1.3 LIMITATIONS AND CONSTRAINTS

Certain contractual limitations were placed on the scope of this study. Observations of the Earth, the Sun, Pluto, planetary satellites, asteroids, comets, meteoroids, and objects outside the solar system are excluded, but Saturn's rings are included. Observations of properties of the interplanetary medium are also excluded. Observations of planetary magnetospheric environments are considered only to the extent that they reveal properties of planetary interiors, surfaces, and atmospheres. Emphasis is placed on remote sensing of electromagnetic radiation emitted, reflected, absorbed, or transmitted by planetary atmospheres and surfaces.

This is not a mission study. It is intended to provide a reasonable range of operational conditions to show their effect on sensor support requirements. The missions considered are unmanned and limited to Earth launch dates from 1975 to 1985. Imaging sensors on flyby encounters of Mercury, Venus, and Jupiter were not considered. Flyby missions to Mars were assumed to have terminated with the Mariner Mars 1969 program.

In assessing sensor state-of-art limitations, foreseeable developments in time to qualify sensors for the selected missions were postulated. Only technical feasibility, and not cost, constrained sensor development estimates.

1.4 RESULTS OF STUDY

A top-down approach began with definition of the scientific and engineering goals of planetary exploration and proceeded through the increasingly specific and quantitative stages of knowledge requirements, observation objectives, observable properties, and observation and measurement requirements. At each stage, branches of the definition process were abandoned when they clearly were not appropriate to remote sensing on unmanned planetary flyby or orbiter spacecraft. The quantitative and verbal descriptions of observation requirements were documented by a data storage and retrieval computer program which gives visibility to the relationships among planetary exploration goals, knowledge requirements, and observation requirements.

The most important knowledge requirements relevant to the study objectives concern planetary interior structure, surface composition and topography, and atmospheric composition and meteorology. Visible imagery of outer-planet cloud formations, and microwave, infrared, and visible spectrometry and radiometry of radiation absorbed or emitted by all planetary atmospheres, provide the most significant support to the knowledge requirements.

The measurement requirements for a given mission depend upon the spacecraft trajectory with reference to the target planet. A computer program was developed to permit determination of these measurement requirements at selected trajectory points, based on the mission parameters. A stereographic projection technique was used to select terminal-planet encounter conditions and to evaluate surface-area coverage in relation to spatial resolution and scene illumination requirements. Flyby missions to Mercury, Venus, Jupiter, Saturn, Uranus, and Neptune were selected for the computation of specific measurement requirements. In addition, nonimaging sensor measurement and support requirements were determined for orbiters at Mercury, Venus, Mars, and Jupiter.

Scaling laws were developed for remote sensors to depict their relationship to operational and support requirements for specific planetary missions. Each scaling law presents functionally or graphically the relationship among measurement capabilities and support requirements of one generic type of sensor. The scaling laws take into consideration the limitations imposed by current state of the art and fundamental physical limits of the sensing technique applied.

Scaling laws were developed for passive optical, active optical, active microwave, passive microwave, and particle and field measuring instruments. Sensor types were further differentiated into image forming and non-image forming, with secondary classifications according to spectral region and function. Image-forming systems include both fixed and scanning types; non-image-forming systems include spectrometric and radiometric types.

Each of the scaling laws, except for particle and field sensors, was developed from the basic concept of signal-to-noise ratio, defined as the ratio of peak-to-peak signal voltage or current to rms noise in the detector. The modulation-transfer-function concept was introduced where several external and internal factors contribute to sensor sensitivity and resolution. A computer program was used for scaling law applications.

The basis for scaling laws for particle and field sensors is to define a point design on the basis of existing and developmental space instrumentation for each of the specific sensors considered. The energy or field intensity range provides the basis for selection of the specific design.

Sensor families were developed for each flyby and orbiter mission. A sensor family is defined as a set of remote sensors that can perform required observations while on a given mission trajectory. Families were developed at two levels: (1) optimal, in which each sensor meets (within mission and state-of-the-art constraints) the maximum measurement requirements for the mission, and (2) marginal, in which the sensor is designed to meet only the observation requirements representing a marginal increase of information. For each mission, separate families were developed for imaging and for nonimaging sensors, and also for integrated groupings consisting of both imaging and nonimaging sensors.

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2.0 STUDY APPROACH

2.1 PROGRAM PLAN

The study approach followed the logical path shown in Figure 2-1. The study phase in which each logical step occurred is indicated in the upper right corner of each box in the figure.

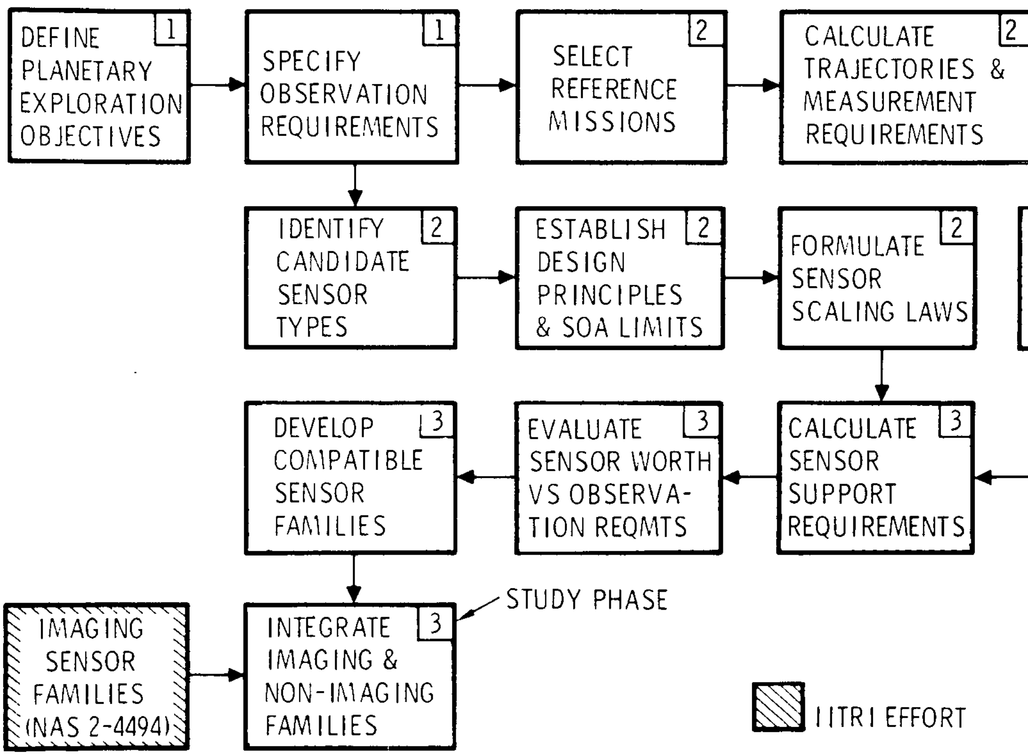

Figure 2-1. Study Logic

The study began with definition of scientific and engineering objectives of planetary exploration. These objectives were used as a basis of quantitatively presented observation requirements. Remote sensor types appropriate to the observations were identified, and the design and operating principles and state of the art of each sensor type were established. Scaling laws were then formulated to allow synthetic design of a sensor capable, within state-of-the-art limits, of meeting given observation requirements when used on a specified mission. Reference unmanned flyby and orbiter missions to the inner and outer planets in the 1975-1985 period were selected, and the mission trajectories were calculated. The mission-independent observation requirements were converted into the measurement capabilities needed by a sensor on selected trajectories. The scaling laws were then applied to determine the support requirements of the sensors appropriate to each mission. The worth of each sensor, measured by its performance relative to measurement requirements, was computed. Finally, compatible groups of imaging and non-imaging sensors were identified for each mission. The imaging and nonimaging families were integrated, using results of Contract NAS2-4494 (Reference 1) in the case of imaging sensors on orbiters of the inner planets and Jupiter.

2.2 OBJECTIVES AND REQUIREMENTS

2.2.1 Planetary Exploration Goals

The general goal of planetary exploration—to acquire information concerning the planets, other objects in the solar system, and the interplanetary medium—may be divided into scientific and engineering aspects. The scientific goals stem from man's desire for knowledge for its own sake; the engineering goals, from his need to understand natural environments in order to improve the design of spacecraft and operations in space. Developing and exploiting technology and enhancing national prestige may be considered as additional engineering goals.

The three generally recognized scientific goals of planetary exploration (Reference 5) are the following:

1. To understand the origin and evolution of the universe and the solar system.
2. To understand the origin and evolution of life.
3. To understand the dynamic processes affecting terrestrial environments.

In addition to having scientific goals, planetary exploration missions have technology goals related to the performance of spacecraft systems, operational mission control, and increased capability for designing improved space vehicles and experiment systems for future missions. These technology goals are:

4. To define the interplanetary and atmosphere environments that affect future spacecraft design and mission operations.
5. To define surface environments that affect future spacecraft and surface exploration equipment design and operations.

2.2.2 Knowledge Requirements

The knowledge requirements are specific, but qualitative, questions of a broad nature concerning planetary and space environments and processes. If all the knowledge requirements are satisfied, the scientific and engineering goals of the planetary exploration program will be attained. Many knowledge requirements can be associated with engineering and scientific goals. A set of knowledge requirements is presented in Table 2-1; some of these are relevant to the total planetary exploration area, but are outside the scope of this study because they relate to nonplanetary objects or to phenomena which by their very nature cannot be remotely sensed.

Table 2-2 indicates the goals associated with each knowledge requirement.

Table 2-1. Knowledge Requirements

Number	Item
1	What types, amounts, and distributions of indigenous extraterrestrial living organisms, or life-associated chemicals, exist? What evidence of previous life exists?
2	What were the environmental conditions and processes in the evolution of past and present life forms?
3	What are the properties and locations of any environments which may favor the future development of indigenous life or the survival and propagation of terrestrial life?
4	What are the physical and chemical properties of planetary atmospheres versus altitude, on global and local bases? What is the role of trace substances in determining atmospheric properties and vehicle performance?
5	What are the circulation regime, energy balance, global and local meteorology, and precipitation processes of planetary atmospheres? How do these factors affect vehicle performance and data transmission?
6	How has the present atmosphere evolved, and how is it likely to evolve in the future? What were the nature and evolution of the primordial atmosphere?
7	What are the physical state, chemical composition, and distribution of any solid or liquid surfaces beneath the atmosphere? How did liquid bodies, if any, evolve? What chemicals are present that may affect lander performance?
8	What are the nature, origin, and evolution of the surface topography? What is the history of environments affecting the surface?
9	What is the shape of the nongaseous body of the planet? What are the parameters, cause, and evolution of its present state of rotation? How do the planet's shape and motion affect vehicle guidance?
10	What are the structure, composition, mass distribution, and radial and horizontal differentiation of the interior?
11	What are the previous and present sources of internal heat, if any, and how is energy transferred to the atmosphere?
12	What motions and flow patterns exist in the interior? How are they related to the problems of energy balance and intrinsic magnetism?
13	What are the sources and energizing mechanisms of trapped charged particles, external magnetic fields, and associated electromagnetic radiation? What processes occur at the interface of the planetary environment and the interplanetary medium?

Table 2-1. Knowledge Requirements (Cont)

Number	Item
14	How do particle and field environments in the interplanetary medium depend on distance from the sun and on solar activity? What are the properties of the interstellar medium and how does it interact with the interplanetary medium?
15	What are the past and present environments and composition of meteoroids and dust in the interplanetary medium and near the planets? How are meteoroids, asteroids, and comets related? What are their origins?
16	What are the topography, composition, internal structure, and surface environments of planetary satellites? How are the orbits of the natural satellites related to their origins?
17	What are the composition, particle size distribution, structure, and origin of Saturn's rings? How do the rings affect vehicle performance and communications?
18	How do satellites and dust belts interact with planetary magnetic fields and trapped radiation? In particular, how does Io affect the decametric radiation from Jupiter? Are the rings of Saturn responsible for the apparent weakness of its trapped particle environment?
19	What are the structure, composition, physical properties, and origin of comets? How is their electromagnetic radiation stimulated? How do they interact with the interplanetary medium?
20	Is the general theory of relativity verified by kinematic and electromagnetic experiments involving solar or planetary gravitational fields?
21	What are the optimum usable visible and RF frequencies with respect to time variations, e.g., diurnal, monthly, yearly, and solar activity? What are the absorption bands in the planetary atmosphere versus frequency?
22	What are the planetary surface features, bearing strength, local thermal or cryogenic environment, and tectonic activity?
23	What natural or induced surface radioactivity exists and how does it affect vehicle performance or surface exploration?
24	What effects to system operations are caused by interplanetary and planetary magnetic and electrostatic fields and their respective transition zones? What effect would planetary airglow have on data transmission?
25	What are the requirements for sterilization of the vehicle, operational systems, and respective payloads, as defined by the planetary environments?
26	What are the magnetic susceptibility, electrical permittivity, and optical emissivity of the planetary surface? What surface and atmospheric electrical charges and currents exist? What are the surface-atmosphere boundary conditions?

Table 2-2. **Relevant Combinations of Goals and Knowledge Requirements**

Goal		Knowledge Requirement																									
		Existence of life	Life evolution	Environments for life	Atmospheric chemistry	Meteorology	Atmospheric evolution	Surface chemistry	Surface topography	Figure and rotation	Interior structure	Interior heat	Internal motions	Magnetosphere sources, interfaces	Interplanetary particles, fields	Meteoroid, asteroid environments	Satellite properties, origin, etc.	Saturn's rings	Satellite-magnetosphere interactions	Comet environments	Verification of general relativity	Propogation of waves	Surface geology	Surface radioactivity	Field effects on system operations	Biological contamination	Electrical properties
No.	Title (Short)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1	Origin of solar system (S)	X	X	X	X	X	X	X	X	X	X	X	X			X	O	X		O	O			O			O
2	Origin of life (S)	X	X	X	X																						
3	Environment processes (S)				X	X	X	X	O			X	X	X	O				X	O		X		O	X		O
4	Environments affecting mission (E)									X				X			X	X				X	X	O	X		X
5	Environments affecting future spacecraft (E)			X	X	X		O	X	X	O			X	O	X		X				X	X	O	X	O	X

Legend: (S) - Scientific goal
(E) - Engineering goal
X - Relevant combination in context of study
O - Relevant combination in some respects, but not in this study

As an example of the association of goals and knowledge requirements, consider the goal of understanding the origin and evolution of the universe and the solar system. This problem involves the original composition of the material from which the solar system was formed. This material is most likely to be preserved in the atmospheres of the outer planets. In order to evaluate the importance of exospheric escape and accretion processes in altering the atmospheric composition, the density and temperature must be determined as functions of altitude.

2.2.3 Observation Objectives

The knowledge requirements presented in Section 2.2.2 are stated in terms of basic phenomena and processes, some directly observable and some inferred from observations. As the next step toward quantitative definition of measurement requirements, a set of observation objectives is formulated which contains descriptions of immediate observation purposes. The following example illustrates the distinction between knowledge and observation requirements; understanding the origin and evolution of planetary atmospheres is a knowledge requirement, while determination of the molecular composition of the atmosphere is an observation requirement. One of the observable properties of the atmosphere is its infrared absorption spectrum. The required spectral observations can be defined by specifying the measurements to be performed and the experimental conditions such as the range of wavelengths and the solar illumination angle.

Table 2-3 is a list of the planetary observation objectives established in this study. A few of these (Numbers 20, 23, and 26) are outside the scope of this study, while others (e.g., Number 8) fail to lead to remote measurement requirements. Table 2-4 indicates by marks (X) the combinations of goal, knowledge requirement, and observation objectives relevant to this study.

2.2.4 Observable Properties

The properties that can be remotely sensed (in principle) to accomplish fully or partly the observation objectives just defined are now considered. At this point the distinction between scientific and engineering data is abandoned.

The observables considered in this study are listed in Table 2-5. Many of these are outside the scope of the study, but are included to provide a list suitable for all classes of planetary observation. Table 2-6 indicates by a mark (X) the relevant associations of observable properties and observation objectives.

2.2.5 Observation Requirements

2.2.5.1 Observation Parameters

The observation parameters used in this study and their units are listed in Table 2-7. Any of the first 15 parameters and any five of the remaining 25 may be used to describe a given observation in the computer program discussed in Section 2.5.2.

To assign values to the worth or importance of various observation parameters and their ranges, a worth function $W_i(a_i)$ is defined. If the i^{th} parameter a_i is relevant to an observation, its "best" (most stringent desired) value a_i', its "worst" (least stringent acceptable) value a_i'', its maximum worth $w_i(a_i')$, and the functional

Table 2-3. Observation Objectives

Number	Description
1	Planetary figure, rotation, precession, perturbations of motion.
2	Atomic, molecular, isotopic composition of interior substances.
3	Internal temperature, pressure, density distributions.
4	Internal energy transfer rate and direction distributions.
5	Geologic structure and activity, and mineralogic composition of interior and surface.
6	Physical properties (mechanical, thermal, electrical) of interior substances.
7	Atomic, molecular, isotopic composition of surface materials.
8	Motion, structure, replication of organic complexes.
9	Surface temperature, heat transfer rate, and direction distributions.
10	Topography; evidences of volcanism, impacts, erosion of surface features; tectonic activity.
11	Physical properties of surface materials.
12	Atomic, molecular, ionic, isotopic composition of atmosphere.
13	Atmospheric temperature, pressure, density distributions.
14	Circulation patterns and energy transfer rate and direction in atmosphere, wind velocity and direction, dust storm intensity, meteor debris, aerosols, and the like.
15	Phase transitions in atmosphere; cloud structure; precipitation forms, composition, and amounts.
16	Electric and magnetic fields (interior, surface, atmosphere, space).
17	Ionizing radiation environments (surface, atmosphere, space).
18	Nonthermal electromagnetic emission characteristics and source location.
19	Gravity field distribution (surface, atmosphere, space).
20	General relativistic optical and mechanical effects.
21	Electromagnetic (radio, optical) reflectivity, absorptivity.
22	Occultation (radio, optical) of natural and artificial sources by planet.
23	Meteoroid, asteroid, cosmic dust environments.
24	Saturn ring gross structure, composition, particle size distribution.
25	Vehicle performance (trajectory, attitude, aerodynamics, subsystems status, and function).
26	Navigation and guidance.
27	Data transmission and signal propagation.
28	Radiation-scattering properties of cloud tops and atmosphere above clouds.

Table 2-4. Association of Knowledge Requirements and Observation Objectives

Knowledge Requirements		Observation Objectives: Figure, rotation	Interior composition	Interior temperature	Interior energy flow	Geologic structure	Interior physical properties	Surface composition	Biological activity	Surface temperature	Topography and tectonics	Surface physical properties	Atmosphere composition	Atmosphere temperature	Atmosphere circulation	Clouds, precipitation	Electric, magnetic fields	Particle radiation	Nonthermal EM emission	Gravity fields	Relativistic effects*	Optical, RF reflectivity	Occultations	Meteoroid environments	Saturn ring properties	Vehicle performance	Guidance and navigation*	Data transmission	Scattering from clouds
No.	Short title	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
1	Existence of life								X				X																
2	Life evolution								X				X	X		X													
3	Environments for life									X	X		X	X		X													
4	Atmospheric chemistry									X			X	X	X	X			X			X	X			X			X
5	Meteorology				X					X			X	X	X	X						X							X
6	Atmospheric evolution		X		X	X				X	X		X	X	X				X										
7	Surface chemistry					X	X	X				X			X	X		X				X	X						
8	Surface topography	X				X				X	X				X	X													
9	Figure and rotation	X				X					X									X		X	X						
10	Interior structure	X	X	X		X	X				X								X	X									
11	Interior heat			X	X		X			X				X	X				X			X							
12	Internal motions	X		X	X		X										X		X										
13	Magnetosphere sources, interfaces																X	X	X										
14	Interplanetary particles, fields*																												
15	Meteoroid, asteroid environments	X											X											X					
16	Satellite properties, origin, etc.												X				X												
17	Saturn's rings																					X	X		X				
18	Satellite-magnetosphere interactions																		X										
19	Comet environments																												
20	Verification of general relativity*																												
21	Propagation of waves	X											X	X			X	X	X			X						X	
22	Surface geology					X					X	X																	
23	Surface radioactivity							X										X											
24	Field effects on system operations												X				X		X										
25	Biological contamination*																												
26	Electrical properties						X					X					X		X			X							

* Not applicable to study

Table 2-5. Observable Properties

Number (j)	Description
1	Optical images of surface and/or atmosphere
2	Radar images of surface and/or atmosphere
3	Satellite orbital parameters*
4	Chemical-nuclear assay (direct)*
5	Spacecraft trajectory parameters*
6	Active seismic detection*
7	Passive seismic detection*
8	Temperature versus depth below surface
9	Magnetic field near surface*
10	Magnetic field above atmosphere
11	Mineralographic, petrographic, crystallographic assay (direct)*
12	Gamma-ray flux and spectrum
13	Charged-particle flux, spectrum, angular distribution
14	Electric field, currents, conductivity at and below surface*
15	Microwave radiation flux, emissivity, absorptivity
16	Microwave spectrum
17	Infrared radiation flux, emissivity, absorptivity
18	Infrared spectrum
19	Visible and ultraviolet radiation flux, emissivity, absorptivity
20	Visible and ultraviolet spectrum
21	Radio flux and spectrum
22	Biological assay and activity*
23	Surface temperature (direct)*
24	Laser beam reflectivity and absorptivity of atmosphere
25	Atmospheric temperature (direct)*
26	Atmospheric pressure (direct)*
27	Radio reflectivity and transmissivity of atmosphere
28	Entry probe trajectory parameters*
29	Electric field and currents in atmosphere*
30	Surface mechanical properties (direct)*
31	Gravitometric data
32	Electromagnetic signal time and ray deflection
33	Wind velocity and direction (direct)*
34	Dust storm intensity and movement (direct)*
35	Radio-frequency permittivity, resistivity, susceptibility
36	Optical permittivity, resistivity, susceptibility
37	Acceleration and deceleration of vehicle*
38	Distance, altitude of spacecraft from topographic features, etc.
39	Electromagnetic phase shift
40	Polarization (amount, type, rotation, etc.)
41	Stellar occultation (photometric)
42	X-ray absorption and emission
43	X-ray spectrum induced by solar electrons
44	Fast/slow albedo neutron flux ratio

*Outside scope of study (in-situ observation or nonplanetary observation)

Table 2-6. Association of Observable Properties With Observation Objectives

No.	Short Title (Observation Objective)	1 Optical images	2 Radar images	3 Satellite orbital parameters	4 Chemical, nuclear assay	5 Spacecraft trajectory parameters	6 Active seismic detection	7 Passive seismic detection	8 Temperature below surface	9 Magnetic field near surface	10 Magnetic field above atmosphere	11 Mineralographic assay	12 Gamma ray spectrum	13 Charged particle spectrum	14 Surface electric field	15 Microwave flux	16 Microwave spectrum	17 Infrared flux	18 Infrared spectrum	19 Visible/ultraviolet flux	20 Visible/ultraviolet spectrum	21 Radio flux and spectrum	22 Biological activity	23 Surface temperature (direct)	24 Laser beam reflectivity	25 Atmospheric temperature (direct)	26 Atmospheric pressure (direct)	27 Radio reflectivity	28 Entry trajectory parameters	29 Atmospheric electricity	30 Surface mechanical properties	31 Gravitometric data	32 Electromagnetic signal time	33 Wind velocity (direct)	34 Dust storms (direct)	35 Radio frequency permittivity	36 Optical permittivity	37 Acceleration of vehicle	38 Altitude of spacecraft	39 Electromagnetic phase shift	40 Polarization	41 Stellar occultation	42 X-ray flux	43 X-ray spectrum	44 Albedo neutron flux
		I	I	N	N	N	N	N	N	N	N	N	N	N	N	I. N	N	I. N	N	I. N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	I. N	N	N	I	N	N	N
1	Figure, rotation	X	O															X							X			X																	
2	Interior composition										O			O																															
3	Interior temperature										O			O																															
4	Interior energy flow										O			O		O		X										X																	
5	Geologic structure																																X												
6	Interior physical properties										X			X				X																										X	
7	Surface composition		O										X				O		O	O	O																								
8	Biological activity																																												
9	Surface temperature															X		X										X																	
10	Topography and tectonics		X																													X													
11	Surface physical properties		O													X																				O	O				X				
12	Atmosphere composition																X	X	X	X	X				O			X					X							O					
13	Atmosphere temperature		O													X	X	X	X	X	O	X			O			O					X						O						
14	Atmosphere circulation	X														X		X							X			X					X												
15	Clouds, precipitation	X																							O			X					X								O				
16	Electric, magnetic fields									X	X			*	X																														
17	Particle radiation										*			X																										X					X
18	Nonthermal EM emission										*			*							X	X																		X					
19	Gravity fields																																												
20	Relativistic effects																																												
21	Optical, RF reflectivity															X		O	O	X					O			O					X			O	O			X					
22	Occultations															X																	X							X		X			
23	Meteoroid environments																			X																									
24	Saturn ring properties	X														O			O	O	O	X																				X			
25	Vehicle performance																																												
26	Guidance and navigation																																												
27	Data transmission																																												
28	Scattering from clouds	O														O		X	X	X																					X				

Legend: X Applicable association
O Inappropriate to remote sensing
* Not applicable to study
I Imaging
N Non-imaging

Table 2-7. Observation Parameters

No.	Definition	Unit
1	Longest wavelength of spectral region	Micron
2	Shortest wavelength of spectral region	Micron
3	Spectral resolution, at wavelength requiring highest resolution	Micron
4	Spatial resolution at target	Meter
5	Fraction of surface area of planet covered	Percent
6	Northernmost latitude of area covered (negative if in northerm hemisphere)	Degree
7	Southernmost latitude of area covered (negative if in northern hemisphere)	Degree
8	Maximum Sun elevation angle above horizon at target	Degree
9	Minimum Sun elevation angle above horizon	Degree
10	Vertical resolution	Meter
11	Maximum altitude of observed property (above surface at Mercury and Mars; above visible cloud tops at other planets)	Meter
12	Minimum altitude of observed property	Meter
13	Number of observations or samples	---
14	Time elapsed during one observation	Second
15	Interval between commencement of two successive observations	Second
16	Intensity resolution (gray scale, spectral line strength, field strength, and particle flux)	Percent of maximum intensity
17	Planetocentric angle from planet center-to-spacecraft line	Degree
18	Angle at planet surface from surface element-to-spacecraft line	Degree
19	Angular resolution	Degree
20	Phase shift precision	Degree
21	Polarization (amount)	Percent
22	Rotation angle of plane of polarization (positive counter-clockwise)	Degree
23	Albedo	Percent
24	Magnetic field strength	Oersted
25	Electric field strength	Volt m^{-1}
26	Gravitational acceleration	m sec^{-2}
27	Particle flux	m^{-2} sec^{-1}
28	Particle or photon energy	Electron volt
29	Electromagnetic energy flux	Watt m^{-2}
30	Maximum temperature	K
31	Minimum temperature	K
32	Temperature resolution	K
33	Maximum pressure	Bar
34	Minimum pressure	Bar
35	Pressure resolution	Bar
36	Velocity	m sec^{-1}
37	Longitude (east of central meridian seen from Earth except standard areographic coordinates are used at Mars)	Degree
38	Latitude interval	Degree
39	Longitude interval	Degree
40	Other than above	

form of w_i (a_i) for values of a_i between a_i' between a_i' and a_i'' are specified. It must be indicated whether greater or smaller values of a_i represent a more stringent requirement; i.e., whether $a_i'>a_i''$ or $a_i''>a_i'$. If a_i is poorer than a_i'', $w_i(a_i) = 0$. If a_i is better than a_i', usually $w_i(a_i) = w_i(a_i')$; but provision can be made for $w_i(a_i')>w_i(a_i')$ in this case. In all cases, $0 \leq w_i(a_i) \leq 1$. The allowed forms of w_i (a_i) are linear, trigonometric, exponential, step, delta, and square-wave functions of a_i or $\log_{10} |a_i|$.

2.2.5.2 Observation Requirements Summary

Table 2-8 is a condensed summary of the observation requirements. It indicates the relevant associations of goals, knowledge requirements, observation objectives, observable properties, observation techniques, and planet. The goals, knowledge requirements, observation objectives, observable properties, and observation techniques are referred to by the numbers assigned in Section 2.2.1 (Tables 2-1, 2-3, and 2-5) and in Reference 2. The table is arranged with inner-planet observations first, observations common to inner and outer planets next, and outer-planet observations last. Each set of observations is arranged in order of decreasing wavelength.

2.3 SENSOR SYSTEMS

2.3.1 Candidate Sensor Types

For the measurable or observable phenomena suitable for remote sensing to meet the requirements of planetary exploration, the various techniques applicable to each are established to provide a basis for identification of candidate sensor types for subsequent evaluation. A tabulation of the observable properties, pertinent observation techniques, and candidate sensor types is presented in Table 2-9. The listing of observable properties includes those which provide useful information in fulfillment of one or more of the engineering goals and objectives; in-situ observations and nonplanetary determinations are not included in this listing.

