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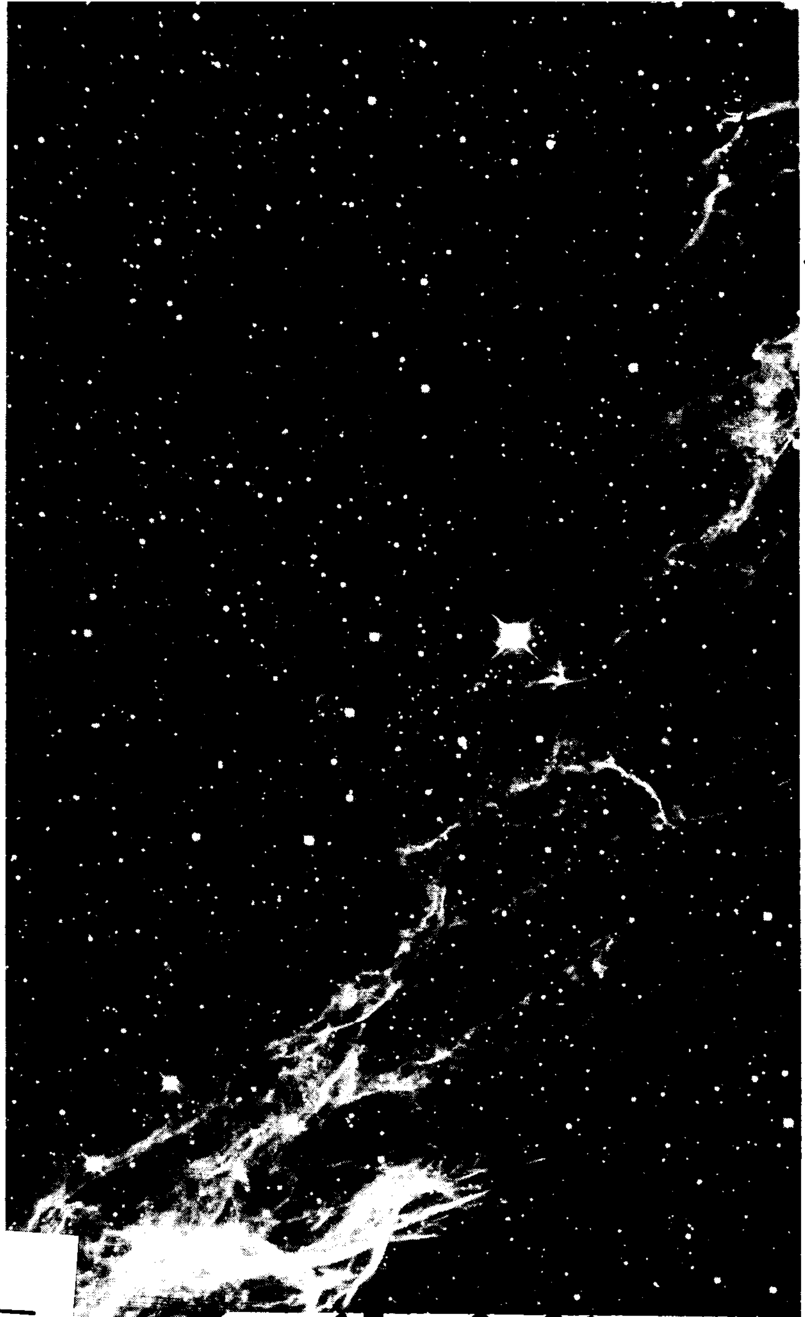

Report M-7

A SURVEY OF COMET MISSIONS

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SUMMARY

This report is one in a series of seven reports by the Astro Sciences Center of IIT Research Institute on a study of periodic comet apparitions suitable for intercept missions. The major objectives are to show the best way in which deep space missions to comets can complement and significantly add to the present understanding of comets and to outline the mission profiles for those cometary intercept missions which are considered worthwhile.

Cometary measurements from a spacecraft can provide new data on the nuclei of comets and on the composition, spatial densities and forces interacting with the gases and particles in the coma and tail. They should also be used to confirm the interpretation of Earth-based measurements on comets, particularly the spectroscopic data. Of these perhaps the most important will be the observation of the comet nucleus. No direct data has been obtained from the Earth on comet nuclei, principally because they are too small (approximately a few km diameter) and in only about 20 cases has a nucleus even been detected as a separate entity.

Comet intercept missions can add considerably to the study of comets, but there is still much to be accomplished by

Earth and near Earth observations, by laboratory studies and by artificial comet experiments. Certainly during the intercept phase of the missions discussed, strong support should be provided by Earth-based observations to provide data which can be correlated with measurements from the spacecraft.

Three basic experimental payloads for comet intercept missions have been considered. It should be borne in mind however that ultimately each cometary apparition should be studied on an individual basis. The types of instruments considered are plasma probes, magnetometers, spectrophotometers, mass spectrometers, micrometeoroid detectors and television. Payload 1 contains particles and fields experiments which would be used in an exploratory fashion to provide background information on which to base the specifications for the more complete payloads. Payload 2 contains the experiments for an intercept mission where the spacecraft velocity is reduced to match the velocity of the comet. Payload 3 contains full complement of instruments and has no restrictions on the data to be transmitted. It is assumed that data will be transmitted for a period of 8 hours per day during interplanetary flight and for 24 hours per day at intercept.

The selection of comets for intercept missions has been made by means of the following criteria. The initial list of possible comets consisted of those periodic comets which have been observed at least twice recently and which will have a perihelion passage before Halley's comet in 1986. The requirement for two recently observed apparitions gives some assurance that the orbital elements are well enough known for perturbation calculations to be able to predict future returns of the comets. However to allow for errors in the prediction of future positions of the comets a stipulation has been included that, except in rare cases of very well known comets, the comet to be intercepted shall be observed at least two months before the launch of the spacecraft. The first sighting on each passage of a comet (recovery) can only be achieved if it is brighter than magnitude 20 and will be visible in a dark sky for a period of two hours or more. A further requirement is that the comet should be visible from the Earth during the intercept phase and be as bright as magnitude 12 so that spectroscopic data can be obtained from the Earth and correlated with spacecraft data.

A number of mission constraints have been considered in compiling the mission characteristics and the payloads. Of the functional constraints, the most important one appears to be guidance and control. Periodic comets suffer perturbations on every orbit, but are only visible for about 10 percent of their orbit, thus their positions in space are never known accurately. The difficulty of locating and recognizing faint, diffuse objects with on-board comet seekers and the generally high approach velocities (of order 20 km/sec) complicate spacecraft guidance for these missions. In order to achieve good viewing of the nucleus a small miss distance of the order of 1000 km would be desirable. Of the experimental constraints, determination of the correct instrument sensitivities appears to be the largest problem. Present knowledge of the constitution and densities of cometary materials is not adequate for the detailed description of the instruments. This is particularly true of short period comets which are generally faint and inactive and for which, in most cases, no spectroscopic data is available. Assessment of the hazard caused by dust particles appears as the greatest environmental constraint. More knowledge about the numbers, mass and construction of cometary dust particles is required to assess the shielding for the spacecraft.

The seven intercept missions to the five selected comets which are described in the report are summarized in the table at the end of this summary. The mission to Tempel 2 in 1967 is basically exploratory and uses the smallest payload considered. Comet Encke is probably the best known of the short period comets and the 1974 apparition is the best, for Encke, in the next 25 years. Two missions have been included, one with a long flight time and a relatively low ideal velocity and carrying the unrestricted payload. The later launch requires a higher ideal velocity and involves a larger approach velocity. The same unrestricted experimental payload is used but the heavier total payload requires a larger launch vehicle.

The mission to D'Arrest in 1976 is probably the most attractive of the missions and the full unrestricted payload has been included with an Atlas-Agena launch vehicle. In 1983 comet Kopff offers the only reasonable opportunity to match the spacecraft velocity to that of the comet. The approach velocity is 8 km/sec and is the lowest of all those considered or selected. Two missions have been included for Kopff. The first uses the full unrestricted experimental payload in a fly-by mission without matching velocities. An Atlas-Centaur launch vehicle is adequate for this. For the second mission the experimental payload contains a larger television capacity because of the velocity matching. In this case the added weight of terminal propulsion requires a Saturn 1B-Centaur launch vehicle. In general it appears that modes of flight other than direct will be required to effect velocity matching with comets. Obvious possibilities are gravity assist maneuvers or thrusted trajectories. Finally, Halley's comet has been included despite the immense approach velocity of 69 km/sec. A great deal of data was obtained on Halley's comet at its last apparition in 1910 and it is felt that it is worth compounding this with a close fly-by mission.

SUMMARY OF COMET INTERCEPT MISSIONS

Comet	Mission Type Miss Distance from Nucleus	Ideal Velocity (30 day window) ft/sec	Approach Velocity km/sec	Time of Flight, days	Total Spacecraft Weight without Shroud, lbs.	Launch Vehicle
Tempel 2 Aug 1967	Fly-by 10,000 km	43,000	11-12	110-135	180	Atlas-Agena
Encke Apr 1974	Fly-by 1,000 km	44,400	28	240-270	650	SLV 3X-Kick
Encke Apr 1974	Fly-by 1,000 km	47,700	35-38	80-110	800	SLV 3X-Centaur-Kick
D'Arrest Aug 1976	Fly-by 1,000 km	41,000	13	100-130	535	Atlas-Agena
Kopff Aug 1983	Fly-by 1,000 km	43,000	8	175-190	700	Atlas-Centaur
Halley Jan 1986	Fly-by 1,000 km	42,500	69	210	1,635	SLV 3X-Centaur
Kopff Aug 1983	Fly-by with Vel. match 1,000 km	43,000	8	175-190	9,650	Saturn 1B-Centaur

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A SURVEY OF COMET MISSIONS

1. INTRODUCTION

Apparitions of comets have been recorded as far back as 467 B.C. but it is only comparatively recently that they have been even partially understood. Comets were first recognized as solar system objects in 1577 but it was not until 1705 that Halley first derived a comet orbit and predicted the return of the comet. Since then a great deal of orbital data have been obtained, some of admittedly dubious accuracy. The standard catalogues of comet orbits are those of Galle (1894), Crommelin (1925, 1932) and, most recently, Porter (1961).

There are three basic groups of comets classified on the basis of their orbits. There are "new" comets which have almost parabolic orbits. Bright new comets are discovered at a rate of about four a year and due to their size, brightness, and generally high level of activity, have contributed most to the present cometary knowledge. A second group consists of long period comets (greater than 100 years period). In the past little value has been derived from their repetitiveness because of relatively inaccurate orbit and perturbation determinations. However from an observational point of view they will increase in importance because they are often bright, active comets and will provide the opportunity to observe on succeeding apparitions the effects of long exposures to the environment of the outer solar system. The third group are periodic comets of short period (mean period $\sim$ 7 years) whose orbits are strongly influenced by the planets, particularly Jupiter. In general, short period comets are faint, inactive and in no sense as spectacular as new or long period comets. However because of the frequent passes of short period comets their orbits can be determined fairly accurately and their future returns predicted. Thus it is to this latter group that most comet intercept missions will be directed.