The listing of candidate sensor types in Table 2-9 includes all that were evaluated during the study. In some instances, as noted in the "Limitations" column, the candidate sensor type could not meet the requirements within existing or projected state of the art, or no feasible experiment for remote sensing could be defined. These sensors were not considered further.

After analysis and evaluation of the measurement requirements and sensor capabilities, suitable sensor types were identified for use in planetary exploration missions. The sensors identified are shown in Table 2-10.

Table 2-10 also shows the application of each sensor type to the missions considered during the study. Scaling laws were developed for these as applicable, and design parameters and support requirements were determined. These items are discussed subsequently in this report.

Table 2-8. Summary of Observation Requirements

Goal	Knowledge Requirement	Observation Objective: Number	Observation Objective: Worth	Observation Objective: Sub-Objective Description	Observable: Property	Observable: Technique	Observable: Worth	Observable: Sub-Observable Description	Planets**†
1*	11	9	0.99	Total thermal emission of planetary disk	15	2	0.80	Effective average thermal radiation of disk	1, 4*
3	11	9	0.99	Total thermal emission of planetary disk	15	2	0.80	Effective average thermal radiation of disk	1, 4
5*	4	12	0.70	Physical properties for engineering model atmospheres	16	12	0.60	Microwave emission spectrum	2
5*	4	13	0.70	Physical properties for engineering model atmospheres	15	2	0.50	Microwave thermal emission flux	2
5*	4	13	0.70	Physical properties for engineering model atmospheres	17	3	0.60	IR thermal emission flux	2
5*	4	12	0.70	Physical properties for engineering model atmospheres	18	13	0.60	IR absorption spectra	2
1*	11	9	0.99	Total thermal emission of planetary disk	17	3	0.80	Effective average thermal radiation of disk	1, 4*
3	11	9	0.99	Total thermal emission of planetary disk	17	3	0.80	Effective average thermal radiation of disk	1, 4
4*	13*	18	0.50	Nature of airglow and aurora near surface	20	57	0.70	Visible/UV spectrum	1*, 4
4	24	18	0.50	Nature of airglow and aurora near surface	20	57	0.70	Visible/UV spectrum	1, 4
4	26	18	0.50	Nature of airglow and aurora near surface	20	57	0.70	Visible/UV spectrum	1, 4
5	13	18	0.50	Nature of airglow and aurora near surface	20	57	0.70	Visible/UV spectrum	1, 4
5	24	18	0.50	Nature of airglow and aurora near surface	20	57	0.70	Visible/UV spectrum	1, 4
5	26	18	0.50	Nature of airglow and aurora near surface	20	57	0.70	Visible/UV spectrum	1, 4
5*	4	12	0.50	Physical properties for engineering model atmosphere	20	15	0.50	UV absorption and emission spectra	2
1*	7	7	0.99	Elemental composition of surface material	43	16	0.50	X-ray spectrum induced by solar bombardments	1
1*	7	7	0.99	Elemental and isotopic composition of surface material	12	17	0.70	Gamma-ray spectrum (decay and cosmic-ray induced)	1*, 4
1*	7	17	0.99	Neutral radioactivity of surface material	13	54	0.80	Alpha spectrum from parent, daughter nuclides	1
1*	7	17	0.99	Hydrogen/silicon ratio at surface	44	55	0.40	Fast/slow albedo neutron flux ratio	1
1*	10	6	0.30	Planet interior electrical conductivity	13	53	0.50	Solar wind proton flux	1
3*	4	12	0.75	General information about planetary ionospheres	32	31	0.50	Radar echo versus time	2, 5*, 6, 7, 8
3*	4*	12	0.80	Ionosphere electron density profile	27	41	0.65	RF reflectivity/signal return time	1, 2, 4, 5*, 6, 7, 8
5	4	12	0.80	Ionosphere electron density profile	27	41	0.65	RF relfectivity/signal return time	1, 2, 4, 5, 6, 7, 8
5	24	12	0.80	Ionosphere electron density profile	27	41	0.65	RF reflectivity/signal return time	1, 2, 4, 5, 6, 7, 8
1*	12	18	0.80	Thermal/nonthermal planetary emissions	21	1	0.80	Radio emissions	1, 2, 4, 5, 6*, 7, 8
3	12	18	0.80	Thermal/nonthermal planetary emissions	21	1	0.80	Radio emissions	1, 2, 4, 5, 6, 7, 8
1*	4	13	0.85	Neutral ion, electron density profiles in atmosphere	32	36	0.85	Bi-frequency radio occultation	1, 2, 4, 5*, 6, 7, 8
3	4	13	0.85	Neutral ion electron density profiles in atmosphere	32	36	0.85	Bi-frequency radio occultation	1, 2, 4, 5, 6, 7, 8
5	4	13	0.99	Neutral ion, electron density profiles in atmosphere	32	36	0.85	Bi-frequency radio occultation	1, 2, 4, 5, 6, 7, 8
3*	5	14	0.80	Heat balance in lower atmosphere	15	2	0.80	Microwave emissions (thermal)	2, 5*, 6, 7, 8
5	5	14	0.80	Heat balance in lower atmosphere	15	2	0.80	Microwave emissions (thermal)	2, 5, 6, 7, 8
3*	5	14	0.80	Heat balance at surface and below clouds	15	2	0.80	Microwave emissions (thermal	2, 4, 5*, 6, 7, 8
5	5	14	0.80	Heat balance at surface and below clouds	15	2	0.80	Microwave emissions (thermal)	2, 4, 5, 6, 7, 8
5*	4	13	0.70	Physical properties for engineering model atmospheres	15	2	**	Microwave thermal emission flux	1, 4(0.5); 5, 6, 7, 8(0.6)
1*	7	11	0.80	Planet surface dielectric properties	15*	42	0.80	Polarization of microwave thermal emissions	1, 2, 4, 5, 6*, 7, 8
3	7	11	0.80	Planet surface dielectric properties	40	42	0.80	Polarization of microwave thermal emissions	1, 2, 4, 5, 6, 7, 8

*Case represented by computer program printed output
**If observation worth depends on planet, worth values for each planet are shown in parenthesis
† 1 = Mercury, 2 = Venus, 4 = Mars, 5 = Jupiter, 6 = Saturn, 7 = Uranus, 8 = Neptune

Table 2-8. Summary of Observation Requirements (Cont)

Goal	Knowledge Requirement	Observation Objective: Number	Worth	Sub-Objective Description	Observable: Property	Technique	Worth	Sub-Observable Description	Planets** +
1*, 3	4*	9	0.90	Microwave thermal emission	15	2	0.90	Thermal emission measurement by radiometry	1, 2, 4, 5, 6*, 7, 8
1, 3	4*	13	0.99	Physical properties for engineering model atmosphere	15	2	0.90	Thermal emission measurement by radiometry	1, 2, 4, 5, 6*, 7, 8
1, 3	4*	21	0.30	Microwave thermal emissions	15	2	0.90	Thermal emission measurement by radiometry	1, 2, 4, 5, 6*, 7, 8
1, 3	4*	22	0.50	Microwave thermal emissions	15	2	0.90	Thermal emission measurement by radiometry	1, 2, 4, 5, 6*, 7, 8
1	5	9	0.30	Microwave thermal emission	15	2	0.90	Thermal emission measurement by radiometry	2, 4, 5, 6, 7, 8
1	5	13	0.80	Physical properties for engineering model atmosphere	15	2	0.90	Thermal emission measurement by radiometry	2, 4, 5, 6, 7, 8
1	11	9	0.99	Microwave thermal emission	15	2	0.90	Thermal emission measurement by radiometry	1, 2, 4, 5, 6, 7, 8
1, 2*	1*	12*	0.80	Abundance of NH_3, NH_2O, H_2O, H/D ratio	16	12	0.80	Microwave spectrum	2, 4, 5, 6*, 7, 8
1, 2	2, 3	12	0.30	Physical properties for engineering model atmosphere	16	12	0.80	Microwave spectrum	2, 4
1, 2	2, 3	13	0.70	Physical properties for engineering model atmosphere	16	12	0.80	Microwave spectrum	2, 4
1	4	12	0.99	Physical properties of engineering model atmosphere	16	12	0.80	Microwave spectrum	1, 2, 4, 5, 6, 7, 8
1	4	13	0.99	Physical properties for engineering model atmosphere	16	12	0.80	Microwave spectrum	1, 2, 4, 5, 6, 7, 8
1	6	12	0.90	Physical properties for engineering model atmosphere	16	12	0.80	Microwave spectrum	1, 2, 4, 5, 6, 7, 8
1	6	13	0.80	Physical properties for engineering model atmosphere	16	12	0.80	Microwave spectrum	1, 2, 4, 5, 6, 7, 8
1*	4	12	0.90	Atmospheric composition	16	2	0.40	Microwave thermal emission spectrum w/absorption	2, 5*, 6, 7, 8
5	4	12	0.90	Atmospheric composition	16	2	0.40	Microwave thermal emission spectrum w/absorption	2, 5*, 6, 7, 8
4*	9	1	0.90	Size, shape, motion of planet	24	35	0.90	Laser beam reflectivity	1*, 4, 6 (rings only)
5	9	1	0.90	Size, shape, motion of planet	24	35	0.90	Laser beam reflectivity	1, 4, 6 (rings only)
1*	4	12	0.90	Brightness temperature over wide frequency range	17	3	0.90	IR thermal emission	1, 2, 5*, 6, 7, 8
5*	4	13	0.70	Physical properties for engineering model atmosphere	17	3	0.60	IR thermal emission flux	1, 5*, 6, 7, 8
3*	5	14	0.80	Heat balance at and beneath clouds	17	3	0.80	IR radiation flux	2, 4, 5*
5	5	14	0.80	Heat balance at and beneath clouds	17	3	0.80	IR radiation flux	2, 4, 5
3*	5	14	0.80	Heat balance in atmosphere	17	3	0.80	IR radiation flux	2, 4, 5*, 6, 7, 8
5	5	14	0.80	Heat balance in atmosphere	17	3	0.80	IR radiation flux	2, 4, 5, 6, 7, 8
1*	4	12	0.90	Cloud composition	18	13	**	IR absorption spectra	2(0.4), 4(0.2);5*, 6, 7, 8(0.7)
5	4	12	0.90	Cloud composition	18	13	**	IR absorption spectra	2(0.4), 4(0.2);5, 6, 7, 8(0.7)
1*	4	12	0.85	Trace substances in atmosphere and clouds	20	18	0.80	IR/visible/UV spectra	2, 5*, 6, 7, 8
3	4	12	0.85	Trace substances in atmosphere and clouds	20	18	0.80	IR/visible/UV spectra	2, 5, 6, 7, 8
5	4	12	0.85	Trace substances in atmosphere and clouds	20	18	0.80	IR/visible/UV spectra	2, 5, 6, 7, 8
1*	4	14	0.50	Aerosol size distribution in atmosphere	24	35	0.50	Laser scattering, transmission in atmosphere	2, 4, 5*, 6, 7, 8
3*	4	28	0.50	Radiation scattering properties of cloud tops	18	13	0.40	IR radiation (spectrum)	2, 5*, 6, 7, 8
3*	4*	28	0.50	Radiation scattering properties of cloud tops	17	3	0.30	IR radiation (flux)	2, 4, 5*, 6, 7, 8
3	5	28	0.30	Radiation scattering properties of cloud tops	17	3	0.30	IR radiation (flux)	2, 4, 5, 6, 7, 8
3*	4*	28	0.50	Radiation scattering properties of cloud tops	40	44	0.70	IR radiation (polarization)	2, 5*, 6, 7, 8
3	5	28	0.50	Radiation scattering properties of cloud tops	40	44	0.70	IR radiation (polarization)	2, 5, 6, 7, 8
5	4	28	0.50	Radiation scattering properties of cloud tops	40	44	0.70	IR radiation (polarization)	2, 5, 6, 7, 8
5	5	28	0.50	Radiation scattering properties of cloud tops	40	44	0.70	IR radiation (polarization)	2, 5, 6, 7, 8
3*	4*	28	0.50	Radiation scattering properties of cloud tops	19	4	0.80	Visible/UV radiation (flux)	2, 4, 5*, 6, 7, 8
3	5	28	0.50	Radiation scattering properties of cloud tops	19	4	0.80	Visible/UV radiation (flux)	2, 4, 5, 6, 7, 8
1*	4*	12	0.90	Hydrogen abundance	20	5	0.90	Lyman alpha line for hydrogen	1, 2, 4, 5*, 6, 7, 8
1	6	12	0.90	Hydrogen abundance	20	5	0.90	Lyman alpha line for hydrogen	1, 2, 4, 5, 6, 7, 8
3	6	12	0.90	Hydrogen abundance	20	5	0.90	Lyman alpha line for hydrogen	1, 2, 4, 5, 6, 7, 8

*Case represented by computer program printed output
**If observation worth depends on planet, worth values for each planet are shown in parenthesis
+1 = Mercury, 2 = Venus, 4 = Mars, 5 = Jupiter, 6 = Saturn, 7 = Uranus, 8 = Neptune

Table 2-8. Summary of Observation Requirements (Cont)

Goal	Knowledge Requirement	Observation Objective: Number	Observation Objective: Worth	Sub-Objective Description	Observable: Property	Observable: Technique	Observable: Worth	Sub-Observable Description	Planets** †
4*	24*	16	0.80	Planet interior structure and motions	9*, 10	51	0.90	Magnetic field distribution above surface	1*, 5, 6, 7, 8
4	26	16	0.80	Planet interior structure and motions	9, 10	51	0.90	Magnetic field distribution above surface	1, 5, 6, 7, 8
5	24	16	0.80	Planet interior structure and motions	9, 10	51	0.90	Magnetic field distribution above surface	1, 5, 6, 7, 8
5	26	16	0.80	Planet interior structure and motions	9, 10	51	0.90	Magnetic field distribution above surface	1, 5, 6, 7, 8
4*	24*	16	0.70	Near-planet, planetary surface electric field	14	52	0.80	Electric potential distribution near surface	1, 2, 4, 5, 6, 7, 8
4	13	16	0.70	Near-planet, planetary surface electric field	14	52	0.80	Electric potential distribution near surface	1, 2, 4, 5, 6, 7, 8
4	16	16	0.70	Near-planet, planetary surface electric field	14	52	0.80	Electric potential distribution near surface	1, 2, 4, 5, 6, 7, 8
4	26	16	0.70	Near-planet, planetary surface electric field	14	52	0.80	Electric potential distribution near surface	1, 2, 4, 5, 6, 7, 8
1*	9*	5*	0.40	Altitude variation over solid surface	32	36	0.40	Bi-frequency radio occultation	1, 2, 4, 5, 6*, 7, 8
1	9	10	0.50	Planetary surface definition-surface topography	32	36	0.40	Bi-frequency radio occultation	1, 4
1	9	21	0.20	RF reflectivity characteristics	32	36	0.40	Bi-frequency radio occultation	1, 2, 4, 5, 6, 7, 8
1	9	22	0.30	RF occultation characteristics	32	36	0.40	Bi-frequency radio occultation	1, 4
1*	4*	12*	0.90	Atmosphere charged particle density	32*	36	0.90	Bi-frequency radio occultation	1, 2, 4, 5, 6*7, 8
1	4	21	0.40	RF reflectivity characteristics	32, 39	36	0.90	Bi-frequency radio occultation	1, 2, 4, 5, 6, 7, 8
1	4	22	0.50	RF occultation characteristics	32, 39	36	0.90	Bi-frequency radio occultation	1, 2, 4, 5, 6, 7, 8
1, 3	5	14	0.99	Atmosphere circulation	32	36	0.90	Bi-frequency radio occultation	1, 2, 4, 5, 6, 7, 8
1, 3	5	21	0.20	RF reflectivity characteristics	32, 39	36	0.90	Bi-frequency radio occultation	1, 2, 4, 5, 6, 7, 8
3	13	17	0.40	Particle radiation	39	36	0.90	Bi-frequency radio occultation	5, 6, 7, 8
3	13	18	0.30	Thermal/nonthermal planetary emissions	39	36	0.90	Bi-frequency radio occultation	5, 6, 7, 8
1*, 3	4*	15*	0.70	Density discontinuities	32	36	0.70	Bi-frequency radio occultation	1, 2, 4, 5, 6*, 7, 8
1, 3	7	15	0.70	Density discontinuities	32	36	0.70	Bi-frequency radio occultation	1, 2, 4, 5, 6, 7, 8
1	7	21	0.30	RF reflectivity characteristics	32	36	0.70	Bi-frequency radio occultation	2, 5, 6, 7, 8
1	7	22	0.20	RF occultation characteristics	32	36	0.70	Bi-frequency radio occultation	2, 5, 6, 7, 8
3*	4*	13	0.50	Transparency of atmosphere to RF radiation	21	1	**	Transmitted RF radiation from Sun vs impact parameter	5*(0.5), 6(0.3), 7(0.15), 8(0.07)
3	21	13	0.50	Transparency of atmosphere to RF radiation	21	1	**	Transmitted RF radiation from Sun vs impact parameter	5(0.5), 6, (0.3), 7(0.15), 8(0.07)
3*	13	18	0.50	Sources of non-thermal planetary RF emissions	21	1	0.50	RF radiations from planet	5*, 6, 7, 8
1*	17	24	0.30	Saturn ring particle size and composition	21	1	0.50	Radio absorption and reflection vs wavelength	6 (rings only).
5*	4	12	0.70	Physical properties for engineering model atmospheres	16	12	0.60	Microwave emission spectrum	5*, 6, 7, 8
1*	4	13	0.75	Atmospheric pressure profile	18	13	0.25	High resolution IR spectroscopy of NH_3	5
1*	4	12	0.70	H/D isotopic abundance in atmosphere	18	13	0.70	Far IR spectroscopy to detect CH_3D, NH_2O, HD	5*, 6, 7, 8
1*	4	13	0.90	Far IR planetary thermal emissions	17	3	0.90	Far IR emissions (100μ - 10μ)	5, 6*, 7, 8
2	4	13	0.90	Far IR planetary thermal emissions	17	3	0.90	Far IR emissions (100μ - 10μ)	5, 6, 7, 8
5*	4	12	0.70	Physical properties of engineering model atmospheres	18	13	0.60	IR absorption spectra	5*, 6, 7, 8
3*	4	13	0.80	Transparency of atmosphere	19	39	**	Sunlight flux versus impact parameter	5*(0.8), 6(0.5), 7(0.3), 8(0.15)
1*	15	1	0.50	Saturn ring particle distribution	17	20	0.30	Flux of sunlight transmitted	6 (rings only)
1*	4	13	0.60	Atmospheric pressure profile	18	13	0.60	High resolution IR spectroscopy of NH_3, CH_4	5*, 6, 7, 8
5*	4	13	0.99	Physical properties for engineering model atmospheres	18	13	0.99	High resolution IR spectroscopy of NH_3, CH_4	5*, 6, 7, 8
1*	4	12	0.70	Hydrogen abundance	18	13	0.60	Pressure-induced spectrum of hydrogen overtones	5, 6*, 7, 8
1*	11	13*	0.90	Planetary Bond albedo	19	4	0.90	Photometric measurement in the visible	5, 6*, 7, 8
1	11	21	0.70	RF reflectivity characteristics	19	4	0.90	Photometric measurement in the visible	5, 6, 7, 8
1*	5	12	0.40	Hydrogen abundance	18	13	0.40	Pressure-induced spectrum of hydrogen overtones	5, 6*, 7, 8
3*	4	12	0.50	Atmospheric properties above magnetic poles	20	15	**	Optical photon spectrum from polar aurorae	5*(0.25), 6(0.2), 7(0.15), 8(0.1)

*Case represented by computer program printed output
**If observation worth depends on planet, worth values for each planet are shown in parenthesis
† 1 = Mercury, 2 = Venus, 4 = Mars, 5 = Jupiter, 6 = Saturn, 7 = Uranus, 8 = Neptune

Table 2-8. Summary of Observation Requirements (Cont)

Goal	Knowledge Requirement	Observation Objective: Number	Observation Objective: Worth	Sub-Objective Description	Observable: Property	Observable: Technique	Observable: Worth	Sub-Observable Description	Planets** †
3*	4*	18	0.55	Ionosphere total density profile and composition	20	57	0.40	Auroral and airglow emission spectra	5*, 6, 7, 8
3	6	18	0.70	Ionosphere total density profile and composition	20	57	0.40	Auroral and airglow emission spectra	5, 6, 7, 8
3	13	18	0.20	Ionosphere total density profile and composition	20	57	0.40	Auroral and airglow emission spectra	5, 6, 7, 8
3	18	18	0.30	Ionosphere total density profile and composition	20	57	0.40	Auroral and airglow emission spectra	5, 6, 7, 8
3	24	18	0.60	Ionosphere total density profile and composition	20	57	0.40	Auroral and airglow emission spectra	5, 6, 7, 8
1*	4	12	0.70	Methane abundance	20	14	0.70	Methane absorption spectra	5*, 6, 7, 8
1*	4	12	0.30	H/D ratio	20	14	**	HD and H_2 absorption spectra	5*(0.3), 6(0.2);7.8(0.1)
1*	4	12	0.30	H/D ratio	20	15	**	HD and H_2 absorption spectra	5*(0.3), 6(0.2);7.8(0.1)
1*	17	24*	0.30	Saturn ring particle density	41	4	0.30	Stellar occultation (photometric)	6
1	17	22	0.20	RF occultation characteristics	41	4	0.30	Stellar occultation (photometric)	6
3*	4*	13	0.50	Transparency of atmosphere to RF radiation	21	39	**	Transmitted RF radiation from Sun vs impact parameter	5*(0.5), 6(0.3), 7(0.15), 8(0.07)
3	21	13	0.70	Transparency of atmosphere to RF radiation	21	39	**	Transmitted RF radiation from Sun vs impact parameter	5(0.5), 6(0.3), 7(0.15), 8(0.07)
1*	4	12	0.70	Ammonia abundance	20	14	0.70	Ammonia absorption spectra	5
5*	15	12*	0.50	Upper atmosphere composition	19	5	0.30	UV light emitted from meteoroid trails	5*, 6, 7, 8
5	15	23	0.20	Meteoroid environments	19	5	0.30	UV light emitted from meteoroid trails	5, 6, 7, 8
1	4	12	0.60	Trace constituents of purines, pyrimidines	20	15	0.60	UV absorption spectra	5, 6*, 7, 8
2*	4	12	0.60	Trace constituents of purines, pyrimidines	20	15	0.60	UV absorption spectra	5, 6, 7, 8
5*	4	12	0.70	Physical properties for engineering model atmospheres	20	15	0.50	UV absorption, emission spectra	5*, 6, 8
5*	4	12	0.70	Physical properties for engineering model atmospheres	20	15	0.50	UV absorption, emission spectra	7
1*	4*	12	0.90	Helium abundance, He/H ratio	20	5	0.90	Helium resonance lines	5*, 6, 7, 8
1	6	12	0.90	Helium abundance, He/H ratio	20	5	0.90	Helium resonance lines	5, 6, 7, 8
3	4	12	0.90	Helium abundance, He/H ratio	20	5	0.90	Helium resonance lines	5, 6, 7, 8
3*	12	6*	0.75	Planetary interior composition	10	51	0.75	Magnetic field components as a function of position	5*, 6, 7, 8
3	12	16	0.40	Planetary interior structure	10	51	0.75	Magnetic field components as a function of position	5, 6, 7, 8
4*	22*	10	0.50	Planetary surface definition-surface topography	2	32	0.30	Microwave imaging	5, 6*, 7, 8
5	3	10	0.20	Planetary surface definition-surface topography	2	32	0.30	Microwave imaging	5, 6, 7, 8
5	8	10	0.30	Planetary surface definition-surface topography	2	32	0.30	Microwave imaging	5, 6, 7, 8
5	22	10	0.50	Planetary surface definition-surface topography	2	32	0.30	Microwave imaging	5, 6, 7, 8
1*	5*	9*	0.30	Formation of large diameter particles in clouds	27	31	0.25	Radar echo vs time	5*, 6, 7, 8
1	5	14	0.90	Atmospheric circulation	27	31	0.40	Radar echo vs time	5, 6, 7, 8
1	5	15	0.70	Atmospheric heat balance	27	31	0.40	Radar echo vs time	5, 6, 7, 8
1	6	9	0.20	Thermal emission from planetary disk	27	31	0.05	Radar echo vs time	5, 6, 7, 8
1	8	9	0.40	Thermal emission from planetary disk	27	31	0.05	Radar echo vs time	5, 6, 7, 8
2	2	15	0.30	Atmospheric heat balance	27	31	0.20	Radar echo vs time	5, 6, 7, 8
2	3	15	0.30	Atmospheric heat balance	27	31	0.20	Radar echo vs time	5, 6, 7, 8
3	4	14	0.90	Atmospheric circulation	27	31	0.25	Radar echo vs time	5, 6, 7, 8
3	4	15	0.70	Atmospheric heat balance	27	31	0.40	Radar echo vs time	5, 6, 7, 8
3	5	14	0.90	Atmospheric circulation	27	31	0.25	Radar echo vs time	5, 6, 7, 8
4*	9*	1	0.90	Size, shape of Saturn's rings	27	34	0.90	RF beam reflectivity	6 (rings only)
4	21	1	0.20	Size, shape of Saturn's rings	27	34	0.90	RF beam reflectivity	6 (rings only)
5	9	1	0.90	Size, shape of Saturn's rings	27	34	0.90	RF beam reflectivity	6 (rings only)
5	21	1	0.30	Size, shape of Saturn's rings	27	34	0.90	RF beam reflectivity	6 (rings only)

*Case represented by computer program printed output
**If observation worth depends on planet, worth values for each planet are shown in parenthesis
† 1 = Mercury, 2 = Venus, 4 = Mars, 5 = Jupiter, 6 = Saturn, 7 = Uranus, 8 = Neptune

Table 2-8. Summary of Observation Requirements (Cont)