The major objectives of this report are to show the best way in which missions to comets can complement and significantly add to the present understanding of comets and, to outline the mission profiles for those cometary intercept missions which are considered worthwhile. Some consideration has therefore been given to the parts which can be played by further observations of comets from the Earth, by the laboratory study of simulated cometary phenomena and by the use of man-made artificial comets launched into orbit around and observed from the Earth.

The second section of the report is used to outline the areas of present understanding of the physics of comets. Section 3 shows how the major problem areas could be investigated through a combination of Earth-based study and comet missions. The remaining sections of the report show the development of the mission profiles for the suggested missions which are summarized in Section 7.

2. THE SCIENTIFIC OBJECTIVES OF COMETARY STUDY

The ultimate objective of cometary study is to understand the state and condition of comets throughout their orbital cycles. One important objective therefore is the determination of the origin of comets. The fact that many new comets have almost parabolic orbits means that they have come at least from very distant regions of the solar system. It is not known whether comets exist as such out beyond the orbit of Pluto, say, as the result of an earlier solar system event, or whether they are continually being formed in the outer solar system. A full understanding of the apparitions of comets will certainly assist in the determination of their origin but it may be necessary to examine them away from solar influences before a final answer can be provided. In either event, the early comet intercept missions will at best only indirectly indicate the origin of comets and hence this objective has not been included in Table 1, a summary of scientific objectives.

Comets, as they pass through perihelion, are influenced very significantly by solar radiation and by the interplanetary medium through which they pass. Thus the achievement of a fuller understanding of comets has more than obvious implications in that it may be possible to view comets as interplanetary probes

Table 1

SUMMARY OF SCIENTIFIC OBJECTIVES

The following are the primary scientific objectives which are used as the basis for the design of comet intercept missions. They cannot all be fulfilled by the early missions.

Nucleus

a) Macroscopic construction (sand-bank - ice nucleus)
b) Diameter, shape, mass, density determination
c) Constitution (nucleus compounds)
d) Temperature and albedo determination
e) Method of gas and dust release
f) Detection of a magnetic field
g) Possible biological species or organic compounds
h) Detection of primeval low density material.

Coma

a) Mechanism of halo formation
b) Determination of parent, daughter and grand-daughter compounds
c) Verification of ionizing and excitation mechanisms
d) Nature of reflecting particles
e) Relationship between size and brightness as a function of solar distance
f) Detection of magnetic field.

Tail

a) Verification of constitution of Type I and Type II or III tails
b) Mechanisms causing tail structures
c) Establishment of mechanisms for accelerations of tail material
d) Detection of magnetic field.

which by their appearance indicate the local state of the interplanetary medium and perhaps reflect solar activity. The potential of this perspective is clearly indicated by Biermann's (1951) original prediction of a solar wind.

The scientific objectives for comet missions are discussed in a previous report (Roberts 1964a) and are reviewed below separately for the nucleus, coma and tail. Appendix 1 gives the median parameters (orbital, physical and spectroscopic) for comets of period less than 100 years.

2.1 The Comet Nucleus

The term nucleus is understood to refer to the optical center of the comet and its appearance depends on the particular apparition of the comet and on the observational apparatus. It usually appears as a bright, almost star-like condensation which it is possible to separate from the coma with large telescopes. The nucleus appears as a small disk and in a few cases the diameter can be estimated at least to an upper limit. The contribution of the nucleus to the total brightness of a comet rarely exceeds one percent. In the few instances where it has been possible to isolate the nucleus with a spectrograph a continuous spectrum has been dominant: this is attributed to scattering and reflection of sunlight by solid particles (Swings 1943).

The above observations, which are applicable to only about 20 or so fairly bright comets, represent the total direct observations of comet nuclei. However a number of important theories and deductions have been made, and these form the basis for a continuing scientific interest.

Two basic theories exist for the nature of the nucleus. The sand-bank model proposes that a comet consists of a loose aggregate of solid particles of varying size, with each particle describing an independent orbit around the Sun. Lyttleton (1953) has strengthened this theory by including a formation mechanism which invokes the gravitational lens effect of the Sun passing through interstellar clouds. It has also been shown that absorbed gases may account for the gaseous release with solar heating (Levin 1943). A more widely accepted model is the "ice-nucleus" suggested by Whipple (1950a,1963, Delsemme and Swings 1952). In this model the nucleus is a discrete mass of solids, including ices of methane, ammonia, carbon dioxide, water and cyanogen and trapped meteoroidal particles. The ices sublime with solar heating, releasing gases and dust particles into the coma.

The size of a cometary nucleus is considered to be of the order of 1 to 10 km diameter. An upper limit to the visual diameter has been estimated for about 20 bright, large comets and is between 10 and 100 km (Richter 1963a). Most other estimates derived from occultations or very close approaches to the Earth suggest diameters again in the 1-10 km range. Using this range for the diameter, the average mass of the nucleus can be estimated, assuming a specific gravity of 1.3 (Whipple 1963) as between 10^{15} gms and 10^{18} gms.

2.2 The Cometary Coma

The coma is a diffuse mixture of gases, molecules, radicals, atoms, ions and dust particles which surround the nucleus. A coma is generally visible on comets inside 3 AU although some distant and faint comets have appeared asteroidal with no fuzziness indicative of a coma. The visual diameters range up to about 10^6 km, with an average value of say 5×10^4 km diameter (Beyer 1933, 1959), although photographic determinations will generally be somewhat larger. Comet heads are usually largest near perihelion, are roughly spherical in shape, and of fairly uniform texture. A special feature of some comets, including Halley's, is the formation of expanding spherical halos, often with sharp boundaries and with an average lifetime of a few days (Bobrovnikoff 1931). They are assumed to be due to a uniform expansion of matter expelled from the nucleus with expansion velocities that rarely exceed 1 km/sec.

The observations of cometary comas which perhaps have the most scientific importance are spectroscopic. Even with low dispersion it is possible to show that the spectrum of a coma in most cases contains emission bands from gas molecules in contrast to the spectrum of a nucleus which is a reflected solar continuum. A table of cometary emissions is given by Richter (1963b). The following compounds and ions have been clearly identified in cometary heads: CN, C_2, CH, CH^+, NH, NH_2,

CO_2^+, CO^+, N_2^+, OH, OH^+, Na and C_3. This list is not complete since there are some suspected compounds which have not been clearly identified and many unassigned spectral bands. The excitation mechanism seems to be principally fluorescence excitation by solar radiation (Hunaerts 1953, McKellar and Climenhaga 1953).

Despite the detection of the above gases it is still not certain what are the "parent" molecules which emanate from the nucleus. The spectra of supposed "parent" molecules such as H_2O, NH_3, etc. have not been observed. It is also possible that the products which are observed dissociate further into compounds which have spectral lines which also cannot or, have not been observed from the Earth. In addition to the line emissions mentioned above, the comas of many comets exhibit a continuum of reflected sunlight. This is attributed to scattering by particles considerably larger than the simple molecules and radicals observed spectroscopically. They are probably dust particles but could possibly be particles polymerized from the existing gases under solar radiation.

There is much to be learned about the constitution of cometary comas particularly in determining what compounds and particles are present. The mechanisms for excitation of compounds in the coma and expansion of material away from the nucleus are not fully understood nor are the details of the process for accelerating coma material into the tail. These problems are in addition to the difficulties attached to obtaining good visual and photographic observations of coma size and brightness as a function of distance from the Sun.

2.3 The Comet Tail

The tails of comets differ greatly in appearance. Visible tails have been observed as long as 1 AU with diameters up to 10^6 km. At the other extreme, many faint, short period comets do not exhibit any discernible tail. There are two general classifications of comet tails known as Type I and Type II or III (Biermann 1951, 1953, 1963). Type I tails consist of relatively easily accelerated particles, mainly ions such as CO^+, N_2^+, CO_2^+, CH^+, OH^+ (Swings and Haser 1961). They are usually long, narrow, active, straight, and directed radially away from the Sun. The differences between Type II and III tails are minor, the essential similarity being that they are short, wide, inactive, curved and lag behind the radius vector. Their major constituent is probably dust particles. Of the comets that develop a tail, about 50 percent possess a Type I tail. Occasionally a comet will show both a Type I and a Type II tail.

Type I tails, in contrast to dust tails, show considerable structure and changes in structure. Relative velocities for cloud-like condensations in tails have been observed to range from ten to several hundred km/sec, and accelerations have been observed as high as 1000 cm/sec^2 (Biermann, Lust 1963). Rays form in the tail at angles up to 30 or 40° to the axis of the tail, the longest ones being formed near the coma and are directed at low angles. In addition, thread-like filaments mostly parallel to the axis are often observed. As a further complication, the condensations, streamers, rays and filaments, in fact the whole structure of a comet tail can have a wave-like or helical structure.

The acceleration of tail material is solar-related but such mechanisms as radiation pressure have been shown to be inadequate. The Biermann (1951) hypothesis that tail accelerations resulted from a reaction between solar corpuscular radiation and cometary ions has been extended by consideration of magnetohydrodynamic interactions with the interplanetary magnetic field and the solar wind (Harwitt and Hoyle 1962).

Many of the constituents of comet tails have been identified but there is a need to prove whether other compounds do or do not exist in comets. The mechanisms of acceleration of tail material are still somewhat sketchy and a solution in this area is probably the most important objective in the study of cometary tails.

2.4 Individual Periodic Comets

The scientific knowledge of individual comets is very limited with the exception of a few relatively well known ones such as Encke and Halley. The available data is tabulated in a previous report (Roberts 1964b) for each of the comets which have been considered for intercept missions.

3. COMPLEMENTARY MEASUREMENT TECHNIQUES

To gain the fuller understanding of comets as we see them from Earth, it is not going to be adequate to just send out one or two intercepting spacecraft - however well instrumented. Visual and spectroscopic astronomy still have a large part to play, as have laboratory experimentation and the technique of launching artificial comets, of known constitution, into Earth orbit. Full advantage should be taken of an interdisciplinary approach with intercept missions as an important but not exclusive contributor. Table 2 gives a summary of the way in which the major technical areas can contribute to the further study of the comets and the success of intercept missions.

3.1 Telescopic Observations

The most direct and in fact essential way for ground-based visual observations to assist intercept missions is through early recovery of comets and accurate determination of the orbital elements. Comets are subject to perturbation to such an extent that it will probably be necessary to verify a predicted comet orbit before a spacecraft is launched to intercept it. Since comets have significant orbital inclinations it is necessary to have available a wide selection of latitudes from which to recover and track comets. Visual and photographic observations will probably be adequate in themselves to determine the coma brightness and size relationships as a function of solar distance.