Goal	Knowledge Requirement	Observation Objective			Observable				Planets** †
		Number	Worth	Sub-Objective Description	Property	Technique	Worth	Sub-Observable Description	
1*	5*	9*	0.30	Thermal emission from planetary surface	27	22	0.30	Spatial variation of microwave emissivity	5*, 6, 7, 8
1	5	14	0.90	Atmospheric circulation	27	22	0.30	Spatial variation of microwave emissivity	5*, 6, 7, 8
1	5	15	0.70	Atmospheric heat balance	27	22	0.30	Spatial variation of microwave emissivity	5, 6, 7, 8
1	6	9	0.20	Thermal emission from planetary disk	27	22	0.30	Spatial variation of microwave emissivity	5, 6, 7, 8
1	8	9	0.40	Thermal emission from planetary disk	27	22	0.30	Spatial variation of microwave emissivity	5, 6, 7, 8
2	2	15	0.30	Atmospheric heat balance	27	22	0.30	Spatial variation of microwave emissivity	5, 6, 7, 8
2	3	15	0.30	Atmospheric heat balance	27	22	0.30	Spatial variation of microwave emissivity	5, 6, 7, 8
3	4	14	0.90	Atmospheric circulation	27	22	0.30	Spatial variation of microwave emissivity	5, 6, 7, 8
3	4	15	0.70	Atmospheric heat balance	27	22	0.30	Spatial variation of microwave emissivity	5, 6, 7, 8
3	5	14	0.90	Atmospheric circulation	27	22	0.30	Spatial variation of microwave emissivity	5, 6, 7, 8
1*	5*	9*	0.30	Surface temperature, heat transfer	27	32	0.50	Microwave imaging	5*, 6, 7, 8
1	5	14	0.30	Atmospheric circulation	27	32	0.50	Microwave imaging	5, 6, 7, 8
1	5	15	0.70	Cloud structure, precipitation forms	27	32	0.50	Microwave imaging	5, 6, 7, 8
1	6	9	0.20	Surface temperature, heat transfer	27	32	0.50	Microwave imaging	5, 6, 7, 8
1	8	9	0.40	Surface temperature, heat transfer	27	32	0.50	Microwave imaging	5, 6, 7, 8
2	2	15	0.30	Cloud structure, precipitation forms	27	32	0.50	Microwave imaging	5, 6, 7, 8
2	3	15	0.30	Cloud structure, precipitation forms	27	32	0.50	Microwave imaging	5, 6, 7, 8
3	4	14	0.90	Atmospheric circulation	27	32	0.50	Microwave imaging	5, 6, 7, 8
3	4	15	0.70	Cloud structure, precipitation forms	27	32	0.50	Microwave imaging	5, 6, 7, 8
3	5	14	0.90	Atmospheric circulation	27	32	0.50	Microwave imaging	5, 6, 7, 8
1*	5*	9*	0.30	Surface temperature, heat transfer	27	42	0.20	Polarization of microwave thermal emissions	5*, 6, 7, 8
1	5	14	0.90	Atmospheric circulation	27	42	0.20	Polarization of microwave thermal emissions	5, 6, 7, 8
1	5	15	0.70	Cloud structure, precipitation forms	27	42	0.20	Polarization of microwave thermal emissions	5, 6, 7, 8
1	6	9	0.20	Surface temperature, heat transfer	27	42	0.20	Polarization of microwave thermal emissions	5, 6, 7, 8
1	8	9	0.40	Surface temperature, heat transfer	27	42	0.20	Polarization of microwave thermal emissions	5, 6, 7, 8
2	2	15	0.30	Cloud structure, precipitation forms	27	42	0.20	Polarization of microwave thermal emissions	5, 6, 7, 8
2	3	15	0.30	Cloud structure, precipitation forms	27	42	0.20	Polarization of microwave thermal emissions	5, 6, 7, 8
3	4	14	0.90	Atmospheric circulation	27	42	0.20	Polarization of microwave thermal emissions	5, 6, 7, 8
3	4	15	0.70	Cloud structure, precipitation forms	27	42	0.20	Polarization of microwave thermal emissions	5, 6, 7, 8
3	5	14	0.90	Atmospheric circulation	27	42	0.20	Polarization of microwave thermal emissions	5, 6, 7, 8
4*	22*	10	0.50	Planetary surface definition–surface topography	2	2	0.20	Microwave imaging	5, 6*, 7, 8
5	3	10	0.20	Planetary surface definition–surface topography	2	2	0.20	Microwave imaging	5, 6, 7, 8
5	8	10	0.30	Planetary surface definition–surface topography	2	2	0.20	Microwave imaging	5, 6, 7, 8
5	22	10	0.50	Planetary surface definition–surface topography	2	2	0.20	Microwave imaging	5, 6, 7, 8
4*	22*	10	0.50	Planetary surface definition–surface topography	2	22	0.40	Spatial variation of microwave emissivity	5, 6*, 7, 8
5	3	10	0.20	Planetary surface definition–surface topography	2	22	0.40	Spatial variation of microwave emissivity	5, 6, 7, 8
5	8	10	0.30	Planetary surface definition–surface topography	2	22	0.40	Spatial variation of microwave emissivity	5, 6, 7, 8
5	22	10	0.50	Planetary surface definition–surface topography	2	22	0.40	Spatial variation of microwave emissivity	5, 6, 7, 8
1*	5*	9*	0.90	Surface temperature, heat transfer	17	23	0.30	IR radiation from planetary surface	5*, 6, 7, 8
1	5	13	0.80	Atmosphere physical properties	17	23	0.30	IR radiation from planetary surface	5, 6, 7, 8
1	5	14	0.90	Atmospheric circulation	17	23	0.30	IR radiation from planetary surface	5, 6, 7, 8
1	4	13	0.99	Atmosphere physical properties	17	23	0.30	IR radiation from planetary surface	5, 6, 7, 8
1	6	4	0.30	Interior energy flow	17	23	0.30	IR radiation from planetary surface	5, 6, 7, 8
1	6	9	0.40	Surface temperature, heat transfer	17	23	0.30	IR radiation from planetary surface	5, 6, 7, 8
2	3	13	0.20	Atmosphere physical properties	17	23	0.30	IR radiation from planetary surface	5, 6, 7, 8
3	4	13	0.90	Atmosphere physical properties	17	23	0.30	IR radiation from planetary surface	5, 6, 7, 8
3	5	14	0.99	Atmospheric circulation	17	23	0.30	IR radiation from planetary surface	5, 6, 7, 8
3	7	6	0.20	Internal physical properties	17	23	0.30	IR radiation from planetary surface	5, 6, 7, 8
3	11	4	0.60	Interior energy flow	17	23	0.30	IR radiation from planetary surface	5, 6, 7, 8

*Case represented by computer program printed output
**If observation worth depends on planet, worth values for each planet are shown in parenthesis
† 1 = Mercury, 2 = Venus, 4 = Mars, 5 = Jupiter, 6 = Saturn, 7 = Uranus, 8 = Neptune

Table 2-8. Summary of Observation Requirements (Cont)

Goal	Knowledge Requirement	Observation Objective: Number	Observation Objective: Worth	Observation Objective: Sub-Objective Description	Observable: Property	Observable: Technique	Observable: Worth	Observable: Sub-Observable Description	Planets**
1*	11*	4*	0.70	Interior energy flow	17	23	0.40	IR radiation from planetary surface	5*, 6, 7, 8
1	5	9	0.80	Thermal emission from planetary disk	17	23	0.40	IR radiation from planetary surface	5, 6, 7, 8
1	5	14	0.90	Atmospheric circulation	17	23	0.40	IR radiation from planetary surface	5, 6, 7, 8
1	6	4	0.30	Interior energy flow	17	23	0.40	IR radiation from planetary surface	5, 6, 7, 8
1	6	9	0.40	Surface temperature, heat transfer	17	23	0.40	IR radiation from planetary surface	5, 6, 7, 8
3	5	14	0.99	Atmospheric circulation	17	23	0.40	IR radiation from planetary surface	5, 6, 7, 8
3	7	6	0.20	Internal physical properties	17	23	0.40	IR radiation from planetary surface	5, 6, 7, 8
3	11	4	0.60	Interior energy flow	17	23	0.40	IR radiation from planetary surface	5, 6, 7, 8
1*	11*	4*	0.70	Interior energy flow	17	3	0.30	IR thermal emission	5*, 6, 7, 8
1	5	9	0.80	Surface temperature, heat transfer	17	3	0.30	IR thermal emission	5, 6, 7, 8
1	5	14	0.90	Atmospheric circulation	17	3	0.30	IR thermal emission	5, 6, 7, 8
1	6	4	0.30	Interior energy flow	17	3	0.30	IR thermal emission	5, 6, 7, 8
1	6	9	0.40	Surface temperature, heat transfer	17	3	0.30	IR thermal emission	5, 6, 7, 8
3	5	14	0.99	Atmospheric circulation	17	3	0.30	IR thermal emission	5, 6, 7, 8
3	7	6	0.20	Internal physical properties	17	3	0.30	IR thermal emission	5, 6, 7, 8
3	11	4	0.60	Interior energy flow	17	3	0.30	IR thermal emission	5, 6, 7, 8
1*	9	1	0.30	Planetary diameter and figure	1	24	0.30	IR radiation from planet albedo	5
5	9	1	0.40	Planetary diameter and figure	1	24	0.30	IR radiation from planet albedo	5
1*	9	1	0.30	Planetary diameter and figure	1	24	0.40	Optical diameter of disk	6
5	9	1	0.40	Planetary diameter and figure	1	24	0.40	Optical diameter of disk	6
1*	9	1	0.30	Planetary diameter and figure	1	24	0.60	Optical diameter of disk	7*, 8
5	9	1	0.30	Planetary diameter and figure	1	24	0.60	Optical diameter of disk	7, 8
3*	5	15	0.60	Atmospheric heat balance	1	28	0.70	IR/Visible/UV images of atmosphere	7
3*	5	15	0.60	Atmospheric heat balance	1	28	0.70	IR/Visible/UV images of atmosphere	5, 6, 8*
1*	11*	14*	0.80	Cloud structure, precipitation forms	1	24	0.80	Optical imaging	5, 6*, 7, 8
1	6	14	0.20	Cloud structure, precipitation forms	1	24	0.80	Optical imaging	5, 6, 7, 8
1	8	14	0.20	Cloud structure, precipitation forms	1	24	0.80	Optical imaging	5, 6, 7, 8
1	8	15	0.30	Atmospheric heat balance	1	24	0.80	Optical imaging	5, 6, 7, 8
3	5	14	0.99	Cloud structure, precipitation forms	1	24	0.80	Optical imaging	5, 6, 7, 8
3	5	15	0.90	Atmospheric heat balance	1	24	0.80	Optical imaging	5, 6, 7, 8
3*	5	14	0.60	Cloud structure, precipitation forms	1	24	0.40	Optical imaging of clouds	5, 6*, 7, 8
1*	17	24	0.30	Saturn ring properties	1	24	0.50	Optical imaging of rings	6 (rings only)
4	17	24	0.40	Saturn ring properties	1	24	0.50	Optical imaging of rings	6 (rings only)
5	17	24	0.30	Saturn ring properties	1	24	0.50	Optical imaging of rings	6 (rings only)
3*	5	14*	0.80	Cloud structure, precipitation forms	1	24	0.60	Sequential cloud images	5*, 6, 7, 8
3	5	15	0.40	Atmospheric heat balance	1	24	0.60	Sequential cloud images	5, 6, 7, 8
5	5	14	0.70	Cloud structure, precipitation forms	1	24	0.60	Sequential cloud images	5, 6, 7, 8
5	5	15	0.30	Atmospheric heat balance	1	24	0.60	Sequential cloud images	5, 6, 7, 8

*Case represented by computer program printed output
**If observation worth depends on planet, worth values for each planet are shown in parenthesis
†1 = Mercury, 2 = Venus, 4 = Mars, 5 = Jupiter, 6 = Saturn, 7 = Uranus, 8 = Neptune

Table 2-9. Candidate Sensor Types

Item	Observable Property	Observation Technique	Sensor Type	Limitations
1	Optical Images	Passive Visible Imagery	Television Camera	
2	Optical Images	Passive Multiband Imagery	Multispectral TV Camera	
3	Radar Images	Microwave Radiometry	Scanning (mapping) Radiometer	
4	Radar Images	Monostatic Radar Imagery	High-Resolution Radar	
5	Radar Images	Passive Microwave Imagery	Scanning Radiometer	
6	Magnetic Field Near Surface	Magnetic Field Measurement	Flux Gate Magnetometer	
7	Magnetic Field Above Atmosphere	Magnetic Field Measurement	Helium Magnetometer	
8	Gamma-Ray Emission	Gamma-Ray Spectrometry	Gamma-Ray Spectrometer	
9	Charged Particle Spectrum	Charged Particle Spectrometry	Charge Particle Spectrometer	
10	Charged Particle Spectrum	Charged Particle Spectrometry	Corpuscular Spectrometer	
11	Charged Particle Spectrum	Charged Particle Spectrometry	Electrostatic Plasma Spectrometer	
12	Charged Particle Spectrum	Charged Particle Flux Measurement	Geiger-Mueller Counter Array	
13	Charged Particle Spectrum	Charged Particle Flux Measurement	Ion Chamber	
14	Charged Particle Spectrum	Charged Particle Flux Measurement	Proportional Counter Array	
15	Electric Field Near Surface	Electric Field Measurement	Langmuir Probe	No feasible experiment
16	Electric Field Near Surface	Electric Field Measurement	Ion Density Probe	No feasible experiment
17	Electric Field Near Surface	Electric Field Measurement	Electric Field Mill	No feasible experiment
18	Microwave Flux	Microwave Polarimetry	Radiometric Polarimeter	
19	Microwave Flux	Microwave Radiometry	Temperature-Measuring Radiometer	
20	Microwave Spectrum	Microwave Spectrometry	Radio Spectrometer	Not state-of-the-art
21	Microwave Spectrum	Microwave Radiometry	Microwave Spectrometer	
22	Infrared Flux	Infrared Radiometry	IR Radiometer	
23	Infrared Flux	Passive Infrared Imagery	IR Thermal Mapper (imaging)	
24	Infrared Flux	Solar Occultation Spectrometry	IR Spectrometer	
25	Infrared Spectrum	Infrared Radiometry	IR Spectrometer	
26	Infrared Spectrum	Infrared Spectrometry	IR Grating Spectrometer	
27	Infrared Spectrum	Infrared Spectrometry	IR Michelson Spectrometer	
28	Infrared Spectrum	Infrared Spectrometry	Filter Spectrometer	
29	Visible-Ultraviolet Flux	Visible Photometry	Visible-UV Photoelectric Photometer Array	
30	Visible-Ultraviolet Flux	Occulation of Natural Sources of Electromagnetic Radiation	Filter Radiometer	
31	Visible-Ultraviolet Flux	Ultraviolet Photometry	Telescope With Visible UL Photoelectric Photometers	
32	Visible-Ultraviolet Spectrum	Ultraviolet Spectrometry	Normal Incidence Grating Spectrometer	
33	Visible-Ultraviolet Spectrum	Ultraviolet Spectrometry	Grazing Incidence Grating Spectrometer	
34	Visible-Ultraviolet Spectrum	Visible Spectrometry	Visible-UV Scanning Spectrometer	
35	Visible-Ultraviolet Spectrum	Multi-Band Spectrometry	Ebert Spectrometer	
36	Visible-Ultraviolet Spectrum	Multi-Band Spectrometery	Michelson Interferometer	
37	Visible-Ultraviolet Spectrum	Ultraviolet Photometry	Visible-UV Photoelectric Photometer Array	
38	Visible-Ultraviolet Spectrum	Ultraviolet Spectral Mapping	UV Scanning Spectrometer	
39	Radio Flux and Spectrum	Occultation of Natural Sources of Electromagnetic Radiation	Microwave Spectrometer	
40	Radio Flux and Spectrum	Radio Flux Measurement (Non-Imaging)	Microwave Spectrometer	
41	Coherent Light Reflectivity	Laser Transmission/Reflection/ Scattering	Laser Radar (lidar)	
42	Radio Reflectivity	Radio Wave Polarimetry	Bistatic Radar	No feasible experiment
43	Radio Reflectivity	Microwave Polarimetry	Radiometric Polarimeter	
44	Radio Reflectivity	Bistatic Radar Imagery	Bistatic Radar	No feasible experiment
45	Radio Reflectivity	Monostatic Radar Imagery	Pulsed Microwave Radar	No feasible experiment
46	Radio Reflectivity	Passive Microwave Imagery	Imaging (mapping) Radiometer	
47	Radio Reflectivity	Monostatic Radar (Non-Imaging)	Pulsed Microwave Radar	No feasible experiment
48	Electromagnetic Signal Propagation Time	Earth Occultation (Radio)	Coherent Transponder	Not state-of-art
49	Electromagnetic Signal Propagation Time	Monostatic Radar (Non-Imaging)	Pulsed Microwave Radar	No feasible experiment
50	Electromagnetic Phase Shift	Earth Occultation (Radio)	Two-Frequency Radio Occultation Receiver	
51	Polarization	Visible Polarimetry	Optical Analyzer and Polarimeter	
52	Polarization	Microwave Polarimetry	Radiometric Polarimeter	No feasible experiment
53	Stellar Occultation	Visible Photometry	Telescope With Visible-UV Photoelectric Photometers	
54	X-Ray Spectrum	X-Ray Spectrometry	X-Ray Spectrometer	
55	Albedo Neutron Flux	Neutral Particle Flux Measurement	LiI Scintillation Spectrometer	

Table 2-10. Applications of Remote Sensors

Sensor			Flyby Missions										Orbital Missions								
			Earth-Mercury	Earth-Venus	Earth-Venus-Mercury		Earth-Jupiter Saturn		Earth-Jupiter* Uranus-Neptune		Earth-Jupiter-Saturn-Pluto**		Mercury 1984		Venus 1977		Mars 1984		Jupiter 1978		
			1984 (2)	1980 (3)	1982 (6)		1976 (7)		1978 (9)		1978 (12)		Orbit 1	10	Orbit 1	9	Orbit 1	8	Orbit 1	9	11
No.	Name	Type	M	V	V	M	J	S	U	N	J	S	M	M	V	V	M	M	J	J	J
1.	Television camera **	○	–	–	–	–	–	○	○	○	–	○	○	○	○	○	○	○	○	○	○
2.	Camera system	○											○				○	○			
3.	Microwave radiometer, mapping **	○	–	–	–	–	–	○	○	○	–	○	○		○		○				
4.	Microwave radiometer, measuring **	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
5.	Synthetic aperture radar **	○	–	–	–	–	–	○	○	○	–	○	○		○						
6.	Noncoherent radar system	○											○		○		○				
7.	Flux-gate magnetometer	●	●			●	●	●	●	●	●	●	●	●					●	●	●
8.	Helium magnetometer	●	●			●	●	●	●	●	●	●	●	●					●	●	●
9.	Scintillation spectrometer	●	●			●							●	●			●	●			
10.	Charged-particle spectrometer †	●																			
11.	Electrostatic or Faraday cup analyzer	●	●			●							●	●							
12.	Geiger-Mueller counter array	●	●			●							●	●							
13.	Proportional counter array	●	●			●							●	●							
14.	Radio polarimeter **	●	–	–	–	–	–	–	–	–	–	–									
15.	Filter radiometer **	●	●	●	●	●	②●	②●	②●	②●	②●	②●	●	●	●	●	●	●	●	●	●
16.	Far IR radiometer **	○	–	–	–	–	–	○	○	○	–	○	○	○	○	○	○			○	
17.	Polychromator radiometer **	●	–	–	–	–	–	–	–	–	–	–									
18.	Scanning spectrometer **	○	–	–	–	–	–	–	–	–	–	–	○	○	○	○	○				
19.	Michelson interferometer **	●	–	–	–	–	①●	①●	①●	①●	①●	①●							●	●	●
20.	Visible/UV photometer **	○	–	+	+	–	+	+	+	+	+	+									
21.	Visible/UV spectrometer **	●	‡	‡	‡	‡	●	●	●	●	●	●							●	●	●
22.	Laser radar **	●	●	●	●	●	●	●	●	●	+	●	●	●	●	●	●	●			
23.	Bi-frequency radio occultation receiver **	●	×	●	●	×	●	●	●	●	●	×	●		●	●	●				
24.	Visible polarimeter **	○	–	–	–	–	–	–	–	–	–	–									
25.	Proportional counter telescope	●																			
26.	Solid-state telescope	●	●			●							●	●							
27.	Li^6I spectrometer	●	●			●							●	●							
28.	Curved plate plasma spectrometer	●	●			●							●	●							

LEGEND

- ○ Imaging sensor
- ● Nonimaging sensor
- – Not within scope of study, or requirement for sensor does not exist
- * Planetary coverage at this encounter outside scope of study
- ** Pluto outside scope of study
- † See Item 26, solid-state telescope
- ① Optimal capability
- ② Marginal capability
- ‡ Observation requirements deal with airglow emission spectra; airglow emission properties not readily available
- × No sensor designed; Earth occultation does not occur
- \+ Sensor design within state-of-art limitations not possible

2.3.2 Scaling Law Development

A major portion of the study concerns the development of sensor system scaling laws. A scaling law is defined as a procedure for relating measurement requirements to critical sensor design parameters and to the support requirements for specific applications of the sensor system. The most common use of scaling laws of this type is to establish trade data for a sensor system in terms of interacting design variables; these data may be used to define a preliminary engineering design model to serve as a guideline for detailed system design. From the preliminary model design, the significant physical properties, such as size, mass, viewing aperture requirements, power consumption, pointing accuracy, etc., may be estimated.

To meet the requirements of the program, scaling laws are developed for the following classes of instruments: passive optical, active optical, active microwave, passive and semiactive microwave and particle and field measurement instruments. The sensor types for which scaling laws (other than simple point designs) were developed in this study are indicated in Table 2-10. These sensor systems are concerned principally with the electromagnetic spectrum. Performance of the sensors for this purpose can be described in terms of a signal-to-noise ratio, which defines all of the significant parameters that establish sensor system performance. System parameters may be established based on the requirement for achieving a given signal-to-noise ratio for either detection or recognition. This approach underlies all of the scaling law developments; although in certain cases, (e.g., television systems), the explicit statement of a signal-to-noise ratio is suppressed in the development of a statement of the attainable resolution of the sensor.

In general, scaling law development consists of two essential steps: (1) derivation of an expression for signal-to-noise ratio for each sensor type or class and (2) imposition of a signal-to-noise ratio requirement to meet a given criterion of sensor system performance. Scaling laws are ordinarily expressed as an unbounded algebraic statement particularized to a given region of the electromagnetic spectrum and/or a given sensor type. Other methods of scaling law presentation include nomographs and mechanical devices such as slide rules. Another technique is the use of ratioing procedures, which consists essentially of establishing a new set of system characteristics from a computed set by a simple adjustment of one or more parameters. This latter type of scaling is most frequently used for deterministic design equations as in antenna size scaling as a function of wavelength. It may be misleading, however, when used to scale complete systems, since more than one variable may be a function of parameters such as viewing distance.

For the purpose of this study, scientific instrumentation for remote sensing is considered in the basic classifications of imaging and nonimaging with secondary classification by spectral region and function, as shown in the following diagram.

Non-Image-Forming	Spectrometry	IR, Visible UV
	Radiometry	Radio Microwave IR Visible, UV
Image-Forming	Fixed	Visible
	Scanning	IR UV

2.3.3 Scaling Law Example

As part of the sample problem of ultraviolet spectrometry at Saturn on the 1976 Earth-Jupiter-Saturn-Mission, the ultraviolet (UV) spectrometer scaling law (Reference 3) is selected as an example. The example is confined to grating spectrometers using photomultipliers.

The UV spectrometer design follows the logical procedure depicted in Figure 2-2. The spectral range requirement governs selection of sensors (i.e., detectors). The spectral resolution requirement determines the grating spacing and diameter. Spatial resolution and area coverage requirements, together with the trajectory constraints, determine the flight path and region of sensor operation (the trajectory may be fixed by gravity-assist requirements or to optimize the TV-camera imaging area coverage). The detectors and spectrometer grating and optics must be matched to each other. The available light and detectability signal-to-noise criterion establish the collector optics aperture and focal length. If the optics design exceeds the state-of-the-art, the spectral and/or spatial resolution capability must be relaxed. Areal coverage requirements lead to selection of a scanning system and calculation of the scan rate. If the spectral range and resolution requirements can not be satisfied in each field-of-view, the scan rate must be decreased and the scanning system redesigned. Finally, the power requirements, data acquisition rate versus time, and platform accuracy and stability requirements are evaluated.

2.3.3.1 UV Spectrometer Design Principles

Signal-to-Noise Ratio. It is necessary to compute the signal-to-noise ratio (S/N) in terms of detector responsivity:

$$\frac{S}{N} = \frac{I_s}{2e\Delta f}$$

where I_s is the output signal current, Δf is the noise equivalent bandwidth, and e is the charge on the electron = 1.6×10^{-19} coulomb.

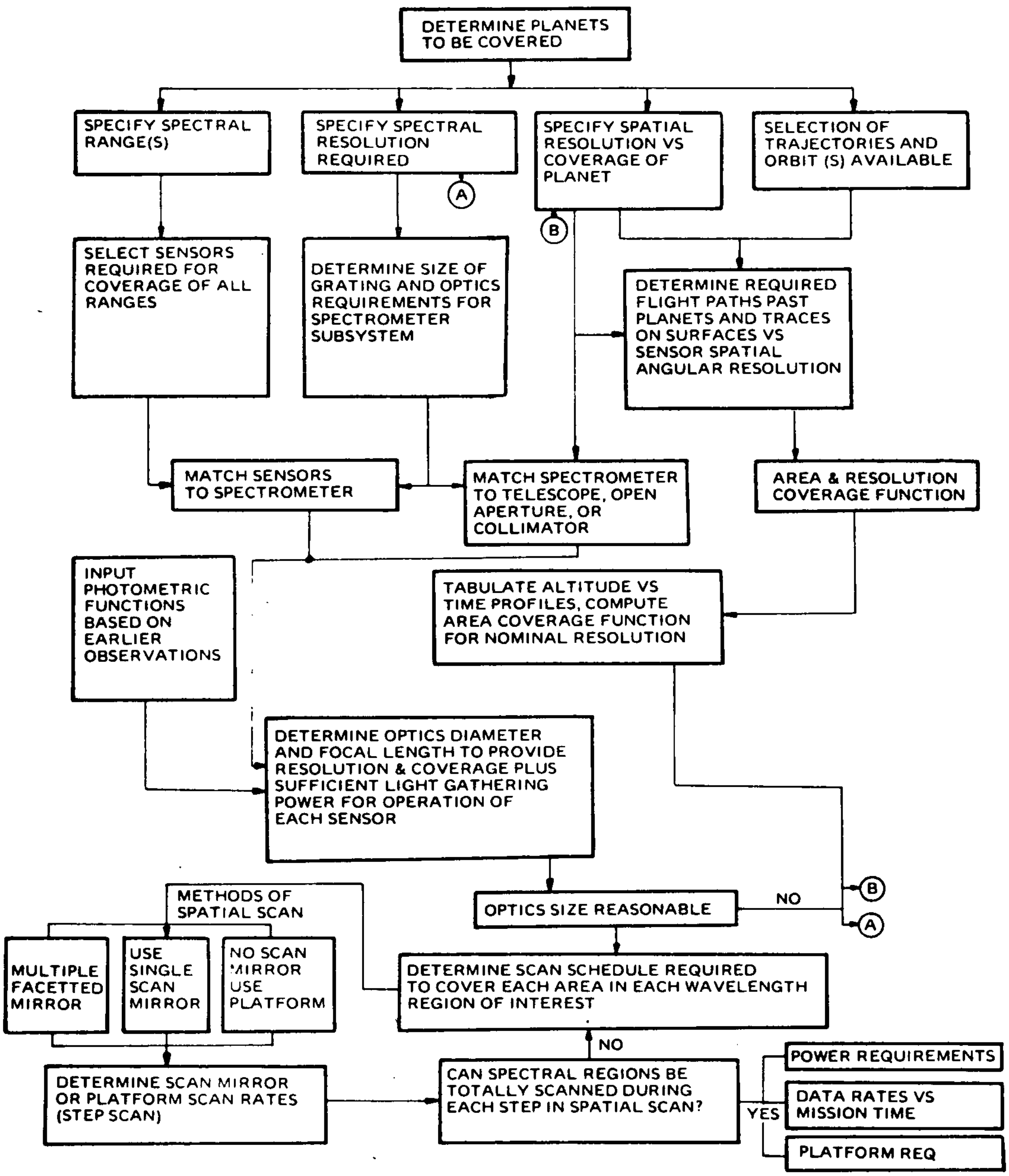

Figure 2-2. UV Spectrometer Design Logic Flow Diagram

The output signal current is determined by the overall responsivity of the photomultiplier and the available radiant power over the wavelength region of interest in the form

$$I_s = \int_{\lambda_1}^{\lambda_2} R(\lambda)\, P(\lambda)\, d\lambda$$

where R (λ) is the spectral responsivity in amperes per watt, $P(\lambda)$ is the spectral radiant power, and $\lambda_2 - \lambda_1 = \Delta\lambda$ is the spectral passband of the detector.

If the spectral resolution is small then R (λ) and P (λ) may be replaced by average values at the wavelength region of interest. Therefore,

$$I_s = \bar{R}_\lambda\, \bar{P}_\lambda\, \Delta\lambda$$

and the signal to noise ratio is

$$\frac{S}{N} = \frac{\bar{R}_\lambda\, \bar{P}_\lambda\ \Delta\lambda}{2e\Delta f}$$

The last equation is actually the power signal-to-noise ratio so that, in terms of peak-to-peak signal to rms noise, the signal-to-noise ratio is

$$\frac{S}{N} = \left[\frac{R_\lambda\, P_\lambda \Delta_\lambda}{2e\Delta f}\right]^{1/2}$$

The available radiant power at the detector is of course determined by the spectral radiance I_λ and the optical parameters in the form $P_\lambda \Delta_\lambda = \eta A_o \Omega I_\lambda \Delta_\lambda$, where η is the overall efficiency of the optical and detection process, A_o is the area of the collection optics, Ω is the instantaneous solid angular field of view of the optical system, I_λ is the spectral radiance, and $\Delta\lambda$ is the spectral bandwidth. The primary design equation, thus, becomes

$$\frac{S}{N} = \left[\frac{\eta R_\lambda\ A_o\, \Omega I_\lambda \Delta_\lambda}{2\epsilon\,\Delta f}\right]^{1/2}$$

As with any system that is limited by detector size A_d, $A_d = A_o\, \Omega\, N^2$, where N is the aperture ratio or f/number of the complete optical system from entrance aperture to the detector including field lenses, collimator, and as appropriate, aperture stops or slits. Since $\Omega \approx \left(1.22\ \frac{\lambda}{D}\right)^2$ for a diffraction-limited system and $\Omega <<1$, it follows that $A_d = K\lambda^2\, N^2$; or the linear dimension of the detector ℓ determines the best spatial resolution attainable with an instrument without loss of signal. It also indicates a primary limitation at short wavelengths, since $\ell = N_\lambda$; and as λ decreases, the attainable value of N must increase to maintain instrument performance.

The available observation time is

$$t = \frac{2H\sqrt{\frac{\Omega}{\pi}}}{V_g}$$

where H is the altitude, V_g is the effective surface velocity, and the value of the instantaneous field of view is

$$\Omega = \frac{\pi t^2 V_g^{\ 2}}{4H^2}$$

Substituting in the signal-to-noise-ratio equation,

$$\frac{S}{N} = \left[\frac{\eta \pi R_\lambda\ A_o\ I_\lambda \Delta\lambda}{2e\Delta f}\right] \frac{t\ V_g}{2H}$$

which is the primary design equation for the optical system of the spectrometer. The values of R_λ (Reference 7) are obtained from Figure 2-3, and I_λ is determined for the wavelength region of interest and the viewing geometry for specific planets.