Table 2

DISCIPLINARY CONTRIBUTIONS TO SCIENTIFIC OBJECTIVES

		Telescopic	Laboratory	Artificial Comets	Intercept Missions
	Nucleus				
a)	Macroscopic construction (sand-bank - ice nucleus)				X
b)	Diameter, shape, mass, density determination	X			X
c)	Constitution (nucleic compounds)		X		X
d)	Temperature and albedo determination	X			X
e)	Method of gas and dust release		X	X	X
f)	Detection of magnetic field				X
g)	Possible biological species or organic compounds	X	X		X
h)	Detection of primeval low density material				X
	Coma				
a)	Mechanism of halo formation				X
b)	Determination of parent, daughter and grand-daughter compounds	X	X	X	X
c)	Verification of ionizing and excitation mechanisms		X	X	X
d)	Nature of reflecting particles	X		X	X
e)	Relationship between size and brightness as a function of solar distance	X			
f)	Detection of magnetic field				X
	Tail				
a)	Verification of constitution of Type I and Type II or III tails	X	X		X
b)	Mechanisms causing tail structures	X		X	X
c)	Establishment of mechanism for accelerations of tail material	X		X	X
d)	Detection of magnetic field				X

The examination of structures in the comas and tails is also probably best achieved by Earth-based observations both visual and spectral because of the large scale and often long duration of these variations.

Excellent spectroscopic observation of comets has been undertaken in recent years. The primary determination of the constitution and differences in constitution of comets relies heavily on the continuation of this work with as high a resolution, spectral and spatial, as possible. In fact, one of the criteria employed later in the selection of comets for intercept missions is that they should be bright enough for spectroscopic observation from the Earth at the time of intercept. To avoid the limitations of the Earth's atmosphere it would be very useful if comet spectra could be obtained from Earth orbital altitudes using the OAO type of satellite system. This would hopefully reveal whether presently undiscovered molecules and compounds are common to comets, and perhaps elucidate the dissociation chain from "parent" molecules.

3.2 Laboratory Studies

Laboratory studies, as has been made clear by those programs which have already been undertaken, can add considerably to the understanding of cometary processes (Donn 1961). Certainly it would be beneficial to decipher the unassigned spectral emissions from comets. Assistance can be gained in the determination of the ionization processes and in assessing the lifetimes of the various species in a simulated space environment. The exposure of comet nuclei models to simulated solar radiation may add to the plausibility of one model at the expense of the others. One experiment would be to establish the possibility of polymerized particles being formed in a comet atmosphere under solar-type radiation (Cunningham 1964).

3.3 Artificial Comets

An artificial comet experiment can provide significant data on the correctness of cometary theories and deductions. For example, a 2000 lb. ice nucleus with closely controlled constituents would probably form an easily observable coma in a matter of hours in Earth orbit (Donn 1961). Its effective lifetime should exceed 10 days. The dimensions, shape and structure of the cometary atmosphere could be observed knowing the size and shape of the nucleus. A comparison would be possible between the theoretically predicted and the actually observed spectra of both the coma and tail knowing the original parent constituents. Rates and mechanisms of ionization could probably be deduced through the knowledge of the environment through which the comet passes.

3.4 Comet Intercept Missions

Intercept missions can provide a major advance in the understanding of comets by close examination. Even simple photographic data on a nucleus will provide more information than has been obtained to date. This can be added to by temperature and albedo measurements, and if possible, by sampling of nucleus material. By using mass spectrometry the quantities and types of compounds in the coma and tail can be detected with a high degree of confidence. But perhaps the greatest advantage can be obtained from measurements of the plasma and magnetic fields in and around the coma. This should add considerably to the magnetohydrodynamic explanation of the acceleration mechanisms involved in comet tail formation. It should also be possible to determine the dust particle concentrations associated with comets. This is of value not only in examining the dust itself to add to the knowledge of its chemical abundances but also in verifying the dispersion relationships between stream meteors and comets.

4. EXPERIMENTAL PAYLOAD

It is stressed that comets should be considered individually when the details of their apparitions are to be analyzed. Similarly, the experiments to be included in intercept missions, although conforming to a common broad outline, should be specified on the basis of the particular comet and the classification of the mission.

The types of instrumentation which should be considered for inclusion in comet intercept missions include:

a) Plasma probes
b) Magnetometers
c) Spectrophotometers
d) Mass spectrometers

e) Micrometeoroid detectors

f) Television.

These instruments will allow the cometary plasma and magnetic fields to be compared to those in the local interplanetary medium, the physiochemical nature of cometary material to be determined, and in favorable circumstances, the nature of the nucleus and its near environment to be observed. Information of pertinence will be gained from measurements of the disturbances and shock waves in the interplanetary medium caused by the comet. Except for the television experiment all of the suggested instruments can be usefully used throughout the flight through interplanetary space. Each of the basic experiments is discussed briefly below.

4.1 Plasma Probes

The objective of plasma measurements is a comparison between the plasma in interplanetary space and in various regions of the coma and tail. It will be necessary therefore to measure the density, energy spectrum and temperature, for electrons, protons and heavier ions. The principal energy range of interest will be up to about 100 eV for electrons and between about 100 eV and 10 keV for ions. These ranges of energy are well within the capabilities of the present state of the art (Lust 1963).

A Faraday cup type of plasma spectrum analyzer with a fairly large area ($\sim 50\ cm^2$) and angle of view (40° x 40°)

would be suitable as a general plasma probe (Bridge et al. 1964). The weight of this probe is estimated to be about 4 lbs. and to require about 1 watt of power. A flux measurement to 5 percent in say a total of 20 energy ranges, inclusive of electrons and ions, once every minute will require a data rate of 2.5 bits/sec from the interplanetary medium and the cometary atmosphere.

A fast response plasma probe, suggested for inclusion in the more sophisticated experimental payload is required to have a high angular resolution of the order of 2.5 square degrees and have a freedom of movement in at least one plane. The narrow acceptance angle will permit accurate directional measurements to be made on the motion of ions and electrons when coupled with a control system which guides the probe to look into the direction of maximum flux. A speed of response such that a plasma measurement can be made every millisecond should allow the fine structure of the plasma to be observed. The information rate from this instrument will be about 5×10^3 bits/sec. A system using secondary emission to generate a pulse for each particle detected would be suitable (Ogilvie et al. 1963). The weight of this plasma probe should not exceed 6 lbs. and the power requirement may be approximately 5 watts.

4.2 Magnetometers

Magnetic field measurements should be made not only in the vicinity of the nucleus but also throughout the coma and, where possible, the tail with attention being paid to any transition region between the comet and interplanetary space. In addition, a shock wave as detected by a plasma probe should also be detectable magnetically. It is important that the plasma and magnetic measurements both be made in such a way that the data can be correlated with respect to time and position.

Two types of magnetometers are well suited to magnetic field measurement in interplanetary space and a cometary atmosphere and both types have been used successfully in space (Cahill 1963, Ness 1964). A Rubidium vapor magnetometer and a fluxgate magnetometer are suggested for inclusion in a comet mission.

The Rubidium vapor magnetometer is an absolute instrument and is extremely useful for calibration throughout the mission. A complete three-axial measurement takes about two minutes by sampling each axis in turn in each direction. Therefore the information rate for continuous operation will be about 0.25 bits/sec. The weight of the unit will be about 6 lbs. and the power demand will be about 8 watts.

A three-axis fluxgate magnetometer which will measure the three components of the magnetic field simultaneously could be used to provide a magnetic field measurement every 3 seconds to coincide with each of the 20 plasma energy measurements every minute. This will require an information rate of about 5 bits/sec.

A development which seems feasible, is to make the fluxgate magnetometer capable of fast operation. To match the fast response plasma probe a measurement every millisecond would be required. A complete unit should only weigh about 5 lbs. and the power demands are quite small, about 1 watt in normal operation. To measure the field vector every millisecond, a total of 2×10^4 bits/sec will be required.

4.3 Spectrophotometry

A great deal of the present understanding of the constitution of cometary atmospheres has been obtained from spectrometric measurements on Earth. Two restrictions are placed on these measurements apart from the brightness of the comet which normally should be greater than 10th magnitude. These are the atmospheric restrictions which make many regions of interest in the spectrum inaccessible from the Earth and the limited spatial resolution which is possible even with the largest telescopes.

Spectrophotometric measurements from a location in Earth orbit will certainly overcome the atmospheric difficulties but will add little to the spatial resolution. Measurements from a spacecraft near the comet will however solve both problems allowing the full spectrum to be observed with good spatial resolution. It should be pointed out that no advantage in brightness, for a given field of view, is obtained by going nearer the comet since it is a diffuse light source, although a much smaller magnification will be required to obtain the same spatial resolution.

Spectral measurements from a spacecraft can be achieved with a moderate viewing system (5" telescope) which will resolve an area approximately 500 km diameter at a distance of about 10^5 km. This would seem adequate resolution for a scanning spectrometer observing a typical comet with a coma of say 10^4 km diameter and a tail some 10^5 km long. The weight of this unit would be in the region of 15-20 lbs. with a power requirement of approximately 5 watts including the scanning mechanisms. The information obtained from a single coarsely measured spectrum would be about 200 bits. For a spectral measurement every 5 minutes, the transmission rate would be less than 1 bit/sec.

4.4 Mass Spectrometry

The mass spectrometer offers a method of directly sampling the cometary atmosphere. Mass spectrometers are being developed for space flight and will respond to ion fluxes of about 10^5 ions/sec for mass numbers up to 45, which will include the most probable ions present OH^+, CO^+, CH^+, CO_2^+.

A mass spectrometer suitable for measuring ion concentrations in cometary comas can probably be made to weigh less than 10 lbs. The power requirement is relatively high at about 8-10 watts. If 15 bits of information are allocated for a readout of the 45 channels every 45 seconds the information rate will be 15 bits/sec. It is unlikely that the mass spectrometer can be used to detect neutral molecules because of the probable low ionization efficiency.

4.5 Solid Particle Detection

The spectral continuum from cometary atmospheres indicates the emission of dust particles from the nucleus along with the gaseous releases (Vanysek 1952, 1958). This is further substantiated by the relatively high dust concentrations which are in evidence in the orbits of comets and which are observed as meteor showers on Earth. However it is not possible at present to predict with any assurance the expected dust density in a cometary coma or tail. The actual solid particle flux experienced by a spacecraft intercepting a comet will be largely a function of the particular comet.

An acoustic detector is probably the least likely detector to be degraded by a high particle flux and is currently available with a sensitivity of 3×10^7 dyne-sec. However this will only detect particles with a mass of 10^{-12} gms at a relative velocity of 3 km/sec (i.e., 1μ particles). Thus the detector will just detect the smallest particles expected. The weight of the detector with an effective area of 10 cm^2 should be 2 lbs. or less and the power required should be less than 1/4 watts. An allocation of 1 bit/sec per channel will probably cover most periodic comet intercepts.

An extension of the measurements on dust particles would be to capture a few dust paricles and analyze them chemically on-board the spacecraft. However this type of experiment can be very demanding in weight, power and transmission requirements.