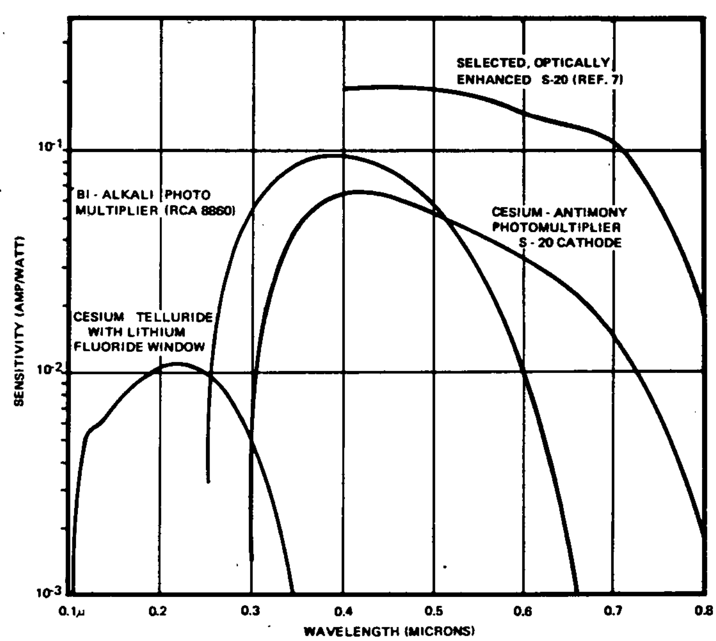

Figure 2-3. Spectral Response of Photomultipliers

It would appear from all of the signal-to-noise-ratio expressions for discrete detectors, that a signal-to-noise ratio as great as required could be obtained by making the bandwidth Δf small enough. The minimum bandwidth, however, is basic to the instrument stability criterion discussed in the spectrometer section. Narrower bandwidths imply bandpass characteristics of increasing Q. The minimum resistance losses of real components tend to limit attainable Q, even with feedback, so that overall instrument stability of approximately 20 seconds is an upper limit on the state of the art.

Spectrometer Gratings. Diffraction gratings produce dispersion as a result of interference of light passing through many parallel slits. The fundamental grating equation is $n\lambda = d(\sin\alpha + \sin\beta)$, where λ is the wavelength, n is an integer, d is the grating width, and α and β are the angles of incidence and transmission or reflection, respectively.

The resolving power of the plane diffraction grating is given by $\frac{\lambda}{\Delta\lambda} = \frac{\omega}{\lambda}(\sin\alpha + \sin\beta)$, where ω is the electrical width of the grating in wavelengths and the other factors are as before. It follows that $\frac{\lambda}{\Delta\lambda} = nN$, where again n is an integer and N is the number of lines in the grating.

The total flux-transmitting power of a spectroscopic instrument may be scaled by the relationship $F = kT\frac{\ell}{f}A\frac{d\theta}{d\lambda}$, where F is the flux transmitted, k is a scaling constant independent of grating parameters, ℓ is the slit height (maximum without changing resolution), f is the focal length, T is the optical transmission, $A = hw \cos i$ (the effective area of the grating), h is height of the grating, w is width of the grating, i is the angle of incidence on the grating, and $\frac{d\theta}{d\lambda}$ is the angular dispersion of the grating. This relationship is for constant resolution and is employed to scale parameters as follows: if two instruments are to be compared with flux transmission F_1 and F_2, then

$$\frac{F_1}{F_2} = \frac{T_1\ \ell_1\ f_2\ A_1\ \left(\frac{\partial\theta}{\partial\lambda}\right)_1}{T_2\ \ell_2\ f_1\ A_2\ \left(\frac{\partial\theta}{\partial\lambda}\right)_2}$$

It is important to note that, for such instruments, the so-called f/number is not a good measure of flux transmission.

The resolution as a function of f varies linearly down to a critical slit width w_c below which the resolution does not improve, but the intensity drops rapidly. This relationship is given by $w_c = \frac{\lambda f}{D}$, where λ is the wavelength, f is the focal length, and D is the diameter of the collimator.

Collimating Optics. The basic assumption in grating design is that that the grating is illuminated by plane waves; that is, a parallel beam of radiation. This requirement imposes an optical transformation between the primary focus of the collecting optics, where the beam of radiation is convergent, and the grating, which requires a parallel beam of radiation. The diameter of the collimated radiation is generally slightly larger than the dimension of the grating to permit motion of the grating in the collimated beam.

A large variety of collimators have been used in grating spectrometers, but two classes are the most common. They are classified as straight-through, or dioptric, and reflective. A somewhat simpler configuration is obtained with reflective components. In place of the field lens and negative lens at the focal plane, a slightly convex mirror is used to reform the convergent beam into an essentially collimated beam. After illuminating the grating the radiation is refocused with a second concave mirror to illuminate the exit slit.

There are many possible optical arrangements for a grating spectrometer. Schematic diagrams for spectrometers using a plane transmission and a reflection grating are shown in Figures 2-4 and 2-5. The choice of mounting is dictated by the required spectral range of the instrument and the resolution requirements in addition to packaging limitations. The Eagle mounting (Figure 2-6) will be assumed for the following discussion of UV and visible spectrometers for the 0.2- to 0.8-μm range. Part of the problem of mounting stems from the requirements of the photodetectors needed to cover the spectral range of interest. An array of phototubes would be required for wide spectral ranges. Each sensor would be placed behind its own slit, and they would be operated in parallel. It is assumed that all of the required photosensors needed to cover the wavelengths of interest could be housed in the same instrument, and the entire spectral region from 0. 2 to 0. 8 μm could be covered by the same optics and diffraction grating.

Detectors. Aside from photovoltaic detectors, the most sensitive and commonly used discrete detector in the visible and ultraviolet is the photomultiplier. In a sense it is similar to an avalanche photodiode since a single photon event may produce as many as 10^6 output electrons. It is substantially different from an avalanche photodiode, however, because the signal-to-noise ratio at the output of a photomultiplier is always less than the signal-to-noise ratio at the detector cathode. The difference is a function of the photomultiplier multiplication ratio.

The performance of photomultipliers is described in a variety of ways. In principle, performance can be described in much the same way as photo-conductive and photovoltaic devices; that is, in terms of specific detectivity D* in the form

$$D^* = \frac{\sqrt{A_D \Delta f}}{NEP}$$

where A_D is the photocathode sensitive area, Δf is the equivalent noise bandwidth, and NEP is the input power required to produce an output signal-to-noise ratio of one in a unit bandwidth. Photomultiplier tube performance, however, is not generally specified in terms of the cathode area so that D* is not used as a figure of merit for photomultipliers. Nevertheless, when it is computed, it generally results in values of D* of the order of 5×10^{14} at wavelengths near peak response.

The noise equivalent input power is sometimes used as a figure of merit for photomultipliers. For background-noise-limited operation, the minimum monochromatic power detectable by a photocathode is that producing a signal current equal to the photon noise shot current which is assumed to have a Poisson probability density function. For background-limited operation, the photon noise current can be shown by $I_{RMS} = 2eI_{dc}\,\Delta f$, where I_{dc} is the steady component of the signal resulting from photon conversion, e is the charge of the electron, and Δf is the equivalent

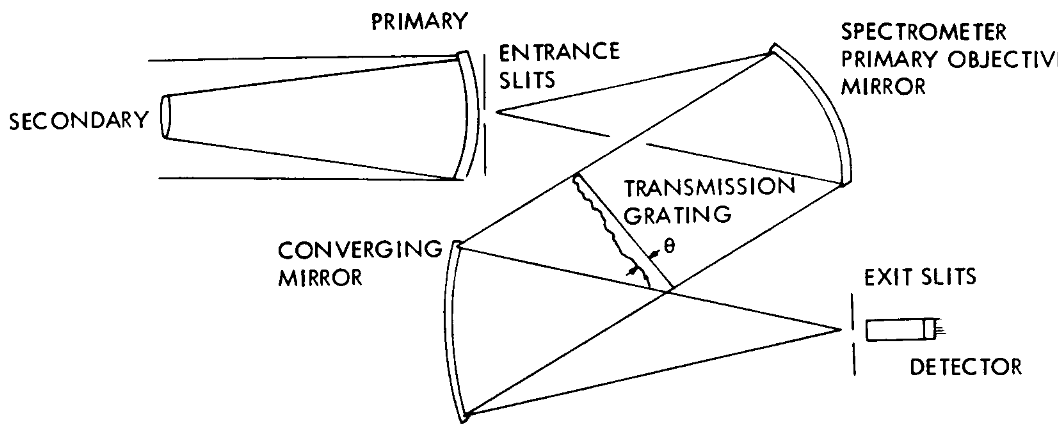

Figure 2-4. Transmission-Grating UV Spectrometer

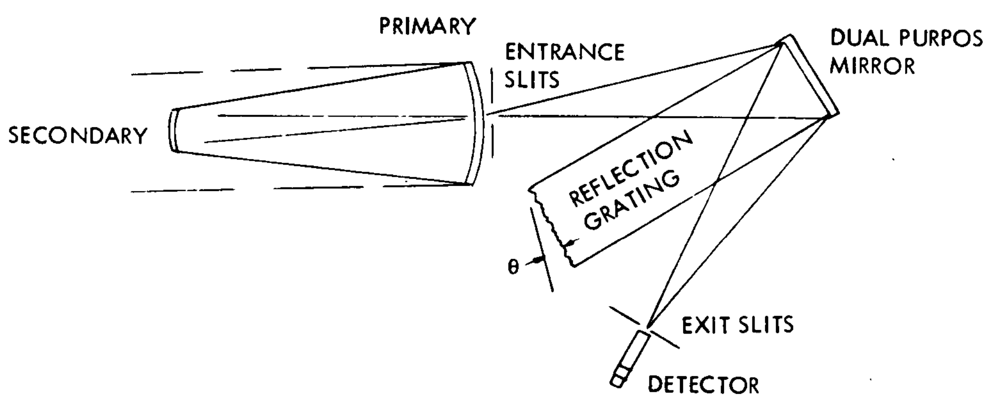

Figure 2-5. Reflection-Grating UV Spectrometer

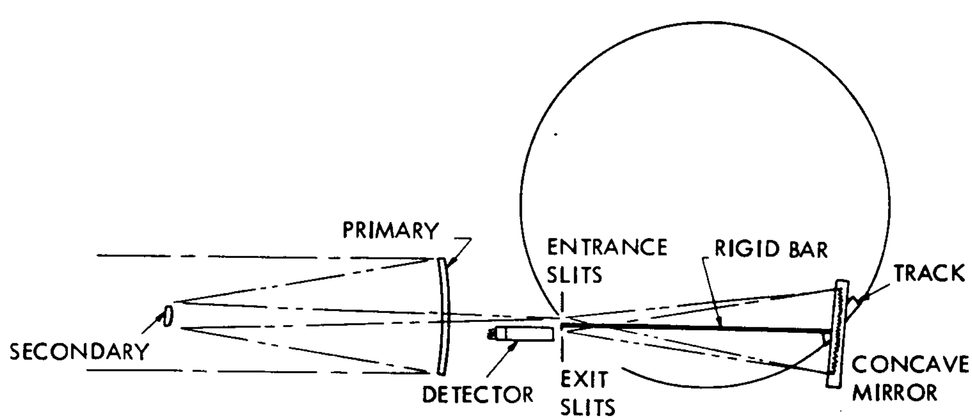

Figure 2-6. Eagle Mounting of a Curved Crystal Spectrometer

noise bandwidth. The signal current is generated by the arrival of photons and is defined as $I_{dc} = \bar{n} Q_e e$, where $\bar{n}$ is the average rate of photon arrival and Q_e is the quantum efficiency of the photocathode. Therefore, $I_{RMS} = \sqrt{2e^2 Q_e \bar{n} \Delta f}$. The product $\frac{Q_e e}{h\nu}$ has the units of amperes per watt where h is Planck's constant and ν is the frequency of the radiation. Therefore, P watts of signal can be converted into a signal current: $I_{dc} = P \frac{Q_e e}{h\nu}$ amperes. The same result can be obtained by taking the product of the average photon rate and the energy of a photon in the form $P = \bar{n} h\nu$ watts and substituting for $\bar{n}$.

Equating the signal current to the shot noise current gives

$$P = h\nu \sqrt{\frac{2\ n\Delta f}{Q_e}}$$

and the noise equivalent power, defined in terms of a unit bandwidth, is

$$NEP = \frac{P}{\sqrt{\Delta f}} = h\nu \sqrt{\frac{2\pi}{Q_e}}\ \frac{\text{watts}}{\sqrt{\text{cps}}}$$

This expression is sometimes convenient if the only data available on the photocathode is the quantum efficiency as a function of spectral wavelength.

The most common method of describing photomultiplier performance is in terms of the responsivity. The responsivity of a detector with a current output is, by definition, the current output in terms of the signal power input; that is,

$$R = \frac{I_{dc}}{P_{in}}\ \frac{\text{ampere}}{\text{watt}}$$

or, in photometric units, in amperes per lumen. While the responsivity is meaningful, some caution must be exercised in its use; since the responsivity may be in terms of the cathode responsivity or the anode responsivity, output measured. The two quantities are related by the current gain of the multiplier chain but are modified by internal noise contributions of the multiplier. By definition of a photon noise-limited photocathode, the signal-to-noise ratio at the output of the cathode is

$$\left(\frac{S}{N}\right)_K = \frac{I_s{}^2}{I_N{}^2}$$

where I_s is the signal current, and I_N is the noise current. But, for photon noise-limited operation, $I_N = \sqrt{2e\ I_s \Delta f}$ so that

$$\left(\frac{S}{N}\right)_K = \frac{I_s}{2e\Delta f}$$

For a cathode responsivity of R amperes per watt and a signal of P watts, the cathode signal-to-noise ratio is

$$\left(\frac{S}{N}\right)_K = \frac{P(R)_K}{2e\Delta f}$$

however, in going through the dynode multiplication structure a decrease in signal-to-noise ratio results; thus, not all of the electrons that leave the cathode are captured by the first dynode so that the signal-to-noise ratio at the input to the first dynode is reduced by the capture efficiency ϵ to

$$\left(\frac{S}{N}\right)_1 = \epsilon \left(\frac{S}{N}\right)_K , \quad \epsilon \leq 1$$

At the first dynode, a secondary emission process occurs such that each incident electron liberates an average of σ electrons. The secondary emission process is assumed to be a Poisson process so that the signal and noise components are similar to the cathode emission. If the process is repeated for each of the dynodes and the electron multiplication σ is assumed equal for all stages it can be shown that the anode signal-to-noise ratio approaches

$$\left(\frac{S}{N}\right)_a = \epsilon \frac{(\sigma - 1)}{\sigma} \left(\frac{S}{N}\right)_K$$

for a large number of dynodes. Typical values for the design parameters are $\sigma = 4$ and $\epsilon = 0.9$ so that the multiplication process reduces the output signal-to-noise ratio by approximately 30 percent. In applying measured data to the computation of signal-to-noise ratio, care should be taken to distinguish between cathode and output responsivities.

The photosensitive materials used in photocathodes exhibit broad, but finite, spectral response characteristics. For photoemission to occur, the incident photons must provide enough energy to raise the energy level above the conduction level and the surface barrier potential before the electrons are ejected. Photocathodes, therefore, exhibit a long-wavelength threshold. At wavelengths shorter than the threshold, the quantum efficiency rises to a maximum until the optical absorption of the photo surface and any window material causes the available energy to decrease.

The limits on spectral bandwidth have resulted in a large variety of photomultiplier tube types. The basic differences among tubes are in the photocathode type and the window material used. The long-wavelength cutoff for photoemitters is approximately 1.2 nm, although high responsivity is generally limited to approximately 0.7 nm. In the ultraviolet region, normal glass envelopes use a radiation cutoff at approximately 0.35 nm. Thin, special-purpose windows cut off at approximately 0.22 nm, while fused-silica glass extends the cutoff to approximately 0.165 nm. Special-purpose UV tubes are available with lithium fluoride windows which extend the cutoff to as low as 0.1 nm.

2.3.3.2 Scaling Law

Mass and Voltage. The requirement for high angular resolution imposes the requirement for large aperture diameter. It is possible to conceive of a space-rated optical system design that is equivalent to the largest Earth-based telescopes, which would lead to the conclusion that a reflective system with an aperture as large as 5 meters could be designed for space use. As a matter of economic feasibility, however, it is doubtful that the investment would be made, since there does not appear to be an overriding requirement to warrant the investment. Several research and development programs have been conducted to design diffraction-limited 2.5-m (100-inch) aperture systems for space applications, but the overall optical quality of such systems is difficult to demonstrate for long-term unattended operation. While improvements can be expected in this area, it appears that a realistic limit on optical apertures for unmanned systems is of the order of 2.5 m.

In estimating support requirements of optical sensors, it is obvious that one of the heaviest, most dense systems to be put on a spacecraft is a large-aperture optical system. For image forming systems with discrete detector arrays such as IR and UV mappers, the difficulty is increased by the addition of a scanning mechanism, which usually consists of a driven mirror system to change the direction of look of a fixed optical aperture. The basic mass estimate for an optical aperture is estimated empirically to be in the form $M_c = 168\ D_c{}^2$, where M_c is the mass of the collector optics in kilograms and D_c is the diameter of the collector optics in meters. The expression was obtained from survey data for actual systems. A better fit to the available data appears to be a 5/2 power law.

For large-diameter optics in spacecraft, the optical path to the detector or image plane is folded in either the Cassegrainian or Newtonian configuration. The primary optical assembly consists of a secondary mirror to fold the optical path and an external mirror that can be driven to rotate the field of view about the primary optical axis. For image-forming systems that employ discrete detectors, the external mirror may be used to scan the object plane in the cross-track direction to spacecraft motion.

In addition to estimating the weight of the primary mirror, it is also necessary to estimate the weight of the secondary mirror and the external mirror to obtain a realistic estimate of total optical system mass. Since the secondary for a Cassegrainian configuration requires the removal of some of the center portion of the primary it follows that the primary mass is reduced as a function of the diameter of the secondary, D_s. In estimating the primary mass of a Cassegrainian telescope the following expression is used

$$M_c = K \left[D_c{}^{5/2} - D_s{}^{5/2} \right]$$

where K is a scaling constant depending upon the material used. From the design equations of a Cassegrainian telescope, the diameter of the secondary is given by

$D_s = 0.5 \frac{D_c}{N}$, where N is the telescope focal ratio. It follows that the mass of the secondary reflector is given by

$$M_s = K \left(\frac{0.5\ D_c}{N} \right)^{5/2}$$

The mass of the associated scan mirror is difficult to estimate because it is highly dependent on overall system requirements and spacecraft limitations. High-speed scan is generally not required for mapping, especially for flyby missions of the outer planets, so that only the single-mirror case has general application. Using the 1/6 thickness criterion and an assumed optimum structural design of the scan mirror, it follows that $M_m = \frac{\pi}{24} \cdot \rho D_c^{5/2}$ where M_m is the mass of the scan mirror, ρ is the material density, and D_c is the diameter of the primary.

It is common practice in the design of large telescopes to design the primary mirror and associated prime aperture with an aperture ratio of 1 to 1.5. Assuming an aperture ratio of one, it follows that the length of the telescope is approximately equal to the aperture diameter. To a first approximation, optimized space structure techniques would permit a structural design that has 80 percent of the primary mirror thickness. The structure considered as applicable is basically thin and rigid truss members with stretched panel cladding. The shell structural volume would then be $V_{ss} = \frac{\pi}{15} D^{5/2}$; and the structural mass would be $M_{ss} = \frac{\pi}{15} \rho D^{5/2}$, where ρ is the density of the structural material, probably aluminum with a density of 2.7 x 10^3 kg/m^3.

For reference purposes, the weight-estimating approximations are summarized in Table 2-11. For the primary mirror system, beryllium is generally optimum on a weight, strength, and temperature coefficient basis. Aluminum structure is assumed.

Certain general scaling laws for the electronics associated with non-image-forming visible and UV systems can be established for mass and volume estimating purposes. The following general considerations apply:

1. For estimating purposes the photomultiplier is assumed to be equivalent to commercially available tubes with masses of approximately 0.1 kg. Some difficulties usually arise in obtaining high-level packaging density of photomultipliers in the image plane. It is common practice to use transfer optics from the image plane to a convenient detector location. Fiber optics are frequently used and add approximately 30 percent to the detector system mass. A realistic estimate for a photomultiplier with transfer optics is therefore 0.13 kg per detector.

2. Reference sources are frequently used with spectrometers as gain control devices and are a necessity for absolute radiometers. The source may be external, the Sun being the most frequently used reference. For absolute

Table 2-11. Mass Relationships for Estimating Primary Cassegrainian Optical System Mass

Telescope Element Characteristic	Material	Algebraic Approximation
1. Primary mirror mass, M_c	Glass	$300\,(D_c^{5/2} - D_s^{5/2})$
	Beryllium	$230\,(D_c^{5/2} - D_s^{5/2})$
2. Secondary mirror diameter, D_s		$\frac{0.5\,D_c}{N}$
3. Secondary mirror mass, M_s	Glass	$195\,(D_c/N^{5/2}$
	Beryllium	$150\,(D_c/N^{5/2}$
4. Scan mirror mass	Glass	$300\,D_c^{5/2}$
	Beryllium	$230\,D_c^{5/2}$
5. Telescope structure mass	Aluminum	$567\,D_c^{5/2}$
Mass in kg Dimensions in meters		

radiometry, an internal calibrated reference source is used. The two types of sources are not essentially different with respect to mass scaling; consequently, a mass penalty of 0.5 kg is used.

3. Auxiliary components, such as field lenses, beamsplitters, filter wheels, drive motors, etc., are generally low-mass devices. The design of auxiliary components is usually optimized after basic design of the instrument is established with factors such as duty cycle, aging characteristics, etc., having an effect on overall system mass or volume. For estimating purposes the masses given in Table 2-12 are assumed although many of the estimates may be in error by as much as 50 percent.

4. The electronics at the output of the instrument depends upon the function performed and the detector type used. Modern microcircuit technology permits functional packaging of the order of 0.005 kg per function and resulting packing densities of the order of 370 kg/m^3. Thus, an electronic package that performs ten functions such as amplification in five stages, automatic gain control, detection and conversion, would have a mass of approximately 0.05 kg and occupy a volume of 1.4×10^{-4} m^3.

5. Solid-state high-voltage power supplies are about 10 times as massive as microminiature circuits but have packing densities that are approximately twice as high. A typical high-voltage power supply with rectifiers, inverters, and regulators would then be sized by power drain and the degree of regulation. A typical 100-milliampere high-voltage supply for a photomultiplier would have 15 functions at 0.05 kg per function or a mass of 0.75 kg. The volume would then be $10^{-3} m^3$.

The first step in the scaling law is to determine the telescope parameters to meet the required signal-to-noise ratio and the spectral resolution requirements.

The spectrometer is assumed to be packaged in a cylindrical structure. The diameter of the spectrometer housing is in the range of 1.5D to 2.5D, depending upon the type. For an Ebert mirror, the diameter would be 2.5D; but for a dioptric spectrometer, it would be 1.5D. For estimating purposes, a value of 2D is a useful average value. The mass of the spectrometer structure can be estimated as a shell structure using the procedure given for telescope structures in Table 2-12.

Power. In terms of the input power, the signal-to-noise ratio is

$$\frac{S}{N} = \int_{\Delta\lambda} \frac{R(\lambda)\ P(\lambda)\ d\lambda}{2e\Delta f}$$

and for narrow spectral bandwidth, this ratio is given approximately by $\frac{S}{N} = \frac{\bar{R}(\lambda)\ \bar{P}(\lambda)\Delta\lambda}{2e\Delta f}$ where $\bar{R}(\lambda)$ is the responsivity in amperes per watt, $\bar{P}(\lambda)\Delta\lambda$ is the available radiant power at the detector in wavelength interval $\Delta\lambda$, e is the charge on the electron, and Δf is the electrical bandwidth.

In terms of the aperture D_c, angular resolution ϕ, and integration time, t, this signal-to-noise ratio can be expressed as

$$\frac{S}{N} = \eta D_c \Delta\phi \frac{R\lambda\Delta\phi I\lambda\Delta\lambda t}{2e}$$

where $I\lambda\Delta\lambda$ is the available spectral radiance from $I\lambda\Delta\lambda = H(\lambda)\ \rho\ (\lambda)\ \cos\theta\Delta\lambda$, and $H(\lambda)$ is the solar constant at the planet of interest in the wavelength region of measurement, $\rho\ (\lambda)$ is the albedo, θ is the observation angle, and a is the exponent determined by planet type (a = 1 for planets without atmospheres, and a = 2 for planets with atmospheres). The value of the efficiency η, which accounts for all losses from input to signal output, is taken as 0.25.

An alternative expression is useful when the quantum efficiency of the photomultiplier is given rather than the responsivity. In terms of the quantum efficiency, the signal-to-noise ratio is

$$\frac{S}{N} = 3.3 \times 10^{11}\ D_c \Delta\phi \left[\frac{Q_e\ (C_p f)\Delta\phi}{\omega}\right]^{1/2}$$

Table 2-12. Mass Estimation for Auxiliary Components of Visible and UV Optical Instruments

Function	Mass	Volume
Photomultiplier (with fiber optics transfer)	0.13 kg/detector	$2 \times 10^{-4} m^3$**
Reference source	0.5 kg	$7.6 \times 10^{-4} m^3$**
Gratings, mirrors, field lenses, etc.	$4 \times 10^2\ \ell^3$ kg*****	$\frac{\ell^3}{6}$
Filter	0.25 kg/channel	***
Beamsplitter	0.05 kg/channel	***
Rotary filter drives and auxiliary motors	0.2 kg/channel	***
Mirror scan drive motor (for scanning mirror)	$0.2\ (0.1 + D_p)$****	***
Electronics	0.05 kg/channel	$1.4 \times 10^{-4} m^3$*
High-voltage power supply	0.75 kg/10 channels	$1 \times 10^{-3} m^3$**

*Microminiature circuit package. $3.7 \times 10^2\ kg/m^3$
**Solid-state distributed circuit package. $7.4 \times 10^2\ kg/m^3$
***Included in volume of primary telescope.
****D_p is the primary optical aperture diameter in meters.
*****ℓ is the diameter or width in meters.

where $\frac{1}{\omega}$ is the dwell time and is equivalent to the integration time and, where $(C_p f)$ is the available spectral radiance and is computed for narrow spectral bandwidth as indicated above. That is, $(C_p f)$ can be replaced by $I\lambda\Delta\lambda$.

The second step is to determine the spectrometer parameters based on the spectral resolution required and the spectral range. The Eagle mount is assumed. The mirrors and grating are sized and the mass estimated assuming that each is a mirror with scale mass given in Table 2-12. The volume required for the spectrometer is generally large because the aperture ratio of spectrometers is generally high. The aperture ratio results from the minimum spatial requirements for the collimation of the incident flux, the formation of the far field pattern of the diffraction grating, and the focal ratio of the collecting optics. True aperture ratios for collimators are highly dependent upon the size of the grating, but are generally in the range of 4 to 15. With folding and optimum design, the overall length can generally be reduced to one-third of the equivalent focal length, which results in an approximate length $L = \frac{1}{3} f = \frac{ND}{3}$, where N is the aperture ratio of the spectrometer and D is the width of the grating.

Power is required for the spectroscopic instrument to operate an external scan mirror if one is used, to operate the spectrometer scan drive if one is used, and to operate the detector electronics. Power requirements for the scan mirror and spectrometer scan drive can be obtained from Table 2-13.

The power required to operate a photomultiplier is relatively modest. For estimating purposes, a value of 1.0 watt per detector is useful. The estimate includes the high-voltage power supply and would tend to be low for a single detector; therefore, if an array of up to five photomultipliers is used, an additional power allowance of 2 watts should be made for the high-voltage power supply.

Table 2-13. Power Required for Scanning and Pointing

Function	Power Required (Watts)
1. Scan mirror rotation	$7.5 \times 10^{-3}\ D_o^2\ M_M \omega^3$
2. Oscillating mirror	$8\ D_M^2\ M_M \phi^2 / t_f^3$
3. Reticles, rotating filters, etc.	0.1 watt per function
4. Gimbaled structure for pointing	See Figure 4-8 of Reference 3

Data Rate. In a photomultiplier, each photoelectron emitted from the photocathode undergoes cascade multiplication inside the tube and comes out of the tube as a pulse of many electrons. Assuming the use of an analog integrator, the data rate is inversely proportional to the integration time and directly proportional to the number of channels and the dynamic range of the instrument, $DR = \frac{nL}{t}$, where n is the number of channels, L is the dynamic range, and t is the integration time. The dynamic range requirements are highly dependent upon the function of the instrument; but for estimating purposes, a value of 100 to one is reasonable, and a maximum of seven bits per sample is assumed.