4.6 Television

The nucleus of a comet is relatively small, 1-10 km, which makes it difficult to consider either orbiting or landing on it. The spectrum of a nucleus seems always to be a continuum of reflected sunlight and so little information on its solid constitution can be gained by direct spectroscopy. Television, although of value, will not in itself be sufficient to analyze a nucleus. It will however aid in answering the question of its macroscopic construction. Even a system with moderate resolution should enable a cloud of particles to be distinguished from a solid ice nucleus. In addition to this minimal information on the construction of a nucleus, data should be obtained on its size, shape and albedo.

It has been shown (STL 1963) that a fairly sophisticated TV system should be able to resolve about 200 meters from a distance of 10,000 km. This resolution would only be adequate to discern whether a nucleus is split in two or three large fragments but is probably not sufficient justification for the television system. However in the cases where a 1000 km miss distance is anticipated, a television system should be included even in the face of the high relative velocity of the spacecraft.

State of the art stable platforms and tracking systems would seem adequate.

The weight of the television system should be about 10 lbs. and it will require about 10 watts of power. The television picture can be adequately resolved into 70 elements each with 5 levels of gray. A total of 350 bits/picture would then be required.

4.7 Detailed Experimental Payloads

Three basic experimental payloads have been compiled from the foregoing considerations. A basic assumption has been that the Deep Space Instrumentation Facility (DSIF) network will be available 8 hours per day to receive transmissions from the cometary missions. Further, it is assumed that 24 hour coverage will be possible for one or two days at the time of intercept.

The bit rates quoted in the following experimental payloads are estimated for the intercept phase. In general this will occur when the communications distance is near a maximum and when the most data is being obtained. Thus they represent a maximum demand on the communications systems. Table 3 represents a minimal fly-by payload for a mission where miss distance to the nucleus is of the order of 10,000 km. In this case the scientific return will be primarily particles and fields data acquired in passing through the coma.

Table 3

EXPERIMENTAL PAYLOAD 1

(Cometary particles and fields payload)

Experiment	Weight lbs.	Power watts	Bits/sec	Remarks
Plasma probe (Faraday cup)	4	1	2.5	20 energy levels per minute. Real time transmission 8 hrs/day and intercept
Magnetometer (Rubidium)	6	8	0.25	3-dimensional field. Real time transmission 8 hrs/day and intercept.
(Fluxgate)	2	0.1	5	1 measurement/plasma energy level (3 secs). Real time transmission 8 hrs/day and intercept.
Mass spectrometer	10	10	10	45 channels/minute, 1000 km resolution during intercept. Nominal bit rate during interplanetary flight.
Micrometeorite (acoustic)	3	0.25	1	Integrate counts and read out each minute during intercept. Nominal bit rate during interplanetary flight.
	25	19.35	18.75	
Engineering data			2	
Approximate totals	25 lbs.	20 w	20 bits/sec	

Table 4

EXPERIMENTAL PAYLOAD 2

(For missions with velocity matching at intercept)

Experiment	Weight lbs.	Power watts	Bits/sec	Remarks
Plasma probe (Faraday cup)	4	1	20	20 energy levels/min. Measured all day & transmitted 8 hrs/day & intercept.
Magnetometer (Rubidium)	6	8	1	1 reading/2 mins. Measured all day & readout for 8 hrs/day. Also throughout intercept phase.
(Fluxgate-normal)	5	0.1	15	1 reading/3 secs to match plasma probe. Measured all day transmitted 8 hrs/day & at intercept.
Spectrophotometer	20	5	1	1 spectrum/5 mins. Real time transmission during approach & intercept.
Mass spectrometer	14	10	20	45 channels/30 secs. (500 km resolution). Real time transmission at intercept. Nominal bit rate during interplanetary flight.
Micrometeorite (acoustic plus stand-by detector)	10	0.35	10	Integrate counts in 10 momentum channels. Transmit real time at intercept. Nominal bit rate during interplanetary flight.
Television	10	10	50	15 pictures/hr. Transmit real time during intercept.
	69	34.45	117	
Engineering data			10	
Approximate totals	70	35 w	125 Bits/sec	

Total data storage required = 10^5 bits

Table 5

EXPERIMENTAL PAYLOAD 3

(Full experimental payload with unrestricted data rate)

Experiment	Weight lbs.	Power watts	Bits/sec	Remarks
Plasma probe (Faraday cup)	4	1	20	20 energy levels/min. Measured all day & transmitted 8 hours/day & intercept.
(fast response)	6	5	100	10 min/day transmitted over 8 hrs. Also throughout intercept phase.
Magnetometer (Rubidium)	6	8	1	1 reading/2 mins. Measured all day & transmitted 8 hrs/day.
(Fluxgate-normal)	5	0.1	15	1 reading/3 secs to match plasma probe. Measured all day. Transmitted 8 hrs/day & intercept.
(fluxgate-fast response)		1	400	10 min/day transmitted 8 hrs/day. Also throughout intercept phase.
Spectrophotometer	20	5	1	1 spectrum/5 mins. Real time transmission during approach & intercept.
Mass spectrometer (with	14	10	20	45 channels/30 secs (500 km resolution). Real time transmission at intercept. Nominal bit rate during interplanetary flight.
Micrometeorite (acoustic plus stand-by detector)	10	0.35	10	Integrate counts in 10 momentum channels at intercept. Nominal bit rate during interplanetary flight.
Television	10	10	50	15 pictures/hr. Transmit real time during intercept.
	75	40.45	617	
Engineering data			10	
Approximate totals	75 lbs.	40 w	625 Bits/sec	

Total data storage required = 105 bits.

Table 4 represents a payload suitable for a mission where the velocity is matched with the comet. The resulting small relative velocity reduces the need for the fast response plasma probe and magnetometer. However a television system is incorporated which can provide 15 pictures per hour.

Table 5 represents an extension of Table 4 in that more information is obtained from the experiments and a larger bit rate is required. No terminal velocity correction is involved.

5. SELECTION CRITERIA FOR COMET INTERCEPT MISSIONS

A set of criteria by which to select comets for intercept missions have been reported previously (Roberts 1964b, Narin and Pierce 1964, Narin and Rejzer 1965). They are summarized here. Comets only become visible as they approach perihelion and become influenced by solar radiation*. They are brightest and most active and therefore most interesting near perihelion. Typically a periodic comet is visible for about 10 percent of each orbit. Thus a reasonable restriction on comet missions is that intercept is required near perihelion.

The orbital elements of periodic comets are subject to changes due to the perturbative effects of the planets and secular perturbations including those due to mass loss while the comet is near the Sun. In calculating the changes in

* Exception is the "annual" comet Schwassmann-Wachmann 1 which can be observed at some time each year. Oterma was an annual comet until perturbed by Jupiter in 1963.

parameters due to perturbations (Narin, Pierce 1964) the major sources of error were felt to be due to inaccuracies in the starting elements and dates. Thus to minimize these errors, only comets which have been observed on two recent passages have been included. Even so, it is still considered necessary to observe a comet for a period of two months prior to the launch of an intercepting spacecraft in order to check its orbit. The limiting conditions for the sighting on each passage (recovery) of a comet are a brightness of magnitude 20 and visibility for a period of about two hours in a dark sky. The relative positions of the Sun, Earth and comet and the brightness of the comet on approach to the Sun makes it impossible to recover many of them in sufficient time before perihelion to launch a spacecraft.

Scientifically it is almost essential that the comet should be visible from Earth during the intercept phase. This allows correlatable data to be obtained between Earth observations and spacecraft measurements. The most important Earth-based measurements will be spectroscopic and for these a magnitude 10 brightness is required. Many periodic comets cannot fulfill this requirement at perihelion in the next 20 years.

A further standard to be met is that sufficient should be known of the intercepted comet prior to the mission to permit the instruments and their sensitivities to be selected within reasonable limits. This means that the comet should have been observed in reasonable detail prior to the passage at which intercept is planned. However, many of the intervening passages will offer very poor visibility from Earth.

Finally a trajectory analysis must be performed to determine the ideal velocity, time of flight and relative velocity at intercept for suggested missions.

Table 6 gives a list of comets which, overall, are considered most suitable for comet missions in the next 20 years. It can be seen from the list, that even of these best choice comets, there are none which represent ideal missions in all respects. However a mission profile has been compiled for each of these intercept opportunities and are described in Section 7.

6. MISSION CONSTRAINTS

The major constraints on intercept missions to periodic comets are caused by the nature of the comet itself. Because of the continual perturbations to comet orbits, and the fact that they can be observed only over a small part of their total orbit, it is difficult to predict accurately the future position of any comet. This fact together with the small size of the nucleus makes close fly-by missions (1000 km or less) heavily dependent on midcourse and terminal guidance and control. This is accentuated by the invariably high spacecraft approach velocity (typically 10-20 km/sec). These and the more normal mission constraints are considered below.

Table 6

COMETS SELECTED FOR INTERCEPT MISSIONS*

Comet Perihelion date	Launch Date	Ideal Velocity (30 day window) (ft/sec)	Approach Velocity (km/sec)	Time of Flight (days)	Intercept				60 Days before Launch	
					Days from Perihelion (days)	Comm. Distance (AU)	Magnitude	Visibility at ± 25° Lat. (hrs)	Magnitude	Visibility at ± 25° Lat. (hrs)
Tempel 2 13 Aug 1967	1 Apr 67	43,000	11-12	110-135	1 before	0.42	10	7/10	18	4/3
Encke 28 Apr 1974	13 Sep 73	44,400	28	240-270	30 after	0.38	9	1/4	22	5/6
Encke 28 Apr 1974	7 Feb 74	47,700	35-38	80-110	43 after	0.40	8	0/2	18	5/4
D'Arrest 13 Aug 1976	21 Apr 76	41,000	13	100-130	0	0.18	7	7/9	17	5/4
Kopff 18 Aug 1983	26 Feb 83	43,000	8	175-190	15 after	1.0	12***	4/6	17	3/2
Halley 8 Jan 1986	Jul 85	42,500	69	210	40 after	1.25	5	2/3	16	Poor**

* The same data for all other comets considered are given in previous reports (Narin, Pierce 1964, Narin, Rejzer 1965).

** Visibility of Halley is good before and after conjunction with the Sun which occurs during May 1985.

***This is less bright than desired but has been included because of the low approach velocity.

6.1 Functional Constraints

6.1.1 Recovery

An essential aspect of a comet intercept mission is that the return of the comet be confirmed sufficiently in advance of the launch date. A lead time of 60 days is considered adequate here. The recovery of the comet is the starting point for a final, accurate determination of the orbit of the comet and of the position of the comet in the orbit. In order that the miss distance may be minimized it will be essential to continue the reduction of the orbital errors up to launch and during the mission.