If dynamic variations in the spectrum are of interest, a sampling rate to meet dynamic measurements must be established. The data rate is then the product of number of channels, the dynamic range, and the sampling rate.

Stabilization. If the angular resolution of the instantaneous field of view of the optics is given by $\phi = \tan^{-1}\left[\frac{W}{2H}\right]$, which is approximately $\phi \approx \frac{W}{2H}$ for small angles, and the time available for sampling is taken as the time in which the field of view traverses a resolution interval W, then $\phi = \frac{t V_g}{2H}$, since $W = tV_g$.

Stabilization of the optical axis in terms of field-of-view scanning rate is $\phi' = \frac{\phi}{t} = \frac{V_g}{2H}$ radians/sec.

2.4 MISSION TRAJECTORY ANALYSIS

A basic objective of the study was development of suitable scaling laws relating mission support requirements to the measurement capabilities of the sensors, along with the methodologies for application of these laws to representative cases. To provide meaningful observational data for these representative cases, a selected set of mission profiles and the accompanying planetary encounter trajectory data were generated.

A NASA-developed trajectory computer program was provided to generate the necessary flyby trajectory data. This program was extended to include an automated graphical output of data along with a time-sequenced pictorial display of the encounter planet as seen from the flyby spacecraft.

NASA SP-35 formed the basic reference for heliocentric trajectory parameters related to specified mission sets, except for the Jupiter-Saturn-Pluto and Jupiter-Uranus-Neptune missions for which special trajectory data were supplied by NASA.

2.4.1 Flyby Missions

The total set of unmanned missions included in this study are flybys of Mercury and Venus (including Venus swingby missions to Mercury), flybys of Saturn using a Jupiter swingby mode, and multiplanet flybys of Jupiter-Saturn-Pluto and Jupiter-Uranus-Neptune. Two mission opportunities for each specified planetary set were evaluated.

As a consequence of the inherent planetary alignments, the period under consideration for swingby missions to the outer planets was restricted to the latter half of the 1970-1980 decade.

2.4.1.1 Mission Selection

A basic criterion used in this study for the selection of the mission sets was minimal Earth departure energy commensurate with "close" encounters with the individual encounter planets. A minimum value (0.25 planet radius) for the altitude of closest approach to Jupiter was selected to alleviate the guidance and navigation requirements; and, for the same reason, the Saturn flybys were restricted to an external passage of the rings. A summary of the mission sets evaluated in the course of the study is contained in Table 2-14.

One mission was chosen as an example to illustrate the methodology, the 1976 Earth-Jupiter-Saturn mission. The Saturn encounter data and a discussion of this particular case are presented in Sections 2.4.1.2 and 2.4.1.3.

2.4.1.2 Analysis Methodology

The 1976 Earth-Jupiter-Saturn mission was chosen as a representative mission for this phase of the study. Encounters with the two most massive planets of our solar system are expected to provide excellent opportunities for detailed planetary measurements. The year 1976 is ideal for this type of mission in that the best combination of minimal departure energy and close planetary encounters occur as a consequence of the favorable alignment of the planets during this period.

For each flyby trajectory, a specific set of planetocentric parameters was generated. These parameters were chosen on the basis of their expected utility in the evaluation of the complete sensor set. The first and most obvious is the altitude, followed by the spacecraft velocity magnitude and the rate of change of the radius. The latitude and longitude of the sequence of subsatellite points were likewise determined. The Earth (Sun)/spacecraft/planet included angles were considered as important parameters, as well as their rates of change. Ground speed of the subsatellite point was calculated, as well as the nadir angle rate. This latter parameter is defined as the required inertial slewing rate for a given sensor to track the instantaneous subsatellite point. Each of these parameters, along with time, was sequentially calculated using true anomaly as the independent parameter. These dependent parameters are illustrated in Figure 2-7.

The point of distance of closest approach is defined as time zero. A negative time or true anomaly denotes the approach phase, and a positive value denoted the departure phase. Latitude is measured in a conventional manner from the planet equator; zero longitude is defined as the meridian passing through the point of closest approach at time zero.

2.4.1.3 Trajectory Data

The data determined are presented in two forms. The first is a set of time-sequenced pictorial displays of each planet as seen by the spacecraft, while the second is a set of graphs on which the selected planetocentric parameters just described are plotted with true anomaly as the independent variable.

2.4.2 Selection of Orbits at Inner Planets and Jupiter

In the calculation of imaging sensor support requirements for orbital missions at the inner planets and Jupiter (Reference 1), ten orbits were considered at each inner planet and eleven at Jupiter. These orbits differ principally in eccentricity, and at Jupiter also in periapsis altitude. The longitude of ascending node and argument of periapsis were not specified.

Table 2-14. Mission Data Summary

1.	Earth-Mercury 1982	Depart	45260.0*	(October 17.5, 1982)
		Arrive	45378.0	(February 12.5, 1983)
		Trip Time 118 days		
2.	Earth-Mercury 1984	Depart	45960.0	(September 16.5, 1984)
		Arrive	46080.0	(January 14.5, 1985)
		Trip Time 120 days		
3.	Earth-Venus 1980	Depart	44330.0	(April 0.5, 1980)
		Arrive	44440.0	(July 19.5, 1980)
		Trip Time 110.0 days		
4.	Earth-Venus 1983	Depart	45480.0	(May 25.5, 1983)
		Arrive	45640.0	(November 1.5, 1983)
		Trip Time 160.0 days		
5.	1979 Earth-Venus-Mercury	Depart	44210.0	(December 2.5, 1979)
		Swingby	44466.5	(August 15, 1980)
		Arrive	44592.0	(December 18.5, 1980)
		Trip Time 256.5/125.5 = 382 days		
6.	1982 Earth-Venus-Mercury	Depart	45000.0	(January 30.5, 1982)
		Swingby	45167.7	(July 17.2, 1982)
		Arrive	45304.0	(December 0.5, 1982)
		Trip Time 167.7/136.3 = 304 days		
7.	1976 Earth-Jupiter-Saturn	Depart	42990.0	(July 30.5, 1976)
		Swingby	43725.5	(August 5.0, 1978)
		Arrive	44700.0	(April 5.5, 1981)
		Trip Time 735.5/974.5 = 1710.0 days		
8.	1977 Earth-Jupiter-Saturn	Depart	43390.0	(September 3.5, 1977)
		Swingby	44133.1	(September 16.6, 1979)
		Arrive	45000.0	(January 30.5, 1982)
		Trip Time 743.1/866.9 = 1610.0 days		
9.	Earth-Jupiter-Uranus-Neptune	Depart	43790.0	(October 8.5, 1978)
		Swingby	44452.0	(August 0.5, 1980)
		Swingby	46521.2	(March 31.7, 1986)
		Arrive	48000.0	(April 18.5, 1990)
		Trip Time 662.0/2069.2/1478.8 = 4210 days		
10.	Earth-Jupiter-Uranus-Neptune	Depart	44190.0	(November 12.5, 1979)
		Swingby	44690.7	(March 27.2, 1981)
		Swingby	46101.7	(February 5.2, 1985)
		Arrive	47200.0	(February 8.5, 1988)
		Trip Time 500.7/1411.0/1098.3 = 3010 days		
11.	Earth-Jupiter-Saturn-Pluto	Depart	43390.0	(September 3.5, 1977)
		Swingby	43837.8	(November 25.3, 1978)
		Swingby	44355.5	(April 26.0, 1980)
		Arrive	46000.0	(October 26.5, 1984)
		Trip Time 447.8/517.7/1644.5 = 2610 days		
12.	Earth-Jupiter-Saturn-Pluto	Depart	43790.0	(October 8.5, 1978)
		Swingby	44229.7	(December 22.2, 1979)
		Swingby	44652.4	(February 16.9, 1981)
		Arrive	46400.0	(December 0.5, 1985)
		Trip Time 439.7/422.7/1747.6 = 2610 days		

*Julian Date - 2400000.

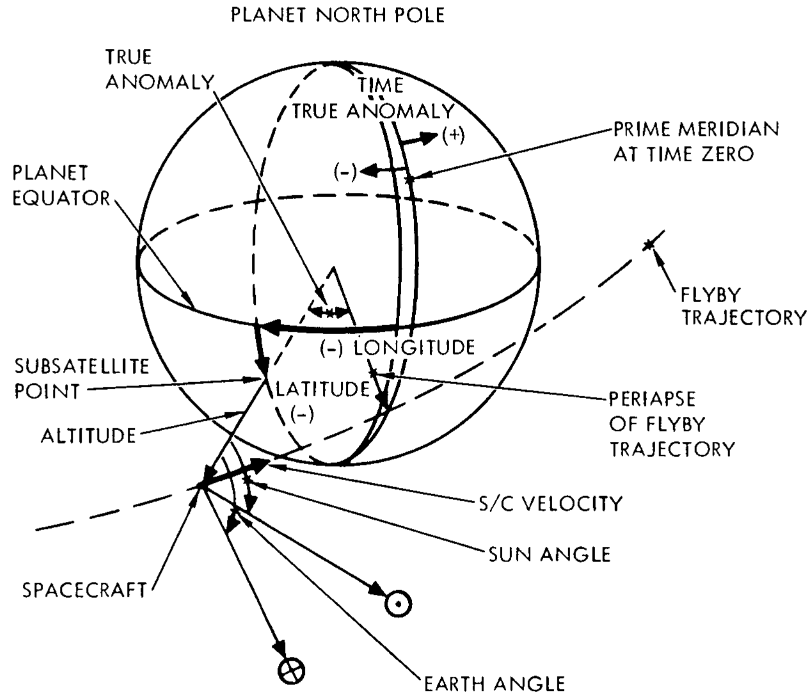

Figure 2-7. Trajectory Parameters

From this set of candidate orbits, certain orbits were selected in Reference 1 on the basis of maximum achievements of observation objectives. Table 2-15 lists the parameters of the orbits selected for evaluation of nonimaging sensor support requirements.

The orbits are assumed initially to have periapsis latitude zero and periapsis longitude (also longitude of ascending node) zero with respect to the subsolar meridian. At Jupiter, the insertion ΔV required for zero periapsis longitude is prohibitive, and a longitude of 90 degrees is assumed. The orbits are not large simple fractions (1/3, 1/2, etc.) or small multiples (2, 3, etc.) of the planetary rotation periods, so a few orbits will suffice for viewing all longitudes at favorable altitudes and Sun angles. Precession of the apsides and regression of the nodes are ignored.

2.4.3 Planetary Surface Area Coverage

2.4.3.1 Flyby Missions

A combination of several sensors, different coverage modes (i.e., optimal and marginal), numerous missions, and several target planets results in the requirement to analyze and determine planetary surface area coverage for 66 separate planetary flybys.

Stereographic Projection. A graphical aid which greatly facilitates the selection of inclination is a planet stereographic projection, which has been known for centuries

Table 2-15. Orbits Selected for Nonimaging Experiments at Inner Planets and Jupiter

Planet	Orbit (Ref. 1)	Periapsis Altitude (km)	Apoapsis Altitude (km)	Inclination (deg)
Mercury	1	500	500	90
Mercury	10	500	53,400	90
Venus	1	454	454	90
Venus	9	255	50,400	90
Mars	1	1016	1,016	90
Mars	8	383	12,525	124
Jupiter	1	1.78×10^5	4.81×10^5	90
Jupiter	9	1.78×10^5	13.47×10^5	90
Jupiter	11	3.57×10^5	6.65×10^5	90

and was used by map makers in the Middle Ages. More recent analysis (Reference 8) commended its use to solve a wide variety of three-dimensional problems and delineated the detailed steps necessary for point-by-point construction. The primary advantage of this spherical projection is that all circles, great or minor, appear as circular arcs in the projection and the projection is isogonic; that is, inclination angles of planes relative to each other are preserved. A transparent coordinate overlay permits graphical solution of all spherical geometric problems.

Since the source of light for planetary imaging analyses is the Sun, a projection about the subsolar point allows the lighting angles to be displayed as concentric circles. An example of the projection is presented in Section 3.2.

Surface Area Computation. The first step in computing surface area required is obtaining a plot of the trajectory in terms of longitude and latitude. Sensor on and off altitudes, as well as sensor field-of-view, are supplied by the sensor analyst. These altitudes are then equated to longitude by the available trajectory data. Swath width S/W represents a great-circle arc as determined by $S/W = 2\gamma \frac{h}{r}$, where r is the planet's radius and 2γ is the aperture angle. Several intermediate altitudes between the sensor on and off altitudes are selected and their corresponding swath widths determined and superimposed on a longitude-latitude plot.

Simple spherical geometry is used to compute surface area coverage. The area of a zone is given by A (zone) = $2\pi R_{\hbar}^2 \sin \delta$, where δ is zone latitude. A latitude of 90 degrees yields the surface area of a hemisphere. When the area of only a portion of the zone is desired, the following relation is used:

$$A = 2\pi R_{\hbar} \sin \delta \left[\frac{\Delta \text{longitude (degrees)}}{360^\circ}\right].$$

If there are no specific requirements to obtain surface area coverage to greater accuracy than about 5 percent, the actual sensor ground swath is approximated by zonal sections on the planet. In this case, the ground swath was first approximated as a truncated pyramid and then the equivalent zonal area specified.

2.4.3.2 Orbiter Missions

The computation of area coverage for the orbiter missions followed essentially the same procedure used for the flybys. In this case, trajectory data were supplied by an NR computer program, and the area coverage was computed automatically. At discrete time intervals (measured in minutes), swath widths (latitude distance) were determined; and the surface area was approximated as a truncated pyramid, where the longitude distance was obtained by multiplying ground speed by the time interval.

2.5 MEASUREMENT REQUIREMENTS

2.5.1 Measurement Requirement Evaluation

Observation requirements refer to intrinsic properties of the remotely sensed object or environment and are, therefore, mission-independent. Measurement requirements refer to the performance of a sensor. Some measurement requirements are independent of the mission trajectory; some may be determined from the observation requirements at certain individual trajectory points; and others depend on an extended trajectory segment.

Table 2-16 is a summary of the mission-independent measurement requirements considered in preliminary selection of candidate sensors. These requirements represent the extremes of the optimal observation. Particle and field measurement requirements, not included in Table 2-16, cover charged and neutral particle energies from 0.02 eV to 300 MeV and magnetic field strengths from 1×10^{-5} to 10 gauss.

Some measurement parameters are determinable directly from the observation parameters at any sensor location and velocity. The more common transformations are described here. The geometry of the spacecraft and field of view is illustrated in Figure 2-8. The angular resolution of the sensor,

$$\Delta\alpha = \frac{\text{projection of spatial resolution normal to viewing direction}}{\text{slant range to field of view}}$$

Table 2-16. Mission-Independent Measurement Requirements

Spectral region (nominal)	Radio	Microwave	Infrared	Visible	Ultraviolet	X-Ray, Y-Ray
Maximum wavelength (micrometer)		1.0×10^4	100	0.7	0.4	0.01
Minimum wavelength (micrometer)	1×10^4	100	0.7	0.4	0.01	
Spectral resolution (micrometer)						
Maximum (finest)	10	100	1×10^{-5}	1×10^{-5}	1×10^{-5}	5×10^{-5}
Minimum (coarsest)	10×10^5	1000	10	0.3	0.1	5×10^{-5}
Imaging required	No	Yes	Yes	Yes	No	No
Nonimaging required	Yes	Yes	Yes	Yes	Yes	Yes
Phase shift measurement	Yes	No	No	No	No	No
Polarization measurement	Yes	Yes	No	Yes	No	No
Vertical resolution required	Yes	No	Yes	No	No	No

or

$$\Delta\alpha = \frac{\Delta r \sin\xi}{R_F}$$

where the slant range,

$$R_F = (R_p - H)\cos\alpha - \left[(R_p + H)^2 \cos^2\alpha - H\,(2R_p + H)\right]^2$$

and R_p = planetary radius (oblateness is ignored), Δr = spatial resolution at surface of planet, H = spacecraft surface altitude, α = viewing direction angle to vertical at spacecraft, and ξ = viewing axis angle to tangent plane at center of viewed area. To obtain greater accuracy, α may be replaced by $(\alpha + r)$, where 2r is the field-of-view angle. The swath width (i. e., the width of the field of view parallel to the direction in which the sensor is scanned) is $Y = R_F\gamma$. The field-of-view length in the direction of scan is $X = R_F\gamma_F/\sin\xi$. The aperture half-angle is a variable design parameter of the sensor, selected during application of the scaling law.

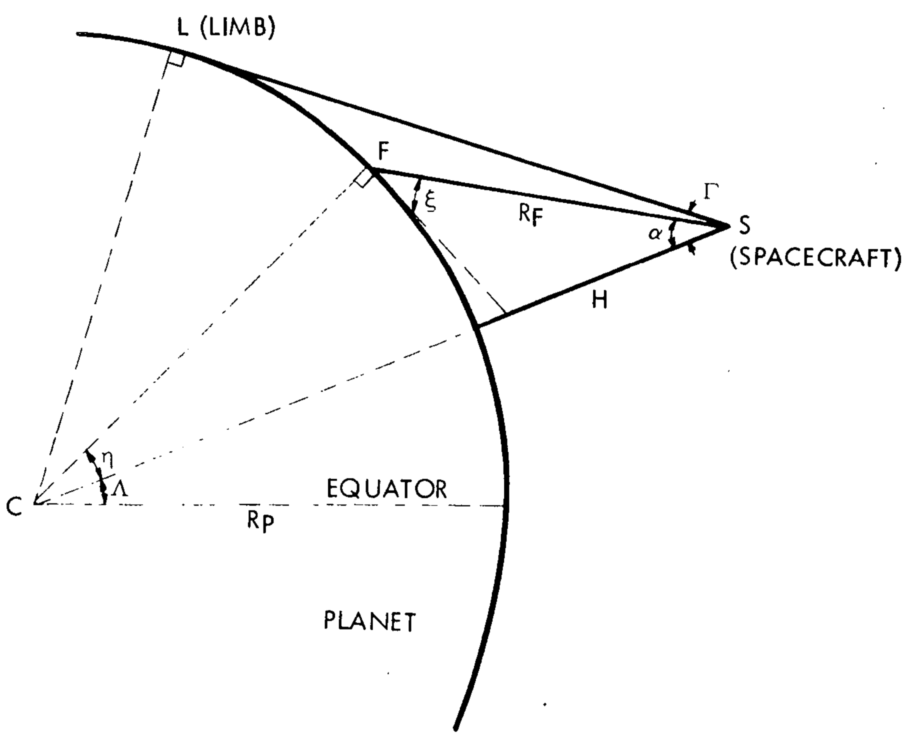

Figure 2-8. Spacecraft-Planet Geometry

2.5.2 Measurement Requirements Computer Program

The processing of information relating to observation requirements, measurement requirements, sensor measurement capabilities, and sensor support requirements is accomplished in this study by means of a Space Experiment Requirements Analysis (SERA) computer program. Since the entire SERA program requires the use of core storage exceeding that available, SERA is structured as three modules called into execution by an executive program with the use of overlay techniques. Briefly, the three modules perform the following operations:

1. Module 1 (SERA-1) stores and prints the observation requirements stated in terms of intrinsic properties of the observed planets.

2. Module 2 (SERA-2) converts the observation requirements to measurement requirements, stated in terms of intrinsic properties of generic sensor types, at selected points on a specified planetary encounter trajectory or orbit.

3. Module 3 (SERA-3) uses sensor scaling laws to design a sensor of a given type to satisfy a set of measurement requirements, subject to state-of-the-art limitations, and then calculates the sensor support requirements. A subroutine is called to apply the appropriate scaling law. Available subroutines are listed in Table 2-10.

In SERA-2, we have the option to evaluate measurement requirement parameters (MRP) based on a single set or on several sets of observation requirement parameter (ORP) values. A single set of ORP is defined as corresponding to one observation objective; however, several sets of ORP may, at least in principle, be satisfiable by a single sensor. If more than one set of ORP is chosen, the optimal value of any measurement parameter corresponds to the most stringent value of the corresponding ORP. That is, suppose a'_{i1}, $a'_{i2}, \ldots,$ a_{iJ} are the optimal values of ORP a_i corresponding to observation objectives 1, 2, ..., J; then the optimal MRP value $b'_m = f_{im}\,(a'_{ij}, p_k)$, where a'_{ij} is the most stringent of the set $(a'_{i1}, a'_{i2}, \ldots, a'_{iJ})$. f_{im} is the operator that transforms the ith ORP to the mth MRP, and p_k represents the I_J different trajectory parameters in the transformation. Attainment of $a'_i = a'_{ij}$ implies attainment of all other a'_i in the set. A similar relationship holds for the marginal MRP.

2.6 SENSOR SYSTEM SUPPORT REQUIREMENTS

To apply a scaling law, the sensor measurement requirements must be evaluated at one or more points on a trajectory. The trajectory must encounter a planet to which the observation requirements are relevant, and the planetary region to be viewed must satisfy conditions of geometric visibility and illumination. If the observation requirements include area, latitude, or longitude coverage, usually they cannot be satisfied at any one point, but only over a segment of the trajectory. The support requirements, which must be sufficient for use of the sensor throughout the entire segment, are usually established by one of the end points.

To apply some scaling laws, it is necessary to select options in the synthetic design logic or to assume fixed values of certain design or operation parameters.

For example, the viewing direction may be constrained to the nadir, or the sensor aperture angle may be fixed. Details of these procedures, and data values, are presented in connection with specific scaling laws, or as part of the support requirement evaluation (see Sections 2.3, 2.4, and 3.1 to 3.5).

2.7 SENSOR FAMILY GROUPINGS

2.7.1 Grouping Methodology

A sensor family is defined as the set of remote sensors that can perform required observations when operated on a common mission trajectory. Two levels of families corresponding to the levels of observation and measurement requirements can be defined:

1. Optimal: each sensor is designed to meet the optimal measurement requirements, subject to limitations imposed by the sensor state-of-the-art (SOA) and the trajectory.

2. Marginal: each sensor is designed to meet only the marginal measurement requirements.

Obviously, if a sensor type cannot be represented in a marginal family due to SOA limitations or mission constraints, that type will not be represented in the optimal family for that mission. Normally, no sensor in a family will be overdesigned relative to its measurement requirements, but in a few instances (e.g., particle and field sensors), the present SOA is limited to sensors overdesigned for the observations defined in Reference 2. Families are defined without reference to interference between sensors. Potential interference problems are indicated in the grouping tables. The grouping procedure depends to some extent on the kind of mission.

2.7.1.1 Single-Planet Flybys

The trajectory is adjustable to permit optimization of the worth of a sensor or a family of sensors, subject to the approach trajectory and the requirement that the planet not be impacted. The procedure adopted is to determine the trajectory that optimizes area coverage and spatial resolution by the visible-light imaging (TV) sensor. An attempt is then made to apply the scaling laws to design imaging sensors of other types to meet the remaining imaging observation requirements applicable to the planet encountered. The sensors that can be so designed, together with the TV sensor, constitute the imaging sensor family for this trajectory, even though some of the non-TV-imaging sensors are not optimized as to worth or support requirements by this trajectory (i.e., some other trajectory may exist on which one or more of the other sensors would more nearly attain the optimal observation requirements).

The nonimaging sensors are then designed for the trajectory used for the TV sensor and, if they meet at least the marginal observation requirements, form an integrated family with the TV sensor and the imaging sensors compatible with the TV.

Missions in this category for which sensor families were designed are (2) 1984 Mercury flyby and (3) 1980 Venus flyby. Only nonimaging sensors are considered. The scope of the study excluded imaging sensors on flybys of the inner planets and Jupiter.

2.7.1.2 Multiplanet Flybys

At all but the terminal planet on a multiplanet flyby trajectory, the trajectory is fixed by gravity-assisted swingby requirements. A sensor type either can meet or exceed the marginal observation requirements from this trajectory, or it cannot. Usually, one of the encounters leads to more stringent support requirements (e.g., greater mass, volume, power input, data acquisition rate, pointing accuracy) than the other encounters, to meet the given levels of observation requirements at the respective planets. The sensor designed for this encounter is usually compatible with the other encounters; i.e., it can meet at least the marginal observation requirements at all planets, and may be overdesigned so as to exceed the optimal requirements at some planets.

In the tables of compatible sensor families for multiplanet missions, the key support requirements are given for sensors designed for each encounter. The sensor belonging to the family, i.e., the one to be used at all encounters, is the one with the greatest mass and power; however, the data rate, data quantity, and sensor worth were calculated in Section 3 for a sensor designed for an individual encounter. The sensor used at all encounters (but designed for one encounter) therefore will have a different data rate, data quantity, and worth at the other encounters.

The terminal planet encounter is not constrained by gravity-assist, and is treated as a single-planet flyby. Missions in this category for which sensor families were defined are (6) 1982 Venus-Mercury, (7) 1976 Jupiter-Saturn, (9) 1978 Jupiter-Uranus-Neptune, and (12) 1978 Jupiter-Saturn-Pluto. Imaging sensor support requirements were computed only for encounters at Saturn, Uranus, and Neptune; therefore, only one imaging sensor of each type is considered for Missions (7) and (12), and none for Mission (6). In Missions (7) and (12), Saturn is the only planet at which imaging observations were within the scope of the study. Single-planet procedures are employed for imaging sensor families for Saturn in Missions (7) and (12). Observations at Pluto are outside the scope of this study, but the requirement to fly past Pluto is a constraint on the Saturn encounter in Mission (12). Analysis of sensor requirements at Jupiter in Mission (9) was omitted, because Missions (7) and (12) provide an adequate variety of Jupiter encounter conditions.

2.7.1.3 Orbiters

Imaging sensor families were defined for orbiter missions at Mercury, Venus, Mars, and Jupiter in Reference 1. In Reference 1, imaging sensor families were developed on the basis of orbital inclination as well as the periapsis altitude and eccentricity which correspond to orbit-type numbers. In our integration of imaging and nonimaging sensor families, inclination was ignored, but the non-imaging sensors designed for these orbits were based on the inclinations given in Table 2-15. It is possible to select an imaging sensor family for a single orbit size and inclination from Reference 1, and design non-imaging sensors for this inclination. However, the non-imaging sensor support requirements generally depend little on orbital inclination. Therefore, the procedure followed in this study results in nearly the same sensor designs as those based on matching of orbital inclinations. Ten orbits were considered at each inner planet, and eleven at Jupiter. In this study, two orbits were selected at each inner planet, and three at Jupiter, as defined in Table 2-15. Nonimaging sensors were designed for use in these orbits and, if they met the observation requirements, were grouped into a nonimaging sensor family for the given orbit.

2.7.2 Compatible Sensor Families

For each of the selected missions, a family of candidate remote sensor types has been established to meet the observation requirements of that mission. The sensors in each of these families are listed in the tables which follow, together with a summary of the more important support requirements. The support requirements are given for both the optimal and marginal levels of sensor capability, as discussed previously. The optimal level is indicated on the first line, and the marginal level is shown immediately below and enclosed in parentheses. These tables represent summary tabulations of data developed during the study and presented in Reference 4.

The support requirements as presented in these summary tables are derived mostly from Reference 4, including data on all nonimaging sensors and data for imaging sensors on flyby missions to the outer planets (Saturn, Uranus, and Neptune). Data for imaging sensors for orbiter missions to Mercury, Venus, Mars, and Jupiter were derived from Reference 1. The data from Reference 1 have been selected on the basis of optimal observation requirements as presented therein, and converted to metric units to provide uniformity. In a few instances, full dimensional data (length, width, and height) were not available from Reference 1 and are indicated by dashes(—) when applicable. In these tables, the numerical designations and the nomenclature are those used in References 3 and 4.

Certain types of sensors are of such nature that their operation may result in electromagnetic interference with other sensor types, thus precluding their simultaneous operation. This condition is indicated in the summary tables, with both the interfering and the affected sensors being identified in each instance.

Sensor families are developed for the missions noted below and presented in the tables as indicated:

Mission	Table
1984 Earth-Mercury	2-17
1980 Earth-Venus	2-18
1982 Earth-Venus-Mercury	2-19

*Encounter not within scope of study.