6.1.2 Comet Seeker

For a miss distance of less than 10,000 km it will be necessary to complement even the most accurate Earth-based observation with an on-board comet seeking photometer. The advantage of the spacecraft comet seeker is that it provides a long and calculable baseline between the spacecraft and the Earth for triangulation measurements. The position of the spacecraft relative to the Earth can be accurately determined using the DSIF network. A combination of a 1 second of arc accuracy on an Earth-based telescope with a 0.1° accuracy on a comet seeker at a million miles from a comet and 1/2 AU from the Earth can give a positional accuracy on the comet nucleus to within about 1000 km. The biggest problem with an on-board comet seeker could be recognition of the comet during the early part of the mission. It is probable that this can be achieved spectroscopically by examining the image for known strong lines in the cometary emission spectra. However such a system would require considerable development and it is only an assumption at this time that final miss distances of the order of 1000 km can be achieved.

6.1.3 Guidance and Control

The way in which the guidance and control requirements have been treated is explained in more detail in Appendix 2. The problems must be considered for each individual comet in the light of the knowledge of the orbit of the comet at the time of launch. In the mission profiles of the next section a miss distance is quoted which is based on the present knowledge of the comets and on the fact that some will have apparitions before the intercept passage and will be carefully observed at that time.

Correction of the miss distance is considered in three phases. The first phase is the correction of launch errors a few days after the launch. An average velocity increment of about 17 m/sec is assumed for this. For all the comets selected it is assumed that their positions will be well enough known to anticipate a miss distance of 100,000 km after this first correction. The second phase occurs about midway through the flight but not less than 3 months after launch. The anticipated miss distance after this maneuver is 10,000 km but this must depend on how well the continued

Earth observations and possibly the comet seeker data have reduced the residuals in the comet's orbital parameters. The third and final phase relies to a great extent on the comet seeker and is used to reduce the miss distance below 10,000 km and in some cases to 1,000 km. This maneuver will take place about a day before intercept and will require a major portion of the propulsion capability.

6.1.4 Launch Window

The values of ideal velocity (ΔV) and approach velocity (VHP), given for the comet missions in Table 6 are quoted for a thirty day launch window. These parameters are calculated at 5 day intervals throughout the period of interest for a number of flight times (TF). The minimum values of ΔV with corresponding values of VHP and TF are then plotted as a function of launch date. A thirty day period surrounding the optimum launch date is selected as the launch window. The value of ideal velocity quoted is the maximum over this launch window, and the corresponding range for VHP and time of flight are quoted.

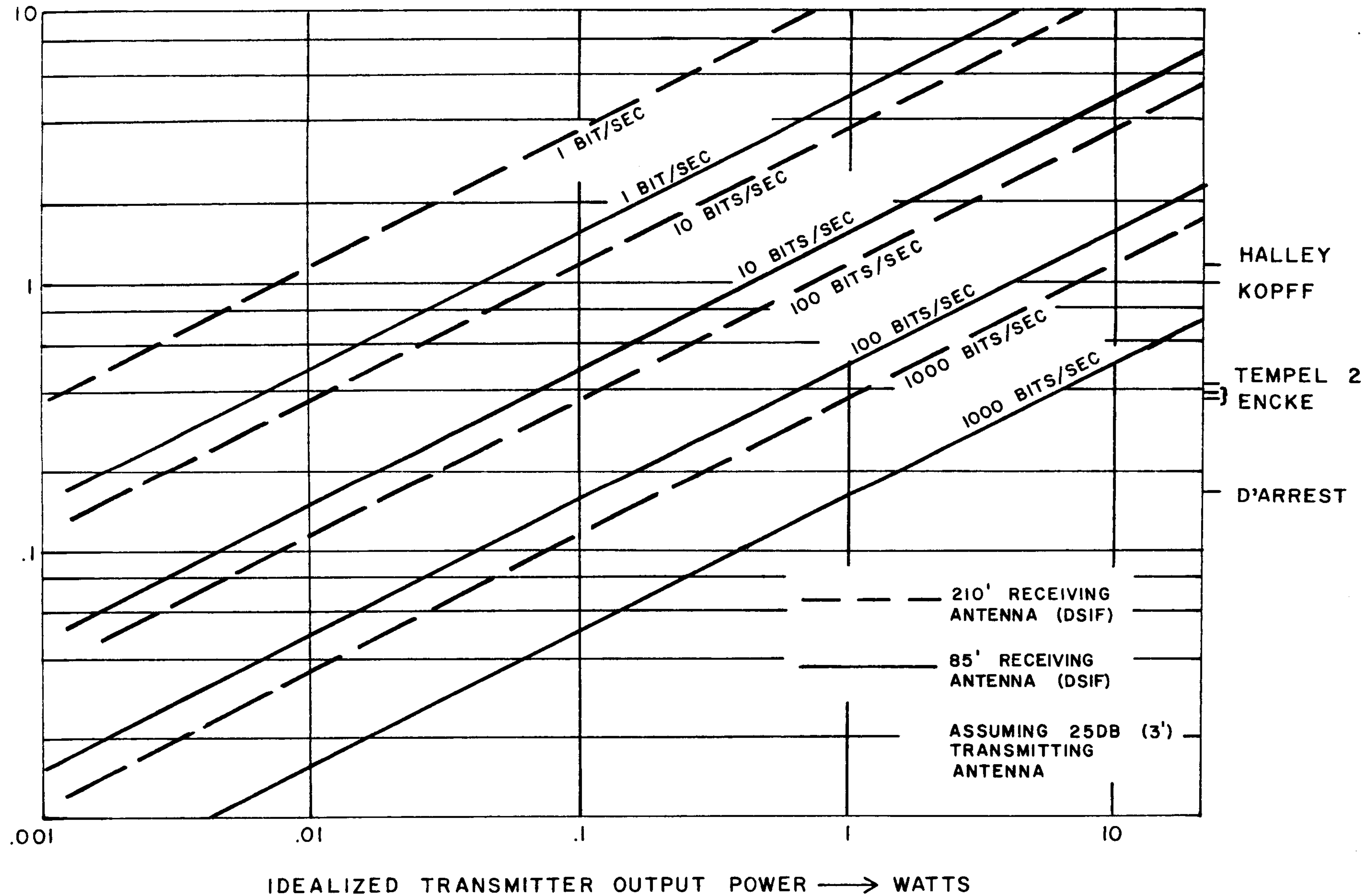
6.1.5 Attitude Control

The comet missions considered will require the spacecraft to be oriented and stabilized. Since all the missions will require a fixed directionality for either solar cells, a directional antenna, or both, spin stabilization has not been used. However it is possible to consider a spacecraft which is spin stabilized during the interplanetary flight and only has a fixed orientation at intercept. The amount of attitude control propulsion assigned to each mission is proportional to the weight of the spacecraft and the duration of the flight.

6.1.6 Communications and Telemetry

The communications and telemetry equipment necessary for each mission is governed by the required bit rate and the distance over which the information must be transmitted. Figure 1 shows a graph of idealized transmitter output power as a function of communications distance and information rate. The system is idealized only insofar as an allowance of only -3 db has been made for the performance coefficient. Idealized performance is assumed for the mission to Halley's comet in 1986. The raw power supplied to the transmitter is assumed to be 10 times the transmitted power.

Of the three experimental payloads discussed in Section 4, the most prominent difference is the information rate and the effect of this has been included in the mission profiles. An inherent part of the payloads will be a data storage capacity which ranges from 10^4 to 10^7 bits/day. A considerable portion of this storage capacity will be required throughout the mission for the fast response plasma probe and magnetometer. The demands made on the communications and telemetry system will be greatest during intercept. During much of the interplanetary phase of the missions, the smaller communications distance and the lower rate of acquisition of data may considerably reduce the communications power requirement.



TRANSMITTER POWER (WATTS) VS. RANGE AND INFORMATION RATE
FIGURE 1

6.1.7 Power Supply

The type of power supply used in the missions has been determined by the launch date and by the type of mission. A solar cell power supply has been selected for the first comet mission to Tempel 2 in 1967. However there is an unknown but possibly considerable risk of micrometeorite damage to the large area panels on passing through the coma. The other six comet missions incorporate isotopic power units which are largely resistant to micrometeorite damage. However they do impose a small penalty in that they may require nuclear shielding. A specific weight of 0.75 lbs/watt is assumed for solar cell power supplies and 1 lb/watt for isotopic units.

6.1.8 Reliability

The reliability coefficient which can be attached to each of the suggested missions has not been considered in any detail and no allowance has been included in the payload weights because of reliability requirements.

6.2 Experimental Constraints

One of the problems in gaining the optimum scientific value from an intercept mission is the difficulty of being able to determine beforehand the required instrument sensitivities. Despite the fairly good general knowledge of comets, there is little detailed knowledge of the constitution of short period comets because of their usual faintness and inactivity. Thus when missions to specific comets are discussed there is little information on which to base the sensitivity of the individual measuring instruments. This will apply to the ion densities, the size and albedo of the nucleus, the dust density and the magnetic field intensity. Thus some measurements will have to be designed on a best guess basis tempered with what information can be gained from observation of passes before the one to be intercepted. In general, however, the same perihelion passages which are selected for missions are also best for observations from Earth, and prior apparitions will probably not add a great deal to the detailed knowledge of the comet. For such phenomena as the magnetic field associated with a comet, the first measurements will have to be made relying on a magnetometer range which will cover two decades above the interplanetary field intensity.

A second limitation in intercept experiments is imposed by the high spacecraft approach velocity which reduces the spatial resolution for a given instrument response time. However, unless a velocity reduction of two orders of magnitude or more can be achieved at intercept, it is perhaps easier to improve instrument performance. For most missions the propellant weight required to achieve the desired velocity range of 10-100 m/sec seems prohibitive. A mission to Kopff in 1983 is one example where a retro-maneuver to remove the 8 km/sec approach velocity is just about feasible.

A further experimental constraint is the requirement that the spacecraft data are correlatable with simultaneous observations from Earth where possible. One of the major objectives of early intercept missions is to provide verification of the interpretation of Earth-based measurements including the cometary spectra, the dust concentration, the dust particle sizes and the models of the nucleus. This requires that the comet be fairly bright and definable at intercept, which for periodic comets means that they should be fairly near to the Earth. This constraint has been included in the selection criteria for the comets listed in Table 6.

6.3 Environmental Constraints

The anticipated flux of dust particles in the coma is expected to be quite large compared with interplanetary space or even with meteor streams which, in the few cases where data have been obtained, have given count rates of a few per minute. The relatively high flux presents a hazard in terms of collision with the spacecraft. The main structure of the spacecraft can probably survive micrometeorite erosion but many of the electronic components will require shielding. The most difficult items to shield will be the instruments with apertures that must be directed towards the nucleus. These include the plasma probes, mass spectrometer, the comet seeker, and the television system. The magnetometers which must be magnetically exposed may also require shielding. It is not possible to determine the full extent of micrometeorite damage on passing through a coma and certainly it will vary from comet to comet. For the moment, a gross weight allowance has been made but this should be considered in more detail for the final spacecraft design.