Table 2-17. Sensor Family for 1984 Earth-Mercury Mission

Sensors	Support Requirements						
	Mass (kg)	Avg Power (w)	Length (m)	Width (m)	Height (m)	Volume (m^3)	Data Rate (bit s^{-1})
4. Microwave radiometer, measuring	1920 (3.3)	75.20 (5.0)	11.31 (0.563)	25.12 (1.25)	25.12 (1.25)	7140 (0.69)	49.5 (0.054)
7. Flux-gate magnetometer	2.1 (2.1)	6.0 (6.0)	0.15 (0.15)	0.10 (0.10)	0.10 (0.10)	2.8×10^{-3} (2.8×10^{-3})	1500 (1.5)
8. Helium magnetometer	3.4 (3.4)	10.0 (10.0)	0.15 (0.15)	0.10 (0.10)	0.10 (0.10)	2.8×10^{-3} (2.8×10^{-3})	40 (40)
9. Scintillation spectrometer	0.9 (0.9)	2.0 (2.0)	0.10 (0.10)	0.12 (0.12)	0.12 (0.12)	1.2×10^{-3} (1.2×10^{-3})	100 (100)
11. Electrostatic Faraday cup analyzer	8.7 (1.5)	8.7 (1.5)	0.10 ① (0.10 ②)	0.16 ① (0.16 ②)	0.16 ① (0.16 ②)	7.8×10^{-3} (1.3×10^{-3})	420 (70)
12. Geiger-Mueller counter array	1.0 (1.0)	0.40 (0.40)	0.080 (0.080)	0.16 (0.16)	0.30 (0.30)	3.8×10^{-3} (3.8×10^{-3})	30.0 (30.0)
13. Proportional counter array	5.0 (5.0)	1.0 (1.0)	0.06 (0.06)	0.20 (0.20)	0.10 (0.10)	1.2×10^{-3} (1.2×10^{-3})	50.0 (50.0)
15. Filter radiometer	4.96 (2.00)	66.5 (25.5)	0.0127 (0.01)	0.01 (0.01)	0.01 (0.01)	1.35×10^{-3} (1.09×10^{-3})	3.40 (1.8×10^{-2})
22. Laser radar	315 (315)	331 (331)	0.25 (0.25)	54.0 (54.0)	54.0 (54.0)	2.5×10^{-3} (2.5×10^{-3})	11.67 (11.67)
26. Solid-state telescope	0.53 (0.53)	1.0 (1.0)	0.011 (0.011)	0.03 (0.03)	0.03 (0.03)	2.5×10^{-3}) (2.5×10^{-3})	100.0 (100.0)
27. Li^6I spectrometer	0.9 (0.9)	2.0 (2.0)	0.10 (0.10)	0.12 (0.12)	0.12 (0.12)	1.2×10^{-3} (1.2×10^{-3})	50.0 (50.0)
28. Curved-plate plasma spectrometer	5.5 (5.5)	7.5 (7.5)	0.13 (0.13)	0.13 (0.13)	0.15 (0.15)	2.5×10^{-3} (2.5×10^{-3})	512 (512)

① Each of 6 units.

② Each of 2 units.

Table 2-18. Sensor Family for 1980 Earth-Venus Mission

Sensors	Support Requirements						
	Mass (kg)	Avg Power (w)	Length (m)	Width (m)	Height (m)	Volume (m^3)	Data Rate (bit s^{-1})
4. Microwave radiometer, measuring	91.36	45.2	2.27	5.05	5.05	57.95	5.26
	(1.09)	(5.0)	(0.113)	(0.25)	(0.25)	(5.53×10^{-3})	(2.57×10^{-5})
15. Filter radiometer	6.58	87.0	0.363	0.242	0.242	1.5×10^{-3}	26.3
	(4.99)	(66.5)	(0.01)	(0.01)	(0.01)	(1.35×10^{-3})	(0.189)
22. Laser radar	316.2	333.3	0.25	54.0	54.0	2.5×10^{-3}	11.67
	(316.2)	(333.3)	(0.25)	(54.0)	(54.0)	(2.5×10^{-3})	(11.67)
23. Bifrequency radio occultation	1658	5.0	14.94	33.22	33.22	164.8	88
	(1658)	(5.0)	(14.94)	(33.22)	(33.22)	(164.8)	(88)

Table 2-19. Sensor Family for 1982 Earth-Venus-Mercury Mission

Sensors	Support Requirements						
	Mass (kg)	Avg Power (w)	Length (m)	Width (m)	Height (m)	Volume (m^3)	Data Rate (bit s^{-1})
4. Microwave radiometer, measuring	1930 (3.34)	75.2 (5.0)	11.3 (0.562)	25.1 (1.25)	25.1 (1.25)	7140 (0.691)	39.4 (0.44)
7. Flux-gate magnetometer	2.1 (2.1)	6.0 (6.0)	0.15 (0.15)	0.10 (0.10)	0.10 (0.10)	2.8×10^{-3} (2.8×10^{-3})	1500 (1.5)
8. Helium magnetometer	3.4 (3.4)	10.0 (10.0)	0.15 (0.15)	0.10 (0.15)	0.10 (0.10)	2.8×10^{-3} (2.8×10^{-3})	40 (40)
9. Scintillation spectrometer	0.9 (0.9)	2.0 (2.0)	0.10 (0.10)	0.12 (0.12)	0.12 (0.12)	1.2×10^{-3} (1.2×10^{-3})	100 (100)
11. Electrostatic Faraday cup analyzer	8.7 (1.5)	8.7 (1.5)	0.10 ① (0.10 ②)	0.16 ① (0.16 ②)	0.16 ① (0.16 ②)	7.8×10^{-3} (1.3×10^{-3})	420 (70)
12. Geiger-Mueller counter array	1.0 (1.0)	0.40 (0.40)	0.08 (0.08)	0.16 (0.16)	0.30 (0.30)	3.8×10^{-3} (3.8×10^{-3})	30 (30)
13. Proportional counter array	5.0 (5.0)	1.0 (1.0)	0.06 (0.06)	0.20 (0.20)	0.10 (0.10)	1.2×10^{-3}) (1.2×10^{-3})	50 (50)
15. Filter radiometer	6.68 (4.99)	87 (66.5)	0.06 (0.01)	0.03 (0.01)	0.03 (0.01)	1.53×10^{-3} (1.35×10^{-3})	97 (0.112)
22. Laser radar	316.2 (307.4)	333.3 (315)	0.25 (0.25)	54.0 (54.0)	54.0 (54.0)	0.0025 (0.0025)	11.67 (11.67)
23. Bifrequency radio occultation receiver	1658 (1658)	5.0 (5.0)	14.94 (14.94)	33.22 (33.22)	33.22 (33.22)	164.8 (164.8)	59 (59)
26. Solid-state telescope	0.53 (0.53)	1.0 (1.0)	0.011 (0.011)	0.030 (0.030)	0.030 (0.030)	2.5×10^{-3} (2.5×10^{-3})	100 (100)
27. Li^6I spectrometer	0.9 (0.9)	2.0 (2.0)	0.10 (0.10)	0.12 (0.12)	0.12 (0.12)	1.2×10^{-3} (1.2×10^{-3})	50 (50)
28. Curved-plate plasma spectrometer	5.5 (5.5)	7.5 (7.5)	0.13 (0.13)	0.13 (0.13)	0.15 (0.15)	2.5×10^{-3} (2.5×10^{-3})	512 (512)

① Each of 6 units.

② Each of 2 units.

Table 2-20. Sensor Family for 1976 Earth-Jupiter-Saturn Mission

Sensors	Support Requirements						
	Mass (kg)	Avg Power (w)	Length (m)	Width (m)	Height (m)	Volume (m^3)	Data Rate (bit s^{-1})
1. Television camera	193.5 (2.61)	57.3 (5.73)	6.54 (3.52)	1.0 (0.1)	1.0 (0.1)	6.11 (0.04)	1.07×10^7 (700)
3. Microwave radiometer, mapping (a)	116.6 (1.1)	51.5 (5.0)	2.25 (5.85×10^{-2})	5.0 (1.3×10^{-1})	5.0 (1.3×10^{-1})	56.4 (7.78×10^{-4})	122 (0.029)
4. Microwave radiometer, measuring (a)	91.3 (2.11)	45.2 (5.0)	2.27 (0.387)	5.05 (0.860)	5.05 (0.860)	57.95 (0.225)	2.9 (0.01)
5. Synthetic-aperture radar (a*)	1.82×10^4 (97.1)	7.64×10^4 (206)	0.305 (0.305)	38.7 (2.12)	103.6 (8.68)	102.5 (0.639)	2.45×10^6 (1.27×10^{-5})
7. Flux-gate magnetometer (a)	2.1 (2.1)	6.0 (6.0)	0.15 (0.15)	0.10 (0.10)	0.10 (0.10)	2.8×10^{-3} (2.8×10^{-3})	1500 (1.5)
8. Helium magnetometer (a)	3.4 (3.4)	10.0 (10.0)	0.15 (0.15)	0.10 (0.10)	0.10 (0.10)	2.8×10^{-3} (2.8×10^{-3})	40 (40)
15. Filter radiometer	5.07 (3.03)	66.5 (66.5)	0.0689 (0.0689)	0.0230 (0.0230)	0.0230 (0.0230)	1.38×10^{-3} (1.14×10^{-3})	1.22 (0.085)
16. Far IR radiometer	33.96 (3.14)	10.0 (6.0)	0.167 (0.927)	0.01 (0.01)	0.01 (0.01)	1.0 (1.0)	6.0 (0.118)
19. Michelson interferometer (b)	1260 (1260)	87 (87)	0.984 (0.984)	0.984 (0.984)	0.984 (0.984)	0.908 (0.0295)	7.66×10^3 (1.07×10^3)
21. Visible/UV spectrometer	889 (2.08)	4.2 (4.2)	4.41 (0.21)	1.0 (0.1)	1.0 (0.1)	4.05 (1.67×10^{-3})	1.19×10^5 (0.404)
22. Laser radar (b*)	100 (100)	83.3 (83.3)	0.25 (0.25)	54.0 (54.0)	54.0 (54.0)	2.5×10^{-3} (2.5×10^{-3})	11.67 (11.67)
23. Bifrequency radio occultation receiver	1658 (1658)	5.0 (5.0)	14.94 (14.94)	33.22 (33.22)	33.22 (33.22)	164.8 (164.8)	247.6 (0.137)

(a) Operational incompatibility caused by (a*).

(b) Operational incompatibility caused by (b*).

Table 2-21. Sensor Family for 1978 Earth-Jupiter-Uranus-Neptune Mission

Sensors	Support Requirements						
	Mass (kg)	Avg Power (w)	Length (m)	Width (m)	Height (m)	Volume (m^3)	Data Rate (bit s^{-1})
1. Television camera	189.0	72.3	6.55	0.963	0.963	5.7	2.9×10^8
	(2.61)	(5.73)	(3.52)	(0.1)	(0.1)	(0.04)	(700)
3. Microwave radiometer, mapping (a)	129.0	54.47	2.25	5.0	5.0	56.4	214
	(1.0)	(5.0)	(0.012)	(0.026)	(0.026)	(6.59×10^{-6})	(2.07×10^{-3})
4. Microwave radiometer, measuring (a)	132.3	49.8	2.80	6.21	6.21	107.8	3.6
	(1.735)	(5.0)	(0.315)	(0.70)	(0.70)	(0.121)	(2×10^{-3})
5. Synthetic-aperture radar (a*)	4.49×10^4	6670	0.305	105.5	96.34	301.8	6.56×10^6
	(79.5)	(27.2)	(0.305)	(7.5)	(3.07)	(0.811)	(4.45×10^{-5})
7. Flux-gate magnetometer (a)	2.1	6.0	0.15	0.10	0.10	2.8×10^{-3}	1500
	(2.1)	(6.0)	(0.15)	(0.10)	(0.10)	(2.8×10^{-3})	1.5
8. Helium magnetometer (a)	3.4	10.0	0.15	0.10	0.10	2.8×10^{-3}	40
	(3.4)	(10.0)	(0.15)	(0.10)	(0.10)	(2.8×10^{-3})	40
15. Filter radiometer	4.99	66.5	0.04	0.01	0.01	1.35×10^{-3}	0.05
	(2.95)	(66.5)	(0.04)	(0.01)	(0.01)	(1.35×10^{-3})	(4.69×10^{-3})
16. Far IR radiometer	33.96	10.0	0.166	0.01	0.01	1.0	17.65
	(3.14)	(6.0)	(0.347)	(0.01)	(0.01)	(1.0)	(0.02)
19. Michelson interferometer (b)	2130	87.0	0.516	1.03	1.03	0.614	4370
	(2130)	(87.0)	(0.516)	(1.03)	(1.03)	(0.614)	(3650)
21. Visible/UV spectrometer	820.4	4.2	2.91	1.0	1.0	2.52	1.62×10^4
	(2.12)	(4.2)	(0.20)	(0.1)	(0.1)	(1.60×10^{-3})	(0.0145)
22. Laser radar (b*)	312.11	324.7	0.25	54.0	54.0	2.5×10^{-3}	11.67
	(312.11)	(324.7)	(0.25)	(54.0)	(54.0)	(2.5×10^{-3})	(11.67)
23. Bifrequency radio occultation receiver	1658.0	5.0	14.94	33.22	33.22	164.8	228.4
	(1658.0)	(5.0)	(14.94)	(33.22)	(33.22)	(164.8)	(0.175)

(a) Operational incompatibility caused by (a*).

(b) Operational incompatibility caused by (b*).

Table 2-22. Sensor Family for 1978 Earth-Jupiter-Saturn-Pluto Mission

Sensors	Support Requirements						
	Mass (kg)	Avg Power (w)	Length (m)	Width (m)	Height (m)	Volume (m^3)	Data Rate (bit s^{-1})
1. Television camera	193.7	57.3	6.54	1.0	1.0	6.11	1.91×10^6
	(2.61)	(5.73)	(3.52)	(0.1)	(0.1)	(0.04)	(7×10^5)
3. Microwave radiometer, mapping (a)	543.2	79.6	5.63	12.5	12.5	88.2	80.6
	(3.46)	(5.0)	(0.288)	(0.64)	(0.64)	(0.093)	(0.046)
4. Microwave radiometer, measuring (a)	507.7	75.2	5.68	12.62	12.62	905.53	34
	(2.1)	(5.0)	(0.387)	(0.860)	(0.860)	(0.225)	(0.004)
5. Synthetic-aperture radar (a*)	6.8×10^4	5.75×10^5	0.305	72.61	95.36	211.19	2.2×10^6
	(2.03×10^4)	(6.26)	(0.305)	(62.4)	(72.5)	(138.0)	(1.93×10^{-4})
7. Flux-gate magnetometer (a)	2.1	6.0	0.15	0.10	0.10	2.8×10^{-3}	1500
	(2.1)	(6.0)	(0.15)	(0.10)	(0.10)	(2.8×10^{-3})	(1.5)
8. Helium magnetometer (a)	3.4	10.0	0.15	0.10	0.10	2.8×10^{-3}	40
	(3.4)	(10.0)	(0.10)	(0.10)	(0.10)	(2.8×10^{-3})	(40)
15. Filter radiometer	5.05	66.5	0.012	0.020	0.020	1.39×10^{-3}	0.0546
	(3.0)	(66.5)	(0.012)	(0.020)	(0.020)	(1.39×10^{-3})	(0.0320)
16. Far IR radiometer	34.7	10.0	0.883	0.053	0.053	1.0	6.06
	(3.14)	(6.0)	(1.23)	(0.01)	(0.01)	(1.0)	(0.071)
19. Michelson interferometer (b)	1320	87	1.00	1.00	1.00	0.96	1660
	(1320)	(87)	(1.00)	(1.00)	(1.00)	(0.96)	(866)
21. Visible/UV spectrometer	974.4	4.2	5.98	1.0	1.0	5.66	2.19×10^4
	(2.08)	(4.2)	(0.207)	(0.1)	(0.1)	(1.67×10^{-3})	(0.475)
22. Laser radar (b*)	316.2	333	0.25	54.0	54.0	2.5×10^{-3}	11.67
	(316.2)	(333)	(0.25)	(54.0)	(54.0)	(2.5×10^{-3})	(11.67)
23. Bifrequency radio occultation receiver	1658	5.0	14.94	33.22	33.22	164.8	92.75
	(1658)	(5.0)	(14.94)	(33.22)	(33.22)	(164.8)	(0.084)

(a) Operational incompatibility caused by (a*).

(b) Operational incompatibility caused by (b*).

Table 2-23. Sensor Family for 1984 Mercury Orbit No. 1

Sensors	Support Requirements: Mass (kg)	Avg Power (w)	Length (m)	Width (m)	Height (m)	Volume (m^3)	Data Rate (bit s^{-1})
1. Television system	86.3	87.0	——	——	——	0.62	5.4×10^7
2. Camera system	272.4	110.0	0.88	0.40	0.73	0.26	1.2×10^8
3. Passive microwave imaging system (a)	217.5	100.0	6.4	——	——	0.0033	2100
4. Microwave radiometer, measuring (a)	1930	75.0	11.3	25.1	25.12	7140	122
	(1.0)	(5.0)	(0.023)	(0.05)	(0.05)	(4.42×10^{-5})	(0.11)
5. Synthetic-aperture radar (a*)	290.6	3300	4.8	10.1	——	0.18	3.3×10^7
	(145.2)	(1300)	(10.1)	(1.0)	——	(0.37)	(9.6×10^5)
6. Noncoherent radar (a*)	87.2	110.0	45.7	0.21	——	0.16	3600
	(70.4)	(120.0)	(6.86)	(0.21)	——	(0.25)	760
7. Flux-gate magnetometer (a)	2.1	6.0	0.15	0.10	0.10	2.8×10^{-3}	1500
	(2.1)	(6.0)	(0.15)	(0.10)	(0.10)	(2.8×10^{-3})	(1.5)
8. Helium magnetometer (a)	3.4	10.0	0.15	0.10	0.10	2.8×10^{-3}	40
	(3.4)	(10.0)	(0.15)	(0.10)	(0.10)	(2.8×10^{-3})	(40)
9. Scintillation spectrometer	0.9	2.0	0.10	0.12	0.12	1.2×10^{-3}	100
	(0.9)	(2.0)	(0.10)	(0.12)	(0.12)	(1.2×10^{-3})	(100)
11. Electrostatic Faraday cup analyzer	8.7	8.7	0.10 1	0.16 1	0.16 1	7.8×10^{-3}	420
	(1.5)	(1.5)	(0.10 2)	(0.16 2)	(0.16 2)	(1.3×10^{-3})	(70)
12. Geiger-Mueller counter array	1.0	0.4	0.8	0.16	0.30	3.8×10^{-3}	30
	(1.0)	(0.4)	(0.8)	(0.16)	(0.30)	(3.8×10^{-3})	(30)
13. Proportional counter array	5.0	1.0	0.06	0.20	0.10	1.2×10^{-3}	50
	(5.0)	(1.0)	(0.06)	(0.20)	(0.10)	(1.2×10^{-3})	(50)
15. Filter radiometer (b)	4.82	66.5	0.01	0.01	0.01	1.35×10^{-3}	1.00
	(1.95)	(25.5)	(0.01)	(0.01)	(0.01)	(1.09×10^{-3})	(0.191)
16. IR scanning system (b)	34.96	4.0	——	——	——	0.28	1.1×10^6
	(0.91)	(4.0)	——	——	——	(0.001)	(1.1×10^4)
18. UV scanning system	23.15	1.0	——	——	——	0.077	1.3×10^6
	(1.0)	(1.0)	——	——	——	(0.0017)	(1.1×10^4)
22. Laser radar (b*)	116	44.9	0.25	54	54	2.5×10^{-3}	11.67
	(116)	(44.9)	(0.25)	(54)	(54)	(2.5×10^{-3})	(11.67)
23. Bifrequency radio occultation	1681	5.0	14.94	37.1	37.1	(165.1)	15.2
	(1681)	(5.0)	(14.94)	(37.1)	(37.1)	(165.1)	(0.015)
26. Solid-state telescope	0.53	1.0	0.011	0.030	0.030	2.5×10^{-3}	100
	(0.53)	(1.0)	(0.011)	(0.030)	(0.030)	(2.5×10^{-3})	(100)
27. Li^6I spectrometer	0.9	2.0	0.10	0.12	0.12	$1.2 \times 10^{-3})$	50
	(0.9)	(2.0)	(0.10)	(0.12)	(0.12)	(1.2×10^{-3})	(50)
28. Curved-plate plasma spectrometer	5.5	7.5	0.13	0.13	0.15	2.5×10^{-3}	512
	(5.5)	(7.5)	(0.13)	(0.13)	(0.15)	(2.3×10^{-3})	(512)

1 Each of 6 units
2 Each of 2 units

Table 2-24. Sensor Family for 1984 Mercury Orbit No. 10

Sensors	Support Requirements						
	Mass (kg)	Avg Power (w)	Length (m)	Width (m)	Height (m)	Volume (m^3)	Data Rate (bit s^{-1})
1. Television system	14.5	32.0	—	—	—	0.018	1.1×10^{6}
4. Microwave radiometer, measuring	1930	75.2	11.3	25.1	25.1	7140	1.23
	(1.01)	(5.0)	(0.405)	(0.09)	(0.09)	(2.58×10^{-4})	(4.14×10^{-5})
7. Flux-gate magnetometer	2.1	6.0	0.15	0.10	0.10	2.8×10^{-3}	1500
	(2.1)	(6.0)	(0.15)	(0.10)	(0.10)	(2.8×10^{-3})	(1.5)
8. Helium magnetometer	3.4	10.0	0.15	0.10	0.10	2.8×10^{-3}	4.0
	(3.4)	(10.0)	(0.15)	(0.10)	(0.10)	(2.8×10^{-3})	(40)
9. Scintillation spectrometer	0.9	2.0	0.10	0.12	0.12	1.2×10^{-3}	100
	(0.9)	(2.0)	(0.10)	(0.12)	(0.12)	(1.2×10^{-3})	(100)
11. Electrostatic Faraday cup analyzer	8.7	8.7	0.10 ①	0.16 ①	0.16 ①	7.8×10^{-3}	420
	(1.5)	(1.5)	(0.10 ②)	(0.16 ②)	(0.16 ②)	(1.3×10^{-3})	(70)
12. Geiger-Mueller counter array	1.0	0.40	0.80	0.16	0.30	3.8×10^{-3}	30
	(1.0)	(0.40)	(0.80)	(0.16)	(0.30)	(3.8×10^{-3})	(30)
13. Proportional counter array	5.0	1.0	0.06	0.20	0.10	1.2×10^{-3}	50
	(5.0)	(1.0)	(0.06)	(0.20)	(0.10)	(1.2×10^{-3})	(50)
15. Filter radiometer (a)	4.82	66.5	0.144	0.0128	0.0128	1.36×10^{-3}	84.5
	(1.94)	(25.5)	(0.43)	(0.01)	(0.01)	(0.01)	(2.40×10^{-3})
16. IR scanning system (a)	5.0	7.0	—	—	—	0.0014	1.2×10^{4}
	(5.0)	(7.0)	—	—	—	(0.0014)	(1.2×10^{4})
18. UV scanning system	1.04	1.0	—	—	—	0.0017	1.7×10^{5}
	(1.04)	(1.0)	—	—	—	(0.0017)	(1.7×10^{5})
22. Laser radar (a*)	314	329	0.25	54	54	2.5×10^{-3}	11.67
	(314)	(329)	(0.25)	(54)	(54)	(2.5×10^{-3})	(11.67)
26. Solid-state telescope	0.53	1.0	0.011	0.030	0.030	2.5×10^{-3}	100
	(0.53)	(1.0)	(0.011)	(0.030)	(0.030)	(2.5×10^{-3})	(100)
27. Li^6I spectrometer	0.9	2.0	0.10	0.12	0.12	1.2×10^{-3}	50
	(0.9)	(2.0)	(0.10)	(0.12)	(0.12)	(1.2×10^{-3})	(50)
28. Curved-plate plasma spectrometer	5.5	7.5	0.13	0.13	0.15	2.5×10^{-3}	512
	(5.5)	(7.5)	(0.13)	(0.13)	(0.15)	$(2.5 \times 10^{-3}$	(512)

① Each of 6 units.
② Each of 2 units.
(a) Operational incompatibility caused by (a*).
— Not available

Table 2-25. Sensor Family for 1977 Venus Orbit No. 1

Sensors	Support Requirements						
	Mass (kg)	Avg Power (w)	Length (m)	Width (m)	Height (m)	Volume (m^3)	Data Rate (bit s^{-1})
1. Television system	10.9	24.0	—	—	—	0.014	1.3×10^4
3. Passive microwave imaging system (a)	16.8	72.0	0.61	—	—	0.0049	440
4. Microwave radiometer, measuring (a)	50.8 (1.00)	75.2 (5.0)	5.68 (0.023)	12.6 (0.05)	12.6 (0.05)	905 (4.42×10^{-5})	905 (0.288)
5. Synthetic-aperture radar (a*)	309 (290)	5.4×10^6 (5900)	0.34 (39.7)	100.7 (1.0)	— —	0.54 (0.37)	7.1×10^8 (3.3×10^6)
6. Noncoherent radar (a*)	136 (86)	540 (540)	67.1 (10.1)	0.20 (0.20)	— —	0.26 (0.341)	6.3×10^4 (9500)
15. Filter radiometer (b)	4.84 (4.82)	66.5 (66.5)	0.01 (0.01)	0.01 (0.01)	0.01 (0.01)	1.35×10^{-3} (1.35×10^{-3})	138.6 (0.090)
16. IR scanning system (b)	3.18 (0.91)	3.0 (1.5)	— —	— —	— —	0.0017 (0.0011)	1.4×10^4 630
18. UV scanning system	1.0 (1.0)	1.0 (1.0)	— —	— —	— —	0.0011 (0.0011)	3.0×10^4 (3.5×10^3)
22. Laser radar (b*)	100 (100)	83.3 (83.3)	0.25 (0.25)	54 (54)	54 (54)	2.5×10^{-3} (2.5×10^{-3})	11.67 (11.67)
23. Bifrequency radio occultation	1681 (1681)	5.0 (5.0)	14.94 (14.94)	37.1 (37.1)	37.1 (37.1)	165.1 (165.1)	26.2 (0.024)

(a) Operational incompatibility caused by (a*)

(b) Operational incompatibility caused by (b*)

— Not available.

Table 2-26. Sensor Family for 1977 Venus Orbit No. 9

Sensors	Support Requirements						
	Mass (kg)	Avg Power (w)	Length (m)	Width (m)	Height (m)	Volume (m^3)	Data Rate (bit s^{-1})
1. Television system	14.5	32.0	—	—	—	0.018	$7.2x10^5$
4. Microwave radiometer, measuring	507 (1.0)	75.2 (5.0)	5.68 (0.033)	12.6 (0.074)	12.6 (0.074)	905 ($1.43x10^{-4}$)	3.22 ($2.63x10^{-4}$)
15. Filter radiometer (a)	6.04 (4.84)	66.5 (66.5)	0.11 ($8.0x10^{-3}$)	0.063 (0.01)	0.063 (0.01)	$1.69x10^{-3}$ ($1.35x10^{-3}$)	754 ($3.67x10^{-3}$)
16. IR scanning system (a)	1.68 (1.0)	2.10 (4.0)	— —	— —	— —	0.0011 (0.0011)	8200 (8200)
18. UV scanning system	1.36 (1.36)	1.0 (1.0)	— —	— —	— —	0.0017 (0.0017)	$7.6x10^5$ ($7.6x10^5$)
22. Laser radar (a*)	100 (100)	83.3 (83.3)	0.25 (0.25)	54 (54)	54 (54)	$2.5x10^{-3}$ ($2.5x10^{-3}$)	11.67 (11.67)
23. Bifrequency radio occultation	1681 (1681)	5.0 (5.0)	14.94 (14.94)	37.1 (37.1)	37.1 (37.1)	165.1 (165.1)	69 (0.023)

(a) Operational incompatibility caused by (a*).
— Not available.

Table 2-27. Sensor Family for 1984 Mars Orbit No. 1

Sensors	Support Requirements						
	Mass (kg)	Avg Power (w)	Length (m)	Width (m)	Height (m)	Volume (m^3)	Data Rate (bit s^{-1})
1. Television system	14.5	32.0	—	—	—	0.018	3.8×10^5
2. Camera system	11.35	36.0	0.30	0.18	0.30	0.016	6.9×10^5
3. Passive microwave imaging system (a)	547	110	10.1	—	—	0.0033	1400
4. Microwave radiometer, measuring (a)	508	75	5.68	12.6	12.6	905	89
	(1.00)	(5)	(0.0225)	(0.05)	(0.05)	(4.42×10^{-5})	(0.06)
6. Noncoherent radar (a*)	172.5	140	58	0.37	—	0.258	2.2×10^4
9. Scintillation spectrometer	0.9	2.0	0.10	0.12	0.12	1.2×10^{-3}	100
	(0.9)	(2.0)	(0.10)	(0.12)	(0.12)	(1.2×10^{-3})	(100)
15. Filter radiometer (b)	4.84	66.5	0.01	0.01	0.01	1.35×10^{-3}	3.59
	(4.82)	(66.5)	(0.01)	(0.01)	(0.01)	(1.35×10^{-3})	(0.0224)
16. IR scanning system (b)	2.6	1.5	—	—	—	0.0057	3520
	(1.0)	(1.5)	—	—	—	(0.0011)	(300)
18. UV scanning system	1.0	1.0	—	—	—	0.0011	430
	(1.0)	(1.0)	—	—	—	(0.0011)	(2200)
22. Laser radar (b*)	98	32	0.25	54	54	2.5×10^{-3}	11.67
	(98)	(32)	(0.25)	(54)	(54)	(2.5×10^{-3})	(11.67)
23. Bifrequency radio occultation	1681	5.0	14.94	37.1	37.1	165.1	20.1
	(1681)	(5.0)	(14.94)	(37.1)	(37.1)	(165.1)	(0.02)

(a) Operational incompatibility caused by (a*).
(b) Operational incompatibility caused by (b*).
—Not available.