Radiation damage to the spacecraft in the vicinity of the comet should be no different from that in the interplanetary medium. The main sources will be the solar wind, solar protons, cosmic rays and perhaps electromagnetic radiation from the Sun. For the comet missions discussed later, one is suggested with solar cells as a power supply. The other six have been assigned a radioactive isotopic power supply with its inherent radiation hazard.

The temperature of the spacecraft is governed largely by its heliocentric distance and to some extent by its attitude. For all the missions considered, present technology is adequately developed to maintain all parts of the spacecraft within working temperature limits. This may be achieved through heat barriers, reflective coatings, louvers or if necessary through local temperature controlled enclosures.

7. SUMMARY OF COMET MISSIONS

A total of five comet apparitions have been selected as the most suitable for intercept missions in the next two decades. The selection has been made from all the apparitions of those periodic comets which have been observed on at least two recent passages and which will pass through perihelion before 1986. Of the 110 apparitions considered, the five chosen provide the best combination of early recovery, brightness at perihelion, and amenable flight parameters for the mission. Table 7 lists seven missions to the five comets and shows the high approach velocity which typically occurs with direct flights to periodic comets.

Table 8 lists the specific impulse which would have to be applied at the comet in order to match the spacecraft and comet velocities. The payload fraction is defined as the ratio of the weight of the spacecraft traveling with the comet (i.e. after the terminal maneuver) to the total weight injected into the transfer orbit from Earth to the comet. Tankage is defined as the structure and adapter of the terminal maneuver rocket system and given as a percentage of the total weight injected from Earth orbit. Although the tankage also attains a velocity match it is not included in the above useful spacecraft weight. The calculated I_{SP} values assume 600 m/sec for midcourse guidance and the approach velocity quoted. Three payload fractions are included, i.e. zero, 0.05 and 0.1 and in each case tankage percentages of 5% and 10% have been assumed. It can be seen

Table 7

SUMMARY OF COMET INTERCEPT MISSIONS

Comet	Mission Type Miss Distance from Nucleus	Ideal Velocity (30 day window) ft/sec	Approach Velocity km/sec	Time of Flight days	Experimental Payload Wt. lbs.	Total Spacecraft Wt. without Shroud, lbs.	Launch Vehicle
Tempel 2 Aug 1967	Fly-by 10,000 km	43,000	11-12	110-135	25	180	Atlas-Agena
Encke Apr 1974	Fly-by 1000 km	44,400	28	240-270	75	650	SLV 3X-Kick
Encke Apr 1974	Fly-by 1000 km	47,700	35-38	80-110	75	800	SLV 3X-Centaur-Kick
D'Arrest Aug 1976	Fly-by 1000 km	41,000	13	100-130	75	535	Atlas-Agena
Kopff Aug 1983	Fly-by 1000 km	43,000	8	175-190	75	700	Atlas-Centaur
Halley Jan 1986	Fly-by 1000 km	42,500	69	210	75	1635	SLV 3X-Centaur
Kopff Aug 1983	Fly-by with Vel. match 1000 km	43,000	8	175-190	70	9650	Saturn 1B-Centaur

Table 8

SPECIFIC IMPULSE REQUIRED TO REDUCE APPROACH VELOCITY TO LESS THAN 100 M/SEC

Comet	Approach Velocity	I_{SP} for Zero Payload Fraction*		I_{SP} for 0.05 Payload Fraction		I_{SP} for 0.1 Payload Fraction	
		5% tank**	10% tank.	5% tank.	10% tank.	5% tank.	10% tank.
Tempel 2 (1967)	11-12	475 secs	510 secs	510 secs	625 secs	625 secs	736 secs
Encke (1974)	28	1170	1265	1265	1535	1535	1810
D'Arrest (1976)	13	555	596	596	730	730	865
Kopff (1983)	8	350	380	380	430	430	545
Halley (1986)	69	2670	2900	2900	3520	3520	4150

* The payload fraction is defined as the ratio of the weight of spacecraft traveling with the same velocity as the comet to the weight injected into a transfer orbit from Earth. (600 m/sec is allowed for midcourse guidance.)

** Tankage refers to the "dry" weight of the terminal rocket as a percentage of the total weight with propellant.

from the table that almost all the required I_{SP}'s are way beyond the state of the art for storable propellants. The only possible opportunity is for Kopff in 1983 and for an 0.05 payload fraction and only 5% tankage the required I_{SP} is 380 secs. Even this would seem optimistic for storable chemical propellants. By way of an example the Kopff velocity matched mission has been included in the mission profiles.

The conclusion is that velocity matching for almost all comet intercept missions is not only difficult but it impossible chemically. In general it appears that modes of flight other than direct will be necessary to achieve a velocity match with comets. Obvious possibilities are gravity assist maneuvers or thrusted trajectories.

7.1 Mission to Periodic Comet Tempel 2 (1967)

Tempel 2 has made 13 observed appearances since it was discovered in 1873. Although it never appears brighter than magnitude 10 it has been recovered as much as 419 days before perihelion. At perihelion in 1967 the Earth will be as close as it ever gets to the comet and an early recovery should be almost certain. The limited spectral data on Tempel 2 shows CN and C as the strongest lines but no reflection continuum is indicated (Bobrovnikoff 1927). A coma diameter of 5×10^4 km may be anticipated from past appearances.

The mission characteristics are summarized in Table 9 and Figure 2. The mission which has been selected and for which the payload is given in Table 10, is for a 2[illegible]0 lb. payload launched with an Atlas-Agena. The small payload has been chosen partly because of the relatively short lead time if this mission is to be accomplished and partly because it would be the first exploratory comet mission. No major advances would be required in present technology to generate this spacecraft which would be essentially an extension of the Pioneer series. The estimated miss distance of 10,000 km is assumed to be possible using Earth-based observations of the comet from recovery and throughout the mission. It is not thought that a suitable comet seeker will be available for the mission. In view of the relatively large miss distance it has not been necessary to include in the payload any instruments to observe the nucleus. Rather the emphasis is placed on obtaining, for the first time, particle and field data from the coma of the comet.

Table 9

SUMMARY OF CHARACTERISTICS FOR MISSION TO TEMPEL 2 (1967)

Orbital Parameters for Tempel 2

Period	5.26 yrs	Eccentricity	0.550
Semi-major axis	0.32 AU	Long. of asc. node	119.3°
Inclination	12°	Arg of perihelion	191°

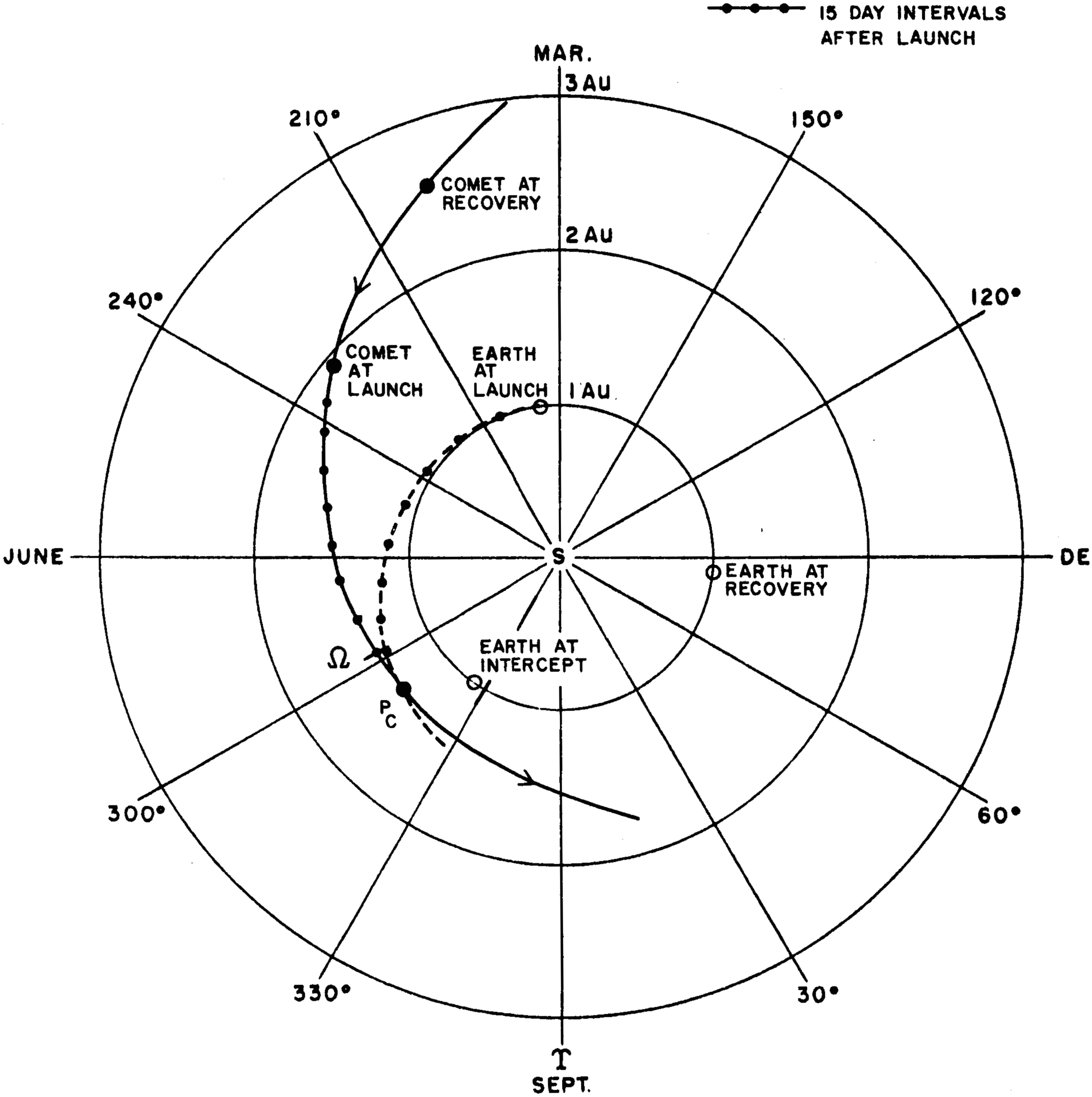
Mission Characteristics

Perihelion date	13 Aug 1967
Launch date	1 April 1967
Flight time (TF)	110-135 days
Communications distance (RC)	0.42 AU
Ideal velocity (ΔV)	43,000 ft/sec
Approach velocity (VHP)	11-12 km/sec
Recovery	110 days before launch
Expected miss distance	10,000 km
Time passing through coma	1 hour
Magnitude at intercept	10

Launch Vehicle Payload Capability

Tat Improved Delta	125 lbs.
Atlas-Agena	250 lbs.
Atlas-Centaur	1300 lbs.