Table 2-28. Sensor Family for 1984 Mars Orbit No. 8

Sensors	Support Requirements						
	Mass (kg)	Avg Power (w)	Length (m)	Width (m)	Height (m)	Volume (m^3)	Data Rate (bit s^{-1})
1. Television system	163.4	47.0	—	—	—	1.87	2.4×10^8
2. Camera system	263.3	280.0	1.5	0.3	1.2	0.71	1.2×10^9
4. Microwave radiometer, measuring	507.7 (1.02)	75.2 (5.0)	5.68 (0.0567)	12.6 (0.126)	12.6 (0.126)	905.5 (0.001)	16.5 (3.3×10^{-3})
9. Scintillation spectrometer	0.9 (0.9)	2.0 (2.0)	0.10 (0.10)	0.12 (0.12)	0.12 (0.12)	1.2×10^{-3} (1.2×10^{-3})	100 (100)
15. Filter radiometer (a)	4.84 (4.82)	66.5 (66.5)	0.028 (0.01)	0.012 (0.01)	0.12 (0.01)	1.35×10^{-3} (1×10^{-6})	28.6 (2.65×10^{-3})
22. Laser radar (a*)	243.7 (243.7)	197.9 (197.9)	0.25 (0.25)	54 (54)	54 (54)	2.5×10^{-3} (2.5×10^{-3})	11.67 (11.67)

(a) Operational incompatibility caused by (a*).

— Not available.

Table 2-29. Sensor Family for 1978 Jupiter Orbit No. 1

Sensors	Support Requirements						
	Mass (kg)	Avg Power (w)	Length (m)	Width (m)	Height (m)	Volume (m^3)	Data Rate (bit s^{-1})
1. Television system	127.1	32.0	—	—	—	1.62	3.8×10^5
4. Microwave radiometer, measuring	507.7 (1.71)	75.2 (5.0)	5.68 (0.310)	12.6 (0.688)	12.6 (0.688)	905.5 (0.115)	3.49 (8.79×10^{-4})
7. Flux-gate magnetometer	2.1 (2.1)	6.0 (6.0)	0.15 (0.15)	0.10 (0.10)	0.10 (0.10)	2.8×10^{-3} (2.8×10^{-3})	1500 1.5
8. Helium magnetometer	3.4 (3.4)	10.0 (10.0)	0.15 (0.15)	0.10 (0.10)	0.10 (0.10)	2.8×10^{-3} (2.8×10^{-3})	40.0 (40.0)
15. Filter radiometer	— (5.04)	— (66.5)	— (0.035)	— (0.031)	— (0.031)	— (1.38×10^{-3})	— (0.0491)
19. Michelson interferometer	1960 —	66.5 —	0.498 —	0.996 —	0.996 —	0.553 —	4360 —
21. Visible/UV spectrometer	166.9 (2.12)	4.2 (4.2)	5.3 (0.2)	0.5 (0.1)	0.5 (0.1)	1.3 (1.6×10^{-3})	1.76×10^4 0.12

— Not available.

Table 2-30. Sensor Family for 1978 Jupiter Orbit No. 9

Sensors	Support Requirements						
	Mass (kg)	Avg Power (w)	Length (m)	Width (m)	Height (m)	Volume (m^3)	Data Rate (bit s^{-1})
1. Television system	20.4	32.0	—	—	—	0.034	3.8×10^5
4. Microwave radiometer, measuring	507.7	75.2	5.68	12.6	12.6	905.5	0.899
	(6.53)	(5.0)	(0.864)	(1.92)	(1.92)	(2.50)	(1.48×10^{-4})
7. Flux-gate magnetometer	2.1	6.0	0.15	0.10	0.10	2.8×10^{-3}	1500
	(2.1)	(6.0)	(0.15)	(0.10)	(0.10)	(2.8×10^{-3})	(1.5)
8. Helium magnetometer	3.4	10.0	0.15	0.10	0.10	2.8×10^{-3}	40.0
	(3.4)	(10.0)	(0.15)	(0.10)	(0.10)	(2.8×10^{-3})	(40.0)
15. Filter radiometer (marginal only; see No. 19)	—	—	—	—	—	—	—
	(24.0)	(66.5)	(0.01)	(0.167)	(0.167)	(3.55×10^{-3})	(0.0137)
16. IR scanning system	726.4	28.0	—	—	—	2.16	1.2×10^6
	(726.4)	(28.0)	—	—	—	(2.16)	(1.2×10^6)
19. Michelson interferometer (optimal only; see No. 15)	2070	66.5	0.509	1.02	1.02	0.592	4450
	—	—	—	—	—	—	—
21. Visible/UV spectrometer	1215	4.2	10.3	1.0	1.0	10.0	1.6×10^4
	(1.96)	(4.2)	(0.24)	(0.1)	(0.1)	(0.002)	(0.013)

—Not available.

Table 2-31. Sensor Family for 1978 Jupiter Orbit No. 11

Sensors	Support Requirements						
	Mass (kg)	Avg Power (w)	Length (m)	Width (m)	Height (m)	Volume (m^3)	Data Rate (bit s^{-1})
1. Television system	18.2	32.0	—	—	—	0.027	3.8×10^5
4. Microwave radiometer, measuring	507.7	75.2	5.68	12.6	12.6	905.5	3.19
	(2.36)	(5.0)	(0.428)	(0.952)	(0.952)	(0.305)	(6.24×10^{-4})
7. Flux-gate magnetometer	2.1	6.0	0.15	0.10	0.10	2.8×10^{-3}	1500
	(2.1)	(6.0)	(0.15)	(0.10)	(0.10)	(2.8×10^{-3})	(1.5)
8. Helium magnetometer	3.4	10.0	0.15	0.10	0.10	2.8×10^{-3})	40.0
	(3.4)	(10.0)	(0.15)	(0.10)	(0.10)	(2.8×10^{-3})	(40.0)
15. Filter radiometer (marginal only; see No. 19)	—	—	—	—	—	—	—
	(4.99)	(66.5)	(0.049)	(0.028)	(0.028)	(1.38×10^{-3})	(0.0303)
19. Michelson interferometer (optimal only; see No. 15)	1990	66.5	0.501	1.00	1.00	0.565	1390
	—	—	—	—	—	—	—
21. Visible/UV spectrometer	193	4.2	7.2	0.5	0.5	1.77	9650
	(2.12)	(4.2)	(0.2)	(0.1)	(0.1)	(0.0016)	(0.062)

—Not available.

3.0 APPLICATION EXAMPLE

3.1 TYPICAL EXAMPLE

3.1.1 Definition

To illustrate the application of a scaling law to derive sensor support requirements to satisfy given observation requirements, the example of a visible-ultraviolet spectrometer at the Saturn encounter on the 1976 Earth-Jupiter-Saturn flyby mission has been selected. The optimal level of observation requirements is considered. This example deals with a nonimaging sensor on an outer-planet flyby mission, and differs most from the imaging sensors on inner-planet and Jupiter orbiter missions described in Reference 1. The encounter chosen is not constrained by gravity-assistance requirements and offers opportunity to use the stereographic projection technique.

3.1.2 Scientific Objectives

The scientific objectives of planetary exploration were described in Section 2.2, and were expanded there to a list of knowledge requirements. Of these requirements, the one leading to a need to observe visible and ultraviolet spectra (Observable Property Number 20) at Saturn is Number 4, "What are the physical and chemical properties of planetary atmospheres versus altitude on global and local bases?" Two observation objectives follow from this knowledge requirement:

12. Atomic, molecular, ionic, isotopic composition of atmosphere.

18. Nonthermal electromagnetic emission characteristics and source location (related here to polar aurorae and synchrotron radiation associated with trapped electrons mirroring above auroral zones).

Ultraviolet spectroscopy at medium resolution (about 1 cm^{-1}) in the spectral range 0.1 to 0.3 μm, is used (1) to extend the absorption-reflection spectrum of the disk; (2) to search for characteristic fluorescence of the upper atmosphere on the dark side; (3) to observe the resonance lines of helium (58.4 nm), hydrogen (121.6 nm), and other light elements; and (4) search for lowest-order resonance lines of ions such as N_2^+ (311.4 nm). Since many other molecules and radicals might be optically active, a complete exploratory program, rather than a selective search at a few wavelengths, appears advisable.

Spectroscopic studies of planetary atmospheres in the visible region of the spectrum are primarily studies of the intensity, polarization, and strength and shape of absorption spectral bands of the reflected solar energy. They pertain mostly to the upper atmosphere in the region near the top of any reflecting cloud layer that may be present. From studies of relative intensity distribution of absorption spectral bands, the temperature of the atmosphere where these bands are formed may be estimated. Studies of the polarization of the reflected solar energy can potentially yield information regarding the properties of the particulate matter of the clouds.

It is generally quite difficult, however, to extract the physical properties of a planetary atmosphere from the observed spectra; and the results obtainable depend almost entirely upon the particular theory of line formation adopted to interpret the spectra. In particular, if the atmosphere is optically opaque and the lines are formed at large optical depths through multiple scattering, the problem can be enormously complicated and can often lead to unreliable results with large uncertainties.

3.1.3 Observation Requirements

Tabulations of observation objectives and requirements for visible and ultraviolet spectroscopy at Saturn are presented in Table 3-1.

3.2 MISSION TRAJECTORY ANALYSIS

3.2.1 Flyby Trajectory Selection

Saturn is the terminal planet in the mission sequence; consequently, there is a free choice of closest approach distance (periapsis) and flyby inclination (with respect to Saturn's equator). The choice of periapsis distance is constrained to avoid Saturn's rings, which are contained in the equatorial plane and extend out to an altitude of approximately 1.5 planet radii.

The selection of flyby inclination requires, in general, a compromise between the conflicting demands of the various types of sensors. For this particular planetary cencounter, the TV sensor had greatest influence on the selection of inclination; consequently, the inclination was selected to satisfy the TV requirements. The TV required that sufficient time be available to scan both north and south latitudes (avoidance of ring masking) prior to crossing the terminator from light to dark.

The planetary display pictures, stereographic projection, and ground swath plot are shown in Figures 3-1, 3-2, and 3-3, respectively. A 12.4-degree inclined orbit was selected to satisfy the requirement for both north- and south-latitude viewing on planet approach.

With the inclination fixed, trajectory data were generated for a flyby with a periapsis surface altitude of 1.0 Saturn radii. The combination of selected values of periapsis altitude and flyby inclination results in a nodal (equatorial) altitude of 4.05 and 3.39 Saturn radii on approach and departure, respectively—well outside Saturn's rings.

Table 3-1. Summary of ORDS Requirements for Visible and UV Spectroscopy Saturn

Objective/Observable	λ'_M (μm)	λ''_M (μm)	λ'_m (μm)	λ''_m (μm)	$\Delta\lambda'$ (μm)	$\Delta\lambda''$ (μm)	Λ'_N (deg)	Λ''_N (deg)	Λ'_S (deg)	Λ''_S (deg)	S' (%)	S'' (%)	$\Delta X'$ (m)	$\Delta X''$ (m)
Trace substances in atmosphere and clouds/IR-visible-UV spectra*	20.0	14.0	0.1	0.2	10^{-3}	10^{-2}	90	45	90	45	-	-	$5x10^{5}$	10^{7}
Atmospheric properties above poles/optical photon spectrum from solar aurorae	1.0	0.1	0.1	1.0	10^{-3}	10^{-1}	90	60	90	60	-	-	-	-
Ionosphere total density profile/auroral and airglow emission spectra	1.0	0.7	0.12	0.4	10^{-4}	10^{-3}	90	80	90	80	-	-	10^{6}	10^{7}
Methane abundance/methane absorption spectra	0.8	0.7	0.5	0.6	10^{-4}	$2x10^{-3}$	90	0	90	0	100	0	10^{5}	10^{7}
H/D ratio/HD and H_2 absorption spectra	0.8	0.5	0.08	0.12	10^{-5}	10^{-4}	-	-	-	-	-	-	-	-
Same as C-98	0.8	0.5	0.09	0.12	10^{-5}	10^{-4}	-	-	-	-	-	-	10^{5}	10^{7}
Trace constituents of purines and pyromidines/UV absorption spectra	0.3	0.25	0.15	0.02	$2.5x10^{-3}$	$2x10^{-2}$	-	-	-	-	-	-	10^{6}	10^{8}
Physical properties for engineering model atmospheres/UV absorption and emission spectra	0.3	0.13	0.03	0.057	$5x10^{-6}$	10^{-4}	90	45	90	45	100	1	$5x10^{6}$	$2x10^{7}$

*Multi-band requirement: visible/UV band requirements are met in all instances if most stringent requirements are met.

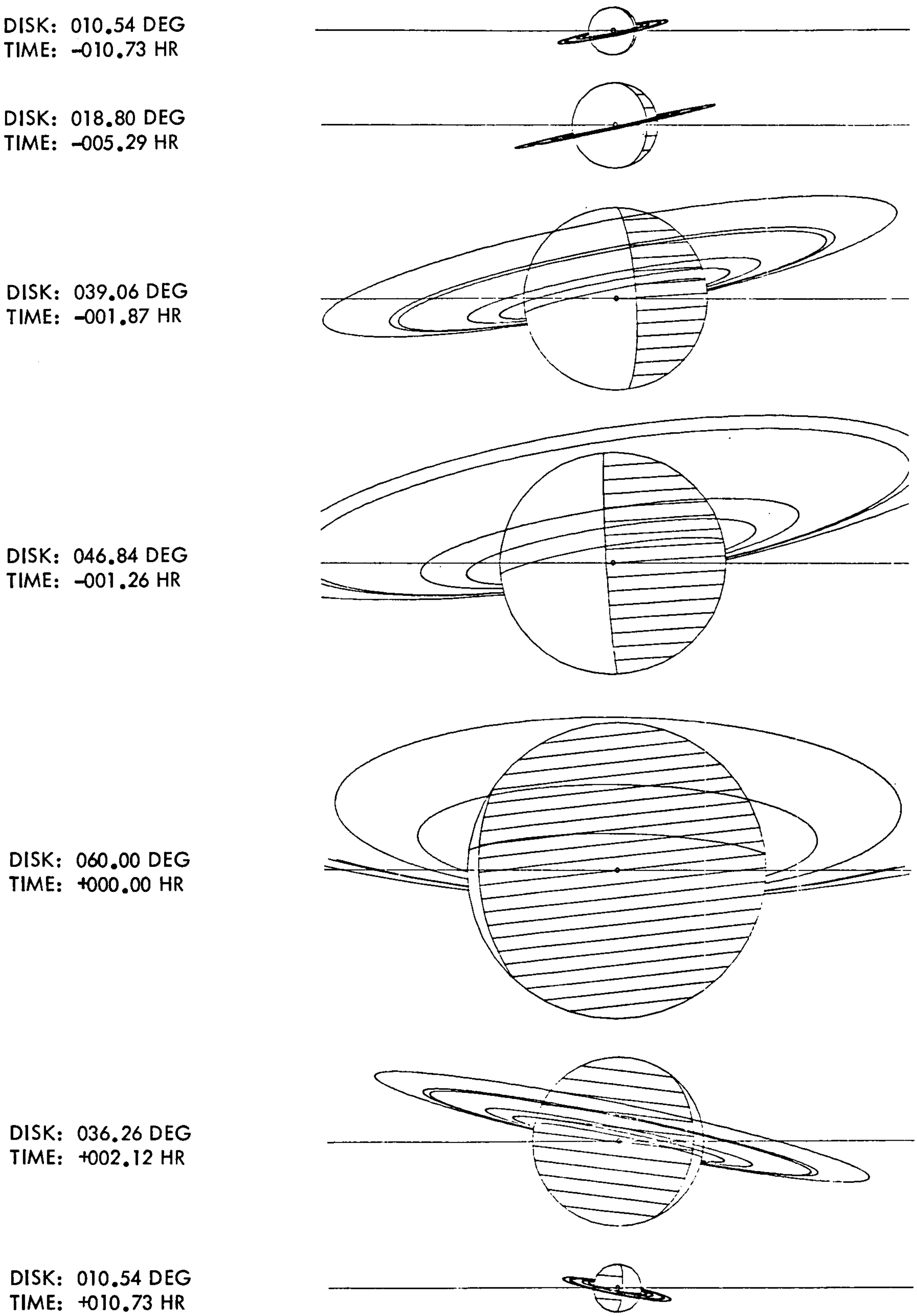

Figure 3-1. Computer-Generated Time-Sequenced Display of Planet

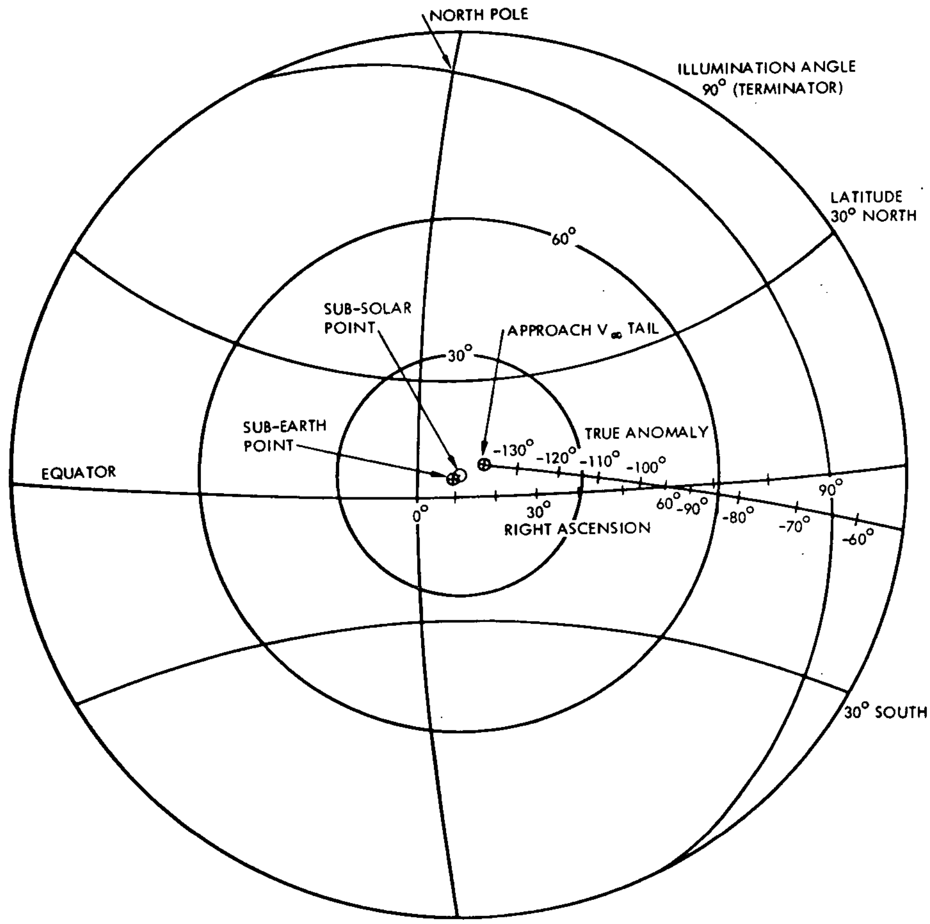

Figure 3-2. Saturn Stereographic Projection

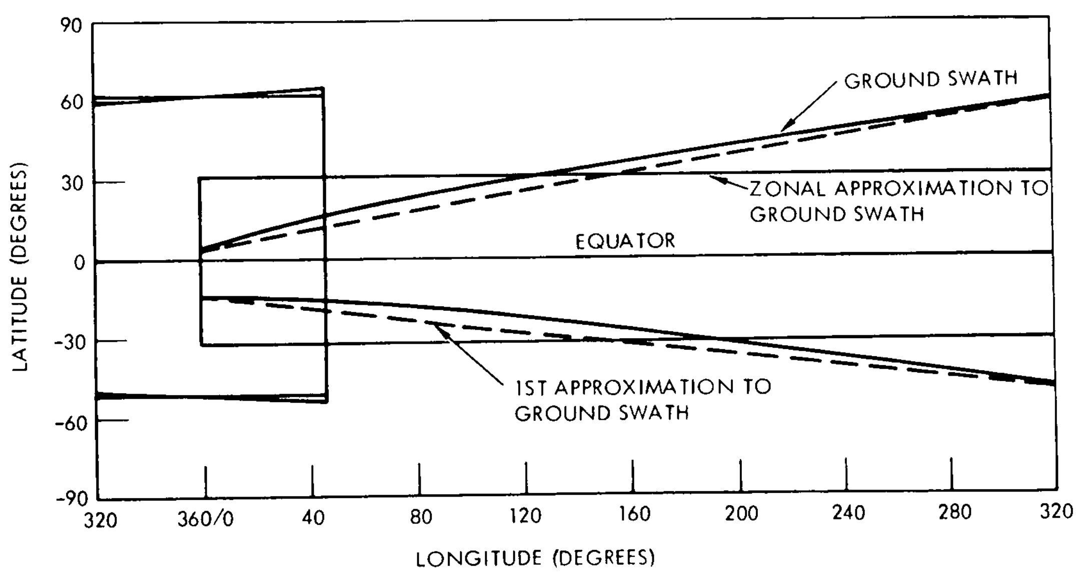

Figure 3-3. Visible/UV Spectrometer Optical Surface Coverage, Saturn Encounter

3.2.2 Trajectory Segment Definition

Sensor scanning is necessary to attain latitude coverage requirements for the low-inclination trajectories involved. Because Jupiter latitudes are relatively more inaccessible than those at Saturn for this mission (lower inclination trajectory and larger planetary radius), the scanning requirements will be initially developed from analysis at Jupiter.

For approximately 2π longitude coverage at Jupiter, sensor usage should be initiated at an altitude (H_M) of the order of 8×10^5 km. For $\Delta\phi = \Delta\phi^*$, the optimal spatial resolution cannot be met at this altitude. Full planetary surface coverage cannot be met unless an extremely large scan angle is used (to allow full latitude coverage at minimum altitude) or if H_M is increased. Further trades between spatial resolution and area coverage capability are not considered, and the above H_M used. It should be noted that the maximum-sized collecting optics system must be used, or else spatial resolution must be further degraded.

The limb-viewing angle at H_M is of the order of 4.68 degrees. To avoid computer program complications associated with calculations performed for near-limb viewing, the total scan angle of 4.45 degrees, corresponding to a ground size viewed of 2.4 R_p (corresponding to a latitude coverage of about 68 degrees in either direction from the nadir), was used. It should be noted that, in actual practice, the approximate 5-percent increase in ϕ required for limb viewing would result in relatively minimal additional subsystem support requirement penalties.

The sensor designed for the Jupiter encounter can now be analyzed at Saturn. If roughly the same initiation altitude is used (the nearest mission point available), the coarsest nadir resolution will be similar to that attained at Jupiter, and the full planet disk can be viewed at H_M. The following results are obtained:

H_M - initiation altitude - 8.06×10^5 km

H_m - cut-off altitude - 1.20×10^5 km

$\Delta\phi = 2.93 \times 10^{-4}$ rad = 0.0168 deg

ΔX - coarsest nadir resolution + $H\Delta\phi = 2.34 \times 10^5$ m

ΔX^* - coarsest resolution at far edge of swath = 5.64×10^5 m

where

$$\Delta X^* = \Delta X\,(r\phi/r_o);\; r\phi/r_o = \frac{R_p}{H_M}\left\{\frac{\cos\phi'}{\left[\left(\frac{R_p}{R_p+H}\right)^2 - \sin^2\phi'\right]^{1/2}} - 1\right\}$$

R_P - planetary radius in units of H_M

$\phi*$ - scan half-angle corresponding to 0.9 limb-viewing half-angle

Maximum latitude coverage in both northern and southern hemispheres is attained at H_M for this encounter. The values represented by the computer output were obtained by using the spacecraft latitude at H_M together with the latitude coverage band which corresponds to a fixed ground size viewed. For this and most other encounters analyzed, viewing at least to within a few degrees of either pole is accomplished.

Latitude coverage and spatial resolution capability associated with the sensor designed is well within both the solar illumination and auroral observation requirements. The optimal-level wavelength coverage and spectral resolution requirements can be met or exceeded. Thus, the sensor designed for observation of reflected solar emissions can also be used satisfactorily for the study of auroral spectra. The points at which the spectrometer is turned on and then off are described in Table 3-2. The planetary area coverage is summarized in Table 3-3.

Table 3-2. Trajectory Segment for Sensor Operation

	Altitude (h, Saturn radii)	True Anomaly (degrees)	Time (hours)	Longitude (degrees)	Latitude (degrees)	Swath Width (degrees)
Sensor On	13.35	-120	14.95	46.4	5.6	118.815
Sensor Off	1.99	-65	-1.87	0.2	-5.8	17.711

Table 3-3. Planetary Surface Area Coverage

Sensor	Measuring Constraints	Coverage Mode	Sensor FOV (deg)	Mission	Planet	Altitude (Planet Radii)		Area Coverage (Percent of Planet)
						Sensor On	Sensor Off	
Visible/ UV Spectrometer	From maximum altitude to minimum altitude on approach only.	Optimal	8.90	1976 J-S	Saturn	13.35	1.99	67.1
		Marginal	10.80	1976 J-S	Saturn	17.70	*	50.0
*Single-frame coverage of required area								

3.3 MEASUREMENT REQUIREMENTS

The trajectory-independent observation requirements were transformed to trajectory-dependent sensor measurement requirements by means of the SERA program, using the techniques described in Section 2. 5. The observation worth values were also transformed to values of the worth of performing the corresponding measurements, where trajectory constraints prevent full attainment of the optimal observation requirements. Sensor constraints are introduced later. Sample results of the transformations are given in Table 3-4.