TEMPEL 2



P_C = PERIHELION OF COMET

Figure 2 135 DAY TRAJECTORY TO TEMPEL 2

Table 10

PAYLOAD FOR TEMPEL 2 FLY-BY MISSION (1967)

Experimental Payload 1 (see page 24)	25	lbs.
Transmitter (2 watts 20 b/sec 85' DSIF)	5	
Antenna (18 db 1.5' dia)	5	
Data encoder, storage, etc.	15	
Power supply (50 watts solar cell)	40	
Batteries	5	
Comet seeker	--	
Shielding	5	
Structure	50	
Guidance and attitude motors (less propellant)	10	
Spacecraft weight at intercept	160	lbs.
Attitude propellant	10	
Midcourse propellant (100 m/sec I_{SP}= 225 secs)	10	
Spacecraft weight at start of trajectory	180	lbs.
Effective weight of shroud and adapter	60	
Total effective payload weight	240	$^{-0}_{+10}$% lbs.

Launch Vehicle

Atlas-Agena

7.2 Missions to Periodic Comet Encke (1974)

Due to the short orbital period of Encke it has been observed on no less than 47 perihelion passes. The short perihelion distance (0.3 AU) makes it relatively bright near perihelion but it is difficult to observe because of its proximity to the Sun. Consequently intercept is preferred at about 40 days after perihelion.

The frequent observation of Encke has resulted in well established orbital parameters and well calculated perturbative influences. The secular perturbation indicates a mass loss of some 0.2% per orbit (Whipple 1950), and the dust fraction apparently contributes to the Taurid meteor showers. However no reflection continuum is observed in the spectra of Encke and it is assumed to have a primarily gaseous coma and tail. The compounds which have been detected in the coma of Encke are CN, C_2, C_3 (stronger in 1947 than in 1937), NH, OH (not as strong as NH), and CH (Swings and Haser 1961). No reliable figures are available for the actual densities of the gases or the dust in the coma. The nucleus diameter has been estimated as 3 km and a coma diameter of 10^5 km may be anticipated.

The mission characteristics for two possible missions are outlined in Table 11 and in Figures 3 and 4. The respective payloads are summarized in Tables 12 and 13.

One of the essential differences between the missions is the flight times which for mission 1 requires launch possibly before recovery of the comet. This however is not an extreme constraint for Encke since it is probably the most predictable of all comets from orbit to orbit. Neither of the flight times is likely to present reliability problems by 1974. The significant differences in ideal velocity required for the missions are reflected in the listed vehicle-payload combinations. The approach velocity is high for both cases.

The payload combination chosen for mission 1 (Table 12) relies on a fairly close passage of the nucleus to justify the full experimental payload with an unrestricted data rate. This miss distance will not be easy to accomplish even though the orbital elements for Encke are well established. Redundancy has been included in the form of a duplicate comet seeker. Also 800 m/sec has been allowed for midcourse guidance.

Mission 2 (Table 13) has been allocated the same full experimental payload with an unrestricted data rate. The same miss distance of 1000 km requires an allowance of 1 km/sec for midcourse guidance because of the higher approach velocity.

Table 11

SUMMARY OF CHARACTERISTICS FOR MISSIONS TO ENCKE (1974)

Orbital Parameters for Encke

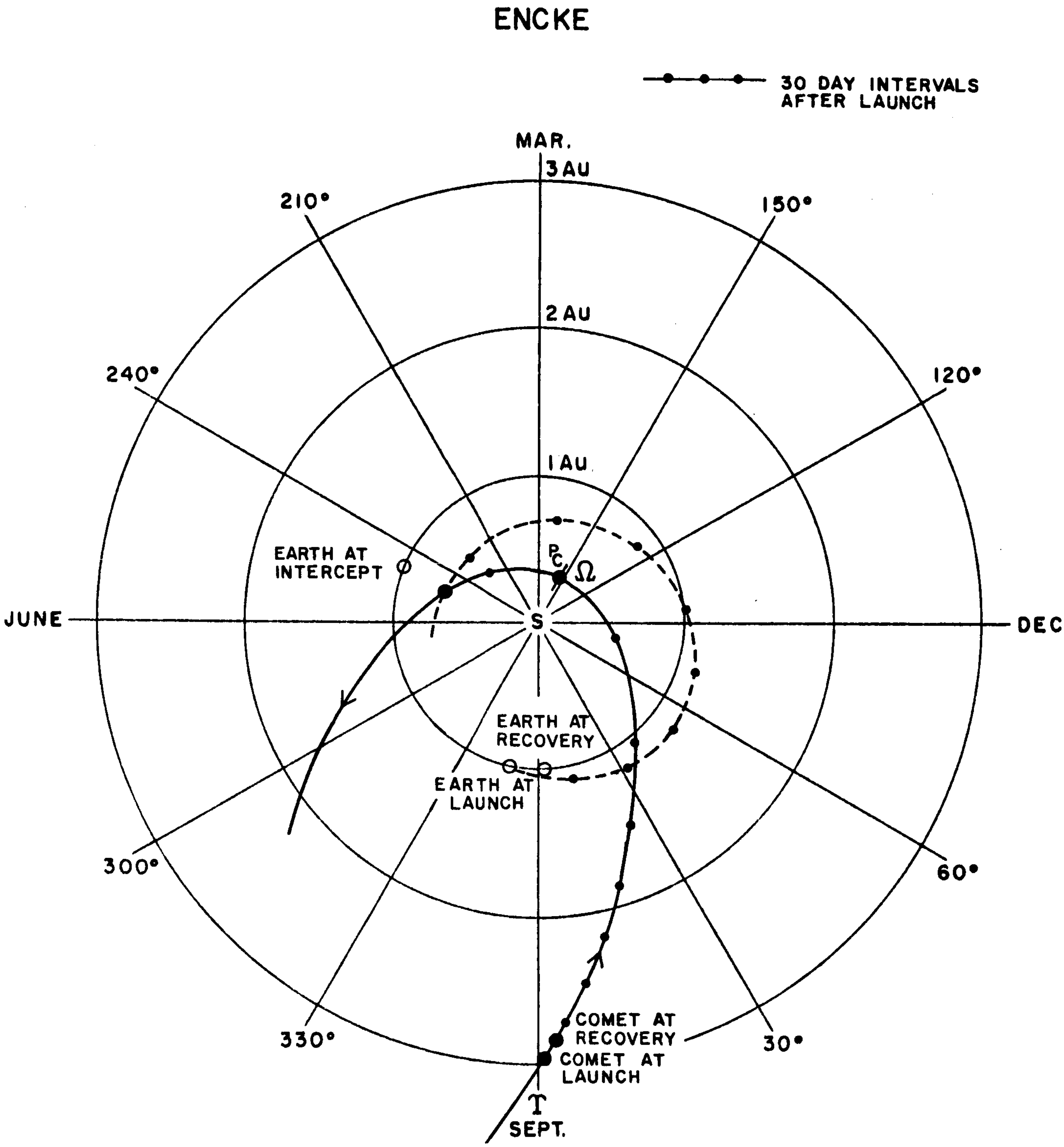
Period	3.3 yrs	Eccentricity	0.847
Semi-major axis	2.22 AU	Long. of asc. node	334°
Inclination	11.9°	Arg of perihelion	186°

Mission Characteristics

	Mission 1	Mission 2
Perihelion date	28 Apr 1974	28 Apr 1974
Launch date	13 Sep 1973	7 Feb 1974
Flight time (TF)	240-270 days	80-110 days
Communications distance (RC)	0.38 AU	0.40 AU
Ideal velocity (ΔV)	44,400 ft/sec	47,700 ft/sec
Approach velocity (VHP)	28 km/sec	35-38 km/sec
Recovery (days before launch)	0	160
Expected miss distance	1000 km	1000 km
Time passing through coma	1 hour	40 minutes
Magnitude at intercept	9	8

Launch Vehicle Payload Capability

Tat-Kick	450 lbs.	-- lbs.
SLV 3X-Kick	1300	700
SLV 3X-Centaur-Kick	3200	1200
Saturn 1B-Centaur	8000	5000



P_C = PERIHELION OF COMET

Figure 3 250 DAY TRAJECTORY TO ENCKE (MISSION 1)

Table 12

PAYLOAD FOR ENCKE FLY-BY MISSION 1 (1974)

Experimental payload 3 (see page 26)	75 lbs.
Transmitter (2 watts 625 b/sec 210' DSIF)	5
Antenna (25 db 3' dia)	10
Data encoder, storage, etc. (10^7 bits storage)	30
Power supply (100 watts RTG)	100
Batteries	25
Comet seeker (duplicate)	30
Shielding	20
Structure	75
Guidance and attitude motors (less propellant)	30
Spacecraft weight at intercept	400 lbs.
Attitude propellant	50
Midcourse propellant (800 m/sec I_{SP}= 225 secs)	200
Spacecraft weight at start of trajectory	650 lbs.
Effective weight of shroud and adapter	90
Total effective payload weight	740 $^{-0}_{+5}$% lbs.

Launch Vehicle

SLV 3X-Kick

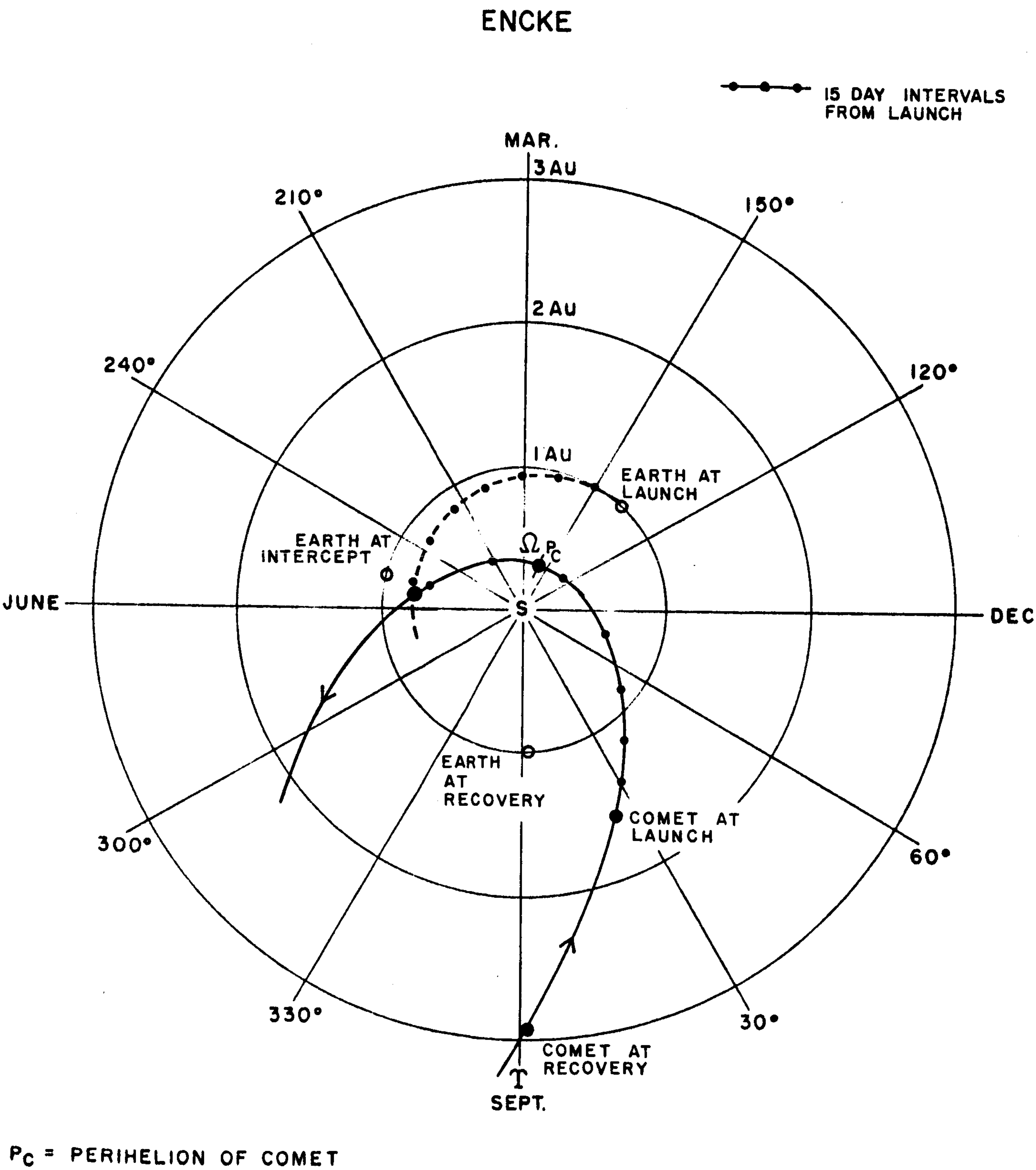


Figure 4 110 DAY TRAJECTORY TO ENCKE (MISSION 2)