3.4 SENSOR IDENTIFICATION

Confinement of the range of sensor designs is provided through application of the following sensor and sensor subsystem limitation formulae:

(I) $D_c = \dfrac{3 \times 10^{-12}\,(S/N)}{\Delta\phi} \; \dfrac{\omega}{Q_e(C_p f)\Delta\phi}^{1/2} \geq D_d$ and $D_c \leq D_c^*$

(collecting optics diameter -m)

(II) $D_d = 1.22\ \sqrt{2}\lambda_M{}'/\Delta\phi$

(collecting optics diffraction-limited diameter -m)

(III) $\tau = \Delta\phi/2\omega \leq \tau_{pm}^*$ (detector response time requirement - sec)

(IV) $f\# = F/D_c \geq f_L^{\#}$ (aperture stop number)

(V) $D_g = (\lambda'_M/\Delta\lambda')\Psi N_g \leq D_g^+$ (grating diameter -m)

(VI) $\omega = 2\pi\,\nu_h/(pmH\Delta\phi) \leq \omega^+ = 193/D_s$

(mirror rotation rate - rad/sec)

where

$\Delta\phi$ - scanning beam angular size (radian)

(S/N) - signal-to-noise ratio

Q_e - quantum efficiency of photomultiplier detector cathode

C_p - available spectral radiance in the bandwidth of interest (watt/m)

f - photometric function (= cos i where i is either solar zenith angle or auroral source - planet - spacecraft angle)

Table 3-4. Measurement Requirements Tabulation (Example)

```
                                                                                                    PAGE   20

                        *** MISSION MEASUREMENT REQUIREMENTS BY TECHNIQUE AND OBJECTIVE ***

MISSION  7. EARTH-JUPITER-SATURN FLYBY, LAUNCH 7/30/76.                     PLANET  6.  SATURN(INCL. RINGS)CASE  1

OBSERVATION TECHNIQUE 15. ULTRAVIOLET SPECTROMETRY
OBS. OBJECTIVE 12. ATOMIC, MOLECULAR, ISOTOPIC COMPOSITION OF ATMOSPHERE.
OBS. WORTH     0.50  SD 70-24 PAGE 0092

FIXED MISSION AND EXPERIMENT PARAMETERS
    1  PERIAPSIS ALTITUDE (KM)                                              6.0370E 04
    2  INCLINATION (DEGREE)                                                 1.2400E 01

SPECIAL CHARACTERISTICS OF SELECTED TRAJECTORY POINTS
 POINT 1- MAXIMUM ALTITUDE FOR SENSOR USAGE
 POINT 2- MINIMUM ALTITUDE FOR SENSOR USAGE


                                                                                                    PAGE   20
                                                                                   CASE   1
                           ** REQUIREMENTS AT SELECTED MISSION POINTS **
                                 PT. 1                     PT. 2                 PT. 3                PT. 4
  TIME TO PERIAPSIS (SEC)      5.3500E 04               6.7400E 03
  TRUE ANOMALY (DEG)          -1.2000E 02              -6.5000E 01
  SURFACE ALTITUDE (KM)        8.0600E 05               1.2020E 05
  LATITUDE (DEGREE)            5.5500E 00              -5.8300E 00
  LONGITUDE (DEGREE)           4.6410E 01               1.7000E-01
  GROUND SPEED (KM/SEC)        9.9900E 00               4.4400E 00
  SPACECRAFT VELOCITY(KM/SEC)  1.4000E 01               2.2990E 01
  RADIUS RATE (KM/SEC)        -1.3480E 01              -1.4110E 01
  NADIR ANGLE RATE (DEG/HOUR)  2.5600E 00               7.6200E 00
  SUN-PLANET-S/C ANGLE (DEG)   2.3400E 01               7.6100E 01
  EARTH-PLANET-S/C ANGLE(DEG)  2.4100E 01               7.6700E 01
  SOLAR ZENITH ANGLE (DEG)     2.3400E 01               7.6100E 01

MEASUREMENT REQUIREMENT  1   MAXIMUM WAVELENGTH (MICRON)
OPTIMAL/MARGINAL VALUES    1.0000E 00/  1.0000E-01    1.0000E 00/  1.0000E-01    0.0        /  0.0          0.0        /  0.0
OPTIMAL WORTH/WORTH FORM   0.06/ 11                   0.06/ 11                   0.0 /  0                0.0 /  0

MEASUREMENT REQUIREMENT  2   MINIMUM WAVELENGTH (MICRON)
OPTIMAL/MARGINAL VALUES    1.0000E-01/  1.0000E 00    1.0000E-01/  1.0000E 00    0.0        /  0.0          0.0        /  0.0
OPTIMAL WORTH/WORTH FORM   0.06/ 11                   0.06/ 11                   0.0 /  0                0.0 /  0

MEASUREMENT REQUIREMENT  3   SPECTRAL RESOLUTION (MICRON)
OPTIMAL/MARGINAL VALUES    1.0000E-03/  1.0000E-01    1.0000E-03/  1.0000E-01    0.0        /  0.0          0.0        /  0.0
OPTIMAL WORTH/WORTH FORM   0.10/ 11                   0.10/ 11                   0.0 /  0                0.0 /  0

MEASUREMENT REQUIREMENT 19   NUMBER OF SAMPLES OR MEASUREMENTS
OPTIMAL/MARGINAL VALUES    1.0000E 02/  1.0000E 00    1.0000E 02/  1.0000E 00    0.0        /  0.0          0.0        /  0.0
OPTIMAL WORTH/WORTH FORM   0.03/ 11                   0.03/ 11                   0.0 /  0                0.0 /  0

MEASUREMENT REQUIREMENT 12   VIEWING AXIS ANGLE TO THE VERTICAL, AT THE SPACECRAFT (DEGREE)
OPTIMAL/MARGINAL VALUES    0.0        /  0.0          0.0        /  0.0          0.0        /  0.0          0.0        /  0.0
OPTIMAL WORTH/WORTH FORM   1.00/  6                   1.00/  6                   0.0 /  0                0.0 /  0

MEASUREMENT REQUIREMENT 13   VIEWING AXIS ANGLE TO THE SURFACE TANGENT PLANE, AT SPACECRAFT (DEGREE)
OPTIMAL/MARGINAL VALUES    9.0000E 01/  9.0000E 01    9.0000E 01/  9.0000E 01    0.0        /  0.0          0.0        /  0.0
OPTIMAL WORTH/WORTH FORM   1.00/  6                   1.00/  6                   0.0 /  0                0.0 /  0


                                                                                                    PAGE   21
                                                                                   CASE   1
                           ** REQUIREMENTS AT SELECTED MISSION POINTS **
                                 PT. 1                     PT. 2                 PT. 3                PT. 4

MEASUREMENT REQUIREMENT 33   NORTHERNMOST LATITUDE OF AREA TO BE COVERED (DEGREES)
OPTIMAL/MARGINAL VALUES    9.0000E 01/  6.0000E 01    9.0000E 01/  6.0000E 01    0.0        /  0.0          0.0        /  0.0
OPTIMAL WORTH/WORTH FORM   0.10/  1                   0.10/  1                   0.0 /  0                0.0 /  0

MEASUREMENT REQUIREMENT 34   SOUTHERNMOST LATITUDE OF AREA TO BE COVERED (DEGREES)
OPTIMAL/MARGINAL VALUES   -6.0000E 01/ -9.0000E 01   -6.0000E 01/ -9.0000E 01    0.0        /  0.0          0.0        /  0.0
OPTIMAL WORTH/WORTH FORM   0.10/  1                   0.10/  1                   0.0 /  0                0.0 /  0

----------
TOTAL OPTIMAL WORTH,       1.0800E-07                 1.0800E-07
```

Table 3-5. Visible/UV Spectrometer Design Constraints and Limitations

Characteristic	SOA Limit	Design Limit
Collecting optics diameter	2.0 m	1.0 m
Number of mirror faces	10	1
Number of detectors	10	2
Photoconductor detector:		
1. waveband response range	0.01μm - 0.1μm	(not used)
2. lower limit response time	10^{-3} sec	(not used)
3. peak detectivity	4.0×10^{9} m-Hz$^{1/2}$/watt	(not used)
Photomultiplier detector:		
1. waveband response range	0.1 - 1.2μm*	0.1 - 1.2μm*
2. lower limit response time	10^{-6} sec	10^{-6} sec
3. quantum efficiency	0.25	0.20
4. signal-to-noise ratio	120	120
Collecting optics aperture stop number lower limit	1.0	1.0
Grating diameter	0.2 m	0.2 m
Reciprocal grating spacing	1.18×10^{6} m^{-1}	1.18×10^{6} m^{-1}
Spectral order	5	2
*Multiple detectors required		

For an assumed collecting optics diameter of 1 meter, the following results then apply:

$$\Delta\phi \text{ (minimum)} = 2.81 \times 10^{-4} \text{ rad at Jupiter}$$

$$\Delta\phi \text{ (minimum)} = 1.39 \times 10^{-4} \text{ rad at Saturn}$$

F - optical focal length (= $\ell/\Delta\phi$ where ℓ is the linear detector dimension = 10^{-3}m) (m)

Ψ - order of spectrum

N_g - reciprocal grating spacing (m^{-1})

h - apparent horizontal ground speed (m/sec)

p - number of detectors

m - number of mirror faces

H - altitude above planetary surface (m)

D_s - scanning mirror diameter (= 1.41 D_c) (m)

The upper-limit usable trajectory segment can be determined in a rather straightforward fashion using Equation I, where an upper limit value of D_c is used. Certain fixed parameter values, of course, must be assumed. Separate analysis indicates that the auroral spectral radiance at both planets is of the order of that for reflected sunlight in the bandwidth of interest; the solar values have been used. Sensor state-of-the-art (SOA) limits and values used to limit the present design are given in Table 3-5.

Substituting for ω in Equation I, a more useful form results:

$$D_c = \left\{ 3 \times 10^{-12} \, (S/N) \left[\frac{2\pi}{pmq}\right]^{1/2} \right\} \frac{1}{(C_p)^{1/2}} \left[\frac{\nu h}{fH}\right]^{1/2} \frac{1}{\Delta\phi^2}$$

or

$$D_c = \frac{3.86 \times 10^{-6}}{\Delta\phi^2} \left[\frac{\nu h}{fH}\right]^{1/2}$$

Limiting the trajectory segment analyzed to that for which solar zenith angles are less than approximately 80 degrees, results are obtained as shown in Table 3-6.

Table 3-6. Saturn Trajectory Parameters for UV Spectrometry

H/ν_h	$(\nu_h/fH)^{1/2}$	H	f	ν_h
2.73×10^4 s	1.34×10^{-2} $s^{1/2}$	1.20×10^5 km	0.206	4.44 km s^{-1}

or

$\Delta\phi^*$ (minimum = 2.81×10^{-4} rad for sensor usage at both encounters

Checking the limits provided in Equations II through V, the following results are obtained:

$$\text{(II)} \quad D_d = 1.22\sqrt{2}\ (1.0 \times 10^{-6} m)/2.81 \times 10^{-4} = 6.1 \times 10^{-3} m < 1.0\ m$$

$$\text{(III)} \quad \tau = 2.81 \times 10^{-4}\ rad/2(3.02\ sec^{-1}) = 4.66 \times 10^{-5}\ sec < 10^{-6}\ sec$$

where

$$\omega_{max} = \left(\frac{2\pi}{pm\,\Delta\phi^*}\right)\left(\frac{H}{\nu_h}\right)^{-1}_{min} = \left(\frac{2\pi}{2 \cdot 2.81 \times 10^{-4}}\right)\left(\frac{1}{3.69 \times 10^{3}}\right) = 3.02\ sec^{-1}$$

$$\text{(IV)} \quad f^{\#} = \frac{F}{D_c} = \frac{\ell}{D_c \Delta\phi^*} = \frac{10^{-3}}{1.0\ (2.81 \times 10^{-4})} = 3.57 > 1$$

$$\text{(V)} \quad D_g = \frac{(1.0\mu/10^{-5}\mu)}{(2 \cdot 1.18 \times 10^{6} m^{-1})} = 4.28 \times 10^{-3} m < 0.2m$$

where

$$\Psi = 2 \text{ and } N_g = 1.18 \times 10^{6} m^{-1}$$

$$\text{(VI)} \quad \omega^{+} = 193/(1.41)\ (1.0) = 136\ \frac{rad}{sec}$$

$$(= 7.82 \times 10^{3}\ deg/sec) > \omega_{max}$$

Thus, for a maximum-sized collecting optics system with optimal angular resolution characteristics, no design limitations have been exceeded. The final design is now restricted by the requirements that $\Delta\phi \geq \phi^*$ and $0.006\ m \leq D_c \leq 1.0\ m$ with other sensor characteristics fixed.

3.5 SUPPORT REQUIREMENTS DEVELOPMENT

3.5.1 Scaling Law Results

Application of the ultraviolet spectrometer scaling law (Section 2.3) is accomplished by the SERA program (Section 2.6). The output is divided into six parts as follows; only the last part is presented in Table 3-7.

Table 3-7. SERA Computer Program Data Output

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*** SENSOR CAPABILITIES AND SUPPORT REQUIREMENTS ***

CASE 1

SENSOR TYPE 4. VISIBLE/UV SPECTROMETER
MISSION 7. EARTH-JUPITER-SATURN FLYBY, LAUNCH 7/30/76. PLANET 6. SATURN(INCL. RINGS)

** SENSOR CAPABILITIES **

	LIMIT	OPTIMAL	MARGINAL	PT. 1	PT. 2	PT. 3	PT. 4	MAX. WORTH
CAPABILITY PARAMETER 1 MAXIMUM WAVELENGTH (MICRON)	1.2000E 00	1.0000E 00	1.0000E 00	1.0000E 00	1.0000E 00	0.0	0.0	0.11
CAPABILITY PARAMETER 2 MINIMUM WAVELENGTH (MICRON)	1.0000E-01	1.0000E-01	1.0000E-01	1.0000E-01	1.0000E-01	0.0	0.0	0.04
CAPABILITY PARAMETER 3 SPECTRAL RESOLUTION (MICRON)	5.0000E-06	1.0000E-05	1.0000E-05	1.0000E-05	1.0000E-05	0.0	0.0	0.03
CAPABILITY PARAMETER 14 ANGULAR RESOLUTION (DEGREE)	5.7290E-04	1.6800E-02	1.6800E-02	1.6800E-02	1.6800E-02	0.0	0.0	1.00
CAPABILITY PARAMETER 19 NUMBER OF SAMPLES OR MEASUREMENTS	1.0000E 03	1.0000E 02	1.0000E 02	1.0000E 02	1.0000E 02	0.0	0.0	0.03
CAPABILITY PARAMETER 18 FRACTION OF SURFACE AREA OF PLANET IN ONE FIELD OF VIEW (PERCENT)	5.0000E 01	6.9468E-04	2.9165E-06	6.9468E-04	2.9165E-06	0.0	0.0	1.00
CAPABILITY PARAMETER 12 VIEWING AXIS ANGLE TO THE VERTICAL, AT THE SPACECRAFT (DEGREE)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.00
CAPABILITY PARAMETER 13 VIEWING AXIS ANGLE TO THE SURFACE TANGENT PLANE, AT SPACECRAFT (DEGREE)	9.0000E 01	9.0000E 01	9.0000E 01	9.0000E 01	9.0000E 01	0.0	0.0	1.00
TOTAL SENSOR WORTH		4.0382E-06	4.0382E-06	4.0382E-06	4.0382E-06			

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*** SENSOR CAPABILITIES AND SUPPORT REQUIREMENTS ***

CASE 1

* SUPPLEMENTARY CAPABILITY DATA *

	VALUE	WORTH
FRACTION OF SURFACE OF PLANET COVERED (PERCENT)	6.7100E 01	0.15
NORTHERNMOST LATITUDE OF AREA VIEWED (DEG)	8.5000E 01	0.14
SOUTHERNMOST LATITUDE OF AREA VIEWED (DEG)	7.5000E 01	0.12
(COARSEST) SPATIAL RESOLUTION AT FAR EDGE OF SWATH (M)	5.6400E 05	********

* FIXED EXPERIMENT PARAMETERS *

PARAMETER	LIMIT	VALUE
NUMBER OF DETECTORS	1.0000E 01	2.0000E 00
NUMBER OF MIRROR FACES	1.0000E 01	1.0000E 00
PHOTOMULTIPLIER RESPONSE TIME LIMIT (SEC)	1.0000E-08	1.0000E-06
PHOTOCONDUCTOR RESPONSE TIME LIMIT (SEC)	1.0000E-03	1.0000E-03
PHOTOMULTIPLIER SIGNAL/NOISE RATIO RQMT.	1.2000E 02	1.2000E 02
PHOTOCONDUCTOR SIGNAL/NOISE RATIO RQMT.	1.2000E 02	1.2000E 02
SPECTRAL ORDER	5.0000E 00	2.0000E 00
S-O-A GRATING DIAMETER LIMIT (M)	2.0000E-01	2.0000E-01
RECIPROCAL GRATING SPACING (LINE/M)	1.1800E 06	1.1800E 06
S-O-A COLLECTOR APERTURE F/NUMBER LOWER LIMIT	1.0000E 00	1.0000E 00
SCAN HALF-ANGLE (DEGREE)	9.0000E 01	4.4500E 00
SCANNING BEAM ANGULAR SIZE (DEGREE)	5.7300E-04	1.6800E-02

OTHER SENSOR TYPES MEETING SOME MEASUREMENT REQUIREMENTS
VISIBLE/UV PHOTOMETER WITH CASSEGRANIAN OPTICS
IR SPECTROMETER

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*** SENSOR CAPABILITIES AND SUPPORT REQUIREMENTS ***

CASE 1

SENSOR TYPE 4. VISIBLE/UV SPECTROMETER
MISSION 7. EARTH-JUPITER-SATURN FLYBY, LAUNCH 7/30/76. PLANET 6. SATURN(INCL. RINGS)

** SUPPORT REQUIREMENTS EVALUATION **

* SCALING LAW COEFFICIENTS AND OPTIONS *

SUPPORT RQMT.	C1/	C2/	C3/	C4/	C5/
1. COEFFICIENT/VALUE	1.0000E 00	0.0	0.0	0.0	0.0
2. COEFFICIENT/VALUE	1.0000E 00	2.2000E 00	0.0	0.0	0.0
3. COEFFICIENT/VALUE	1.0000E 00	0.0	0.0	0.0	0.0
4. COEFFICIENT/VALUE	1.0000E 00	0.0	0.0	0.0	0.0
5. COEFFICIENT/VALUE	1.0000E 00	0.0	0.0	0.0	0.0
6. COEFFICIENT/VALUE	1.0000E 00	7.3000E-01	1.3000E 00	1.0000E-03	0.0
9. COEFFICIENT/VALUE	1.0000E 00	0.0	0.0	0.0	0.0
10. COEFFICIENT/VALUE	1.0000E 00	0.0	0.0	0.0	0.0
11. COEFFICIENT/VALUE	1.0000E 00	0.0	0.0	0.0	0.0
14. COEFFICIENT/VALUE	1.0000E 00	0.0	0.0	0.0	0.0
15. COEFFICIENT/VALUE	1.0000E 00	0.0	0.0	0.0	0.0

* SUPPORT REQUIREMENTS *

SUPPORT REQUIREMENT	MAXIMUM REQUIREMENT	MINIMUM REQUIREMENT	PT. 1	PT. 2	PT. 3	PT. 4
MASS (KG)	8.88667E 02	8.88667E 02	8.88667E 02	8.88667E 02		
AVERAGE POWER (WATT)	4.20000E 00	4.20000E 00	4.20000E 00	4.20000E 00		
LENGTH (M) (ORIENTED)	4.41046E 00	4.41046E 00	4.41046E 00	4.41046E 00		
WIDTH (M) (ORIENTED)	1.00000E 00	1.00000E 00	1.00000E 00	1.00000E 00		
HEIGHT (M) (ORIENTED)	1.00000E 00	1.00000E 00	1.00000E 00	1.00000E 00		
VOLUME (CUBIC M) (ORIENTED)	4.05548E 00	4.05548E 00	4.05548E 00	4.05548E 00		
DATA OUTPUT RATE (BIT/SEC)	1.61970E 04	5.43485E 03	5.43485E 03	1.61970E 04		
POINTING ACCURACY (DEG)	9.00936E 00	9.07922E 00	9.07922E 00	9.00936E 00		
ASPECT ANGLE RATE LIMIT (DEG/SEC)	3.60439E 00	1.13379E 01	3.60439E 00	1.13379E 01		
ROLL RATE LIMIT (DEG/SEC)	3.60439E 00	1.13379E 01	3.60439E 00	1.13379E 01		
SCAN RATE LIMIT (DEG/SEC)	7.82043E 03	7.82043E 03	7.82043E 03	7.82043E 03		

1. "Mission Description" - definition of the usable trajectory segment.

2. "Information Requirements Supported" - summary of measurement requirements data.

3. "Sensor Capabilities" - definition of actual sensor measurement capabilities, including the total sensor worth at each mission point.

4. "Supplementary Capability Data" - definition of sensor measurement capabilities where analysis of data over the entire trajectory segment is required, including the individual worth of each capability for the entire encounter (the coarsest resolution value is presented for its informative value only).

5. "Fixed Experiment Parameters" - fixed design parameters and design constraints.

6. "Support Requirements Evaluation" - a summary of selected scaling law coefficients used and resulting sensor support subsystem requirements.

3.5.2 Sensor Support Requirements Summary

A summary of the sensor measurement capabilities and subsystem support requirements is presented in Table 3-8. The capability parameters listed are underlined in Table 3-7. Support requirements listed are underlined below the "Support Requirements" heading. Generally, the extrema ("maximum" for optimal level, "minimum" for marginal level) of all requirements are not incurred at a single mission point, but rather at various points along the trajectory segment. Ofent, however, the maximum values of some support requirements correspond to the first point on the segment at which the sensor is operated; and the maximum values of the other requirements correspond either to the lowest point or the last point.

3.6 COMPATIBLE SENSOR GROUPING

Compatible imaging, nonimaging, and integrated sensor families were defined for the 1976 Earth-Jupiter-Saturn mission by means of the grouping methods described in Section 2.7. These families, including the UV spectrometer, are described inTables 3-9 through 3-11. Operational interferences between members of the integrated family are indicated in Table 3-11. Similar groupings were made for sensors based on the marginal observation requirements.

Table 3-8. Sensor Support Requirements Summary

Sensor Type Visible/UV Spectrometer — Mission No. 7 — Planet Saturn

Observation Objectives: Total Observation Worth = 2.95

SD70-24 Page C - 92 Worth = 0.50
Page C - 96 Worth = 0.55
Page C - 97 Worth = 0.70
Page C - 99 Worth = 0.30
Page C - 104 Worth = 0.60

Capability Level	Maximum
Observation Requirements Level	Optimal
Trajectory Points:*	
Point	1
Characteristics	Max. Alt.
Time of periapsis (s)	-5.39E04**
Latitude (deg)	5.55
Longitude (deg)	46.4
Sun angle (deg)	23.4
Support Requirements:	
Mass (kg)	888.7
Average power (w)	4.20
Length (m)	4.41
Width (m)	1.0
Height (m)	1.0
Volume (m^3)	4.05
Data rate (bit/s)	1.62E04
Pointing accuracy (deg)	9.0
Pointing stability (deg/s)	3.8
Roll Rate limit (deg/s)	3.8
Scan Rate limit (deg/s)	7.82E03
Scan amplitude (deg)	8.90
Collecting optics diameter	1.0
Capability Parameters:	
Max. wavelength (λM) (μ)	1.0
Min. wavelength (λm) (μ)	0.1
Spectral resolution ($\Delta\lambda$) (μ)	1.E-05
Spatial resolution (m)	2.34E+05
Angular resolution (deg)	0.0168
Exposure time (sec)	-
Field/view length (km)	-
Swath width (km)	-
Area/frame (%)	1.2E-04
Total area (%)	67.1
Total Sensor Worth	1.1E-08
Notes: Number of detectors	2
Number of mirror faces	1
Detector type	Photomultiplier

*Extrema of all requirements not necessarily incurred at point listed
**-5.39E04 = -5.39×10^4

Table 3-9. Nonimaging Sensor Family for 1976 Earth-Jupiter-Saturn Mission, Optimal Measurement Requirements

Number	Sensor Type and Observational Purpose	Planet	Support Requirements: Mass (kg)	Power (w)	Data Rate (bit/sec)	Data (bit)	Total Sensor Worth
4.	Microwave Radiometer-Measuring						
	Antenna diameter: 5.05 m	Jupiter	91.36	45.2	2.9	57.8×10^3	1.84×10^{-9}
	Cloud structure and temperature	Saturn	43.25	34.5	0.404	31.2×10^3	1.49×10^{-8}
7.	Flux-Gate Magnetometer						
	Triaxial	Jupiter	2.1	6.0	1500	1.82×10^{10}	1.22
	Interior composition and motion	Saturn	2.1	6.0	1500	1.53×10^{10}	1.22
8.	Helium Magnetometer						
	Interior composition and motion	Jupiter	3.4	10.0	40	4.84×10^8	1.22
19.	Michelson Radiometer						
	Antenna diameter: 0.984 m	Jupiter	1260	87	7.66×10^3	18.1×10^7	1.46×10^{-6}
	Atmospheric composition and pressure						
	Atmospheric composition and pressure; ring composition	Saturn	1260	87	1.07×10^3	3.4×10^7	9.35×10^{-7}
21.	Visible/UV Spectrometer						
	Collector diameter: 1.0 m	Jupiter	888.7	4.2	1.19×10^5	9.05×10^9	5×10^{-9}
	Atmospheric composition	Saturn	888.7	4.2	1.62×10^4	17.5×10^8	1.1×10^{-8}
22.	Laser Radar						
	Nd YAG	Jupiter	100	83.3	11.67	11.6×10^4	1.13×10^{-17}
	Aerosol size and distribution	Saturn	100	83.3	11.67	20.5×10^4	2.26×10^{-17}
23.	Bi-Frequency Radio Occultation						
	Antenna diameter: 33.22 m	Jupiter	1658	5.0	247.6	20×10^3	1.92×10^{-3}
	Ionosphere density; figure	Saturn	1658	5.0	225.8	20×10^3	1.92×10^{-3}

Table 3-10. Imaging Sensor Family for 1976 Earth-Jupiter-Saturn Mission, Optimal Measurement Requirements

Number	Sensor Type and Observational Purpose	Planet	Support Requirements				Total Sensor Worth
			Mass (kg)	Power (w)	Data Rate (bit/sec)	Data (bit)	
1.	Television Camera Vidicon tube diameter: 9.1 cm. Cloud structure and motion; figure; ring structure	Saturn*	193.5	57.3	1.07×10^{7}	2.43×10^{11}	7.95×10^{-5}
3.	Microwave Radiometer-Mapping Antenna diameter: 5.0 m. Cloud structure and temperature	Saturn*	116.6	51.5	121.9	5.7×10^{6}	6.7×10^{-11}
5.	Synthetic Aperture Radar Antenna shape: 38.7 x 103.6 m Cloud structure	Saturn*	1.82×10^{4}	7.64×10^{4}	2.45×10^{6}	12×10^{9}	8.37×10^{-17}
16.	Far IR Radiometer Collector diameter: 1 cm Atmospheric temperature	Saturn*	33.96	10.0	6.0	1.48×10^{5}	2.26×10^{-9}

*Imaging sensors for Jupiter encounter not within scope of study.

Table 3-11. Integrated Sensor Family for 1976 Earth-Jupiter-Saturn Mission

Number	Sensor Type
OPTIMAL MEASUREMENT REQUIREMENTS	
1.	Television camera
3	Microwave radiometer - mapping (a)
4.	Microwave radiometer - measuring (a)
5.	Synthetic-aperture radar (a*)
7.	Flux-gate magnetometer (a)
8.	Helium magnetometer (a)
16.	Far IR radiometer
19.	Michelson interferometer (b)
21.	Visible/UV spectrometer
22.	Laser radar (b*)
23.	Bifrequency radio occultation

(a) Operational incompatibility caused by (a*)
(b) Operational incompatibility caused by (b*)

4.0 CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS DRAWN FROM STUDY

The essential result of this study is the demonstration that remote sensors are generally capable of significant investigations of planetary environments when used on realistic flyby and orbital missions. However, this is not a mission study. The full range of observations desired to satisfy scientific and technological space exploration goals can, in several cases, be performed. In other cases, such full performance is limited by the mission trajectory or by the sensor state of the art; however, these limitations seldom prevent observations that represent clear advances beyond present knowledge. The observations require mostly passive optical (i.e., ultraviolet, visible, and infrared) and microwave sensors of both imaging and nonimaging types. Sensor state of the art somewhat limits the applications of active optical (laser radar) and electronic (radar) sensors, but some valuable and feasible uses of these sensors were found. Particle and field sensors now existing are adequate for all required observations.

This study has proved significant both in the methodology developed and its specific results. The most important methods include the synthetic sensor design techniques embodied in the scaling laws, the calculation of trajectory segments on which sensors must be operated to satisfy area coverage and spatial resolution requirements, and the quantitative evaluation of sensor worth in terms of satisfaction of observation requirements. Computer programs were developed which not only perform numerical analyses but also document the top-down approach from planetary exploration goals to sensor support requirements.

Specific study results of greatest lasting value include a restatement by qualified scientists of planetary observation objectives, the flyby trajectory analyses, the sensor support requirements for a variety of missions and observations, and the compatible sensor families which guide the selection of candidate experiments and payloads. These results are summarized throughout this report and in condensed form in Section 1.4.

The primary value of the methodology developed in this study is the planning of planetary and other space exploration missions. One area of application is the evaluation of the contribution of candidate missions and payloads to exploration objectives. Another application is to trade analyses. For example, sensor support requirements can be related parametrically to trajectory elements. The measurement capability of a given sensor design can be evaluated as a function of trajectory parameters by fixing sensor design parameters.

In multiplanet flyby missions, a sensor may be optimized for best performance at one planet, or for greatest total performance in the mission, provided that minimum requirements are met at all planets. The study methods can determine which approach is most effective in terms of mission objectives or minimizes sensor support requirements.

The study methodology is directly applicable to synthetic sensor design as a guide to designers of actual sensor hardware. Technology limits that restrict sensor performance are identified so that technology development can be concentrated on these aspects. Trade analyses of sensor measurement capability versus support requirements can be made. Sensor designs can be used in tentative selection of sensors and evaluation of payload support requirements. Commonality of sensor component and support subsystems can be recognized and used in payload integration studies.

4.2 RECOMMENDATIONS FOR FURTHER WORK

This study has covered a major portion of the field of sensor application to space investigations. Its usefulness would be enhanced by covering the remaining significant portions. These include other candidate missions, such as the NASA-OSSA Grand Tour baseline*, and other solar system objects such as Pluto, the Sun itself, satellites, asteroids, and comets. Additional experiments worthy of study are imaging sensors on inner-planet flybys, particle and field sensors to measure magnetospheric and interplanetary environments, and atmospheric entry probe and surface-lander experiments.

The utility of the results also would be increased if the results in Reference 1 were entered into the documentation file and if more realistic limits were placed on some observation requirements and sensor technology developments. The limits used in this study were based on unrestricted scientific and technological considerations and did not reflect spacecraft, launch vehicle, schedule, or budgetary constraints.

*Consists of Jupiter-Saturn-Pluto flyby missions launched in 1976 and 1977, and two Jupiter-Uranus-Neptune flyby missions launched in 1979.

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