Table 13

PAYLOAD FOR ENCKE FLY-BY MISSION 2 (1974)

Experimental payload 3 (see page 26)	75 lbs.
Transmitter (2 watts 625 b/sec 210' DSIF)	5
Antenna (25 db 3' dia)	10
Data encoder, storage, etc. (10^7 bits storage)	30
Power supply (100 watts RTG)	100
Batteries	25
Comet seeker (duplicate)	30
Shielding	20
Structure	75
Guidance and attitude motors (less propellant)	60
Spacecraft weight at intercept	430 lbs.
Attitude propellant	50
Midcourse propellant (1 km/sec, I_{SP} = 225 secs)	320
Spacecraft weight at start of trajectory	800 lbs.
Effective weight of shroud and adapter	100
Total effective payload weight	900 $^{-0}_{+5}$% lbs.

Launch Vehicle

SLV 3X-Centaur-Kick

7.3 Mission to Periodic Comet D'Arrest (1976)

D'Arrest has been observed at 10 perihelion passages since its discovery in 1851. Its orbital elements are well known and the established secular perturbations indicate a mass loss of 0.05% per passage (Whipple 1950). However a fairly large perturbation by Jupiter is expected in 1968 and the calculated change in the orbital parameters will provide an unusually bright (mag 7) apparition in 1976 (Narin, Rejzer 1965). In previous passages the comet has appeared diffuse and too faint for detailed spectroscopic analysis. Thus the final specifications for the experiments on the mission should await observation of D'Arrest in 1970 and the results of missions to other comets. Nevertheless the D'Arrest mission is very attractive from both a trajectory point of view and its expected brightness at perihelion. A visible coma diameter of about 2×10^5 km may be anticipated.

Table 14 lists the characteristics for the mission to D'Arrest in 1976 and the trajectory is shown in Figure 5. The payload listed in Table 15 includes the full experimental payload with the unrestricted data rate. The miss distance of 1000 km should be attainable if a good orbit determination is made in 1970 after the Jupiter perturbation and with a comet seeker on-board. Despite the present lack of detailed knowledge of D'Arrest it still offers the best of the missions considered between 1965 and 1986.

Table 14

SUMMARY OF CHARACTERISTICS FOR MISSION TO D'ARREST (1976)

Orbital Parameters for D'Arrest (1976)

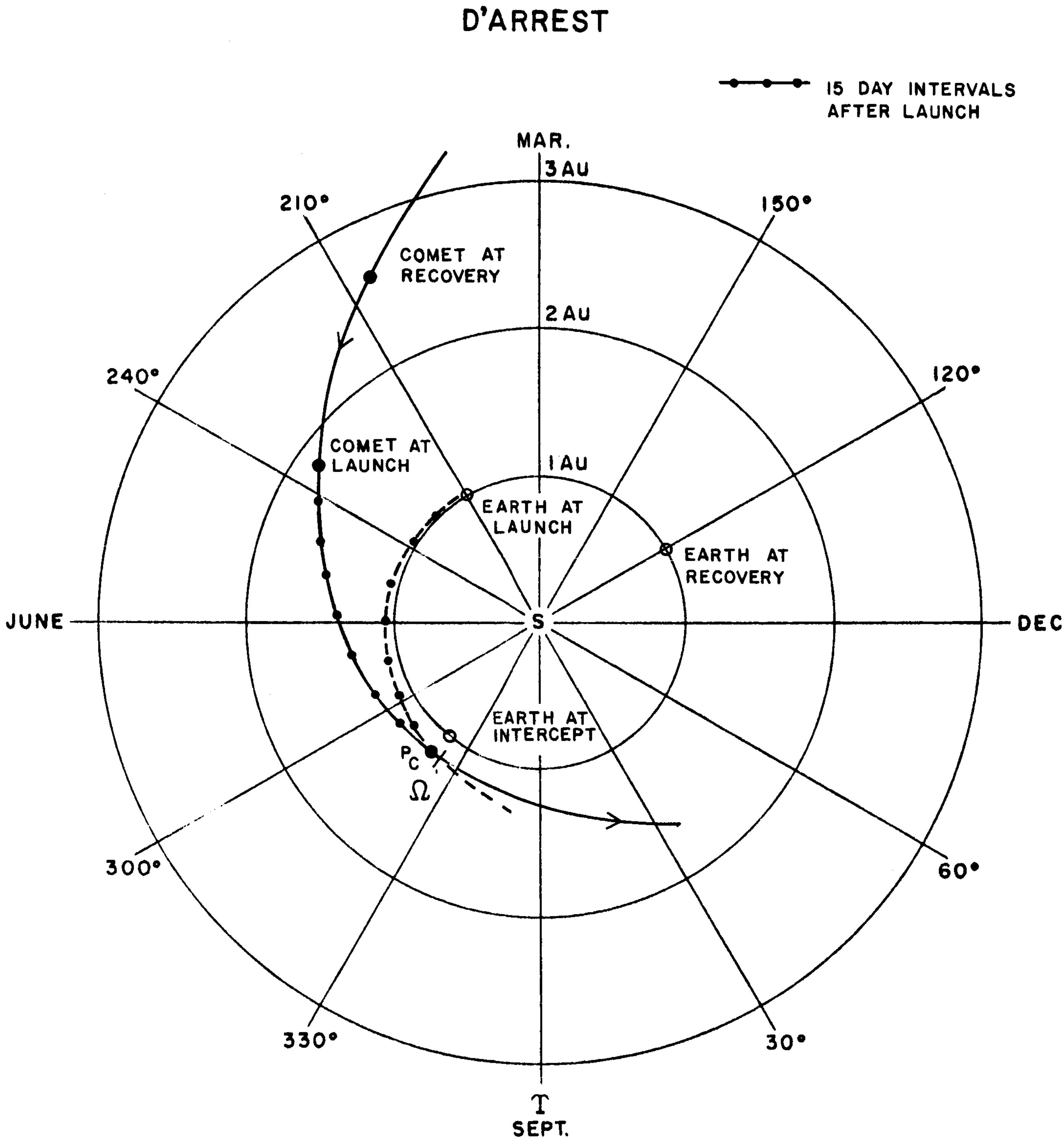
Period	6.1 yrs	Eccentricity	0.655
Semi-major axis	3.39 AU	Long. of asc. node	141.4°
Inclination	16.76	Arg of perihelion	178.9°

Mission Characteristics

Perihelion date	13 Aug 1976
Launch date	21 April 1976
Flight time (TF)	100-130 days
Communications Distance (RC)	0.18 AU
Ideal velocity (ΔV)	41,000 ft/sec
Approach velocity (VHP)	13 km/sec
Recovery	100 days before launch
Expected miss distance	1000 km
Time passing through coma	4 hours
Magnitude at intercept	7

Launch Vehicle Payload Capability

Thor-Kick	620 lbs.
Atlas-Agena	700 lbs.
Tat-Kick	870 lbs.
SLV 3X-Kick	2100 lbs.
Atlas-Centaur	2200 lbs.



P_C = PERIHELION OF COMET

Figure 5 130 DAY TRAJECTORY TO D'ARREST

Table 15

PAYLOAD FOR D'ARREST FLY-BY MISSION (1976)

Experimental payload 3 (see page 26)	75 lbs.
Transmitter (1 watt 625 b/sec 210' DSIF)	5
Antenna (18 db 1.5' dia)	5
Data encoder, storage, etc. (10^7 bits storage)	20
Power supply (100 watts RTG)	100
Batteries	25
Comet seeker (duplicate)	30
Shielding	20
Structure	75
Guidance and attitude motors (less propellant)	20
Spacecraft weight at intercept	385 lbs.
Attitude propellant	30
Midcourse propellant (400 m/sec I_{SP}= 225 secs)	120
Spacecraft weight at start of trajectory	535 lbs.
Effective weight of shroud and adapter	90
Total effective payload weight	625^{-0}_{+5}% lbs.

Launch Vehicle

Atlas-Agena

7.4 Missions to Periodic Comet Kopff (1983)

Kopff has been included in the list of missions principally because it is one of the few periodic comets which offer a feasible rendezvous mission. The detracting feature is that its brightness at intercept will only be about magnitude 12 which will make high quality spectroscopic data difficult to obtain from the Earth. Kopff has been observed on every orbit but one since its discovery in 1906 and for its 1964 apparition its orbit had been well predicted. No clearly defined tail is associated with Kopff but a coma diameter of 10^5 km may be anticipated.

The mission characteristics are shown in Table 16 and the trajectory in Figure 6. Two mission profiles are given in Tables 17 and 18, the first being for a fly-by mission and the second for a fly-by with a velocity matching maneuver at intercept. The fly-by mission incorporates the full experimental payload with an unrestricted data rate. The 1 AU communications distance is the main contributor to the weight of the payload which will require an Atlas-Centaur launch vehicle.

For the mission with velocity matching it can be seen how expensive it is, in weight, to remove the approach velocity. Even so the values given are based on an optimistic I_{SP} = 380 secs and a tankage of only 5%. The payload listed can be launched with a Saturn 1B-Centaur launch vehicle.

Table 16

SUMMARY OF CHARACTERISTICS FOR MISSION TO KOPFF (1983)

Orbital Parameters for Kopff

Period	6.32 yrs	Eccentricity	.556
Semi-major axis	3.42	Long of asc. node	121
Inclination	4.71°	Arg of perihelion	162°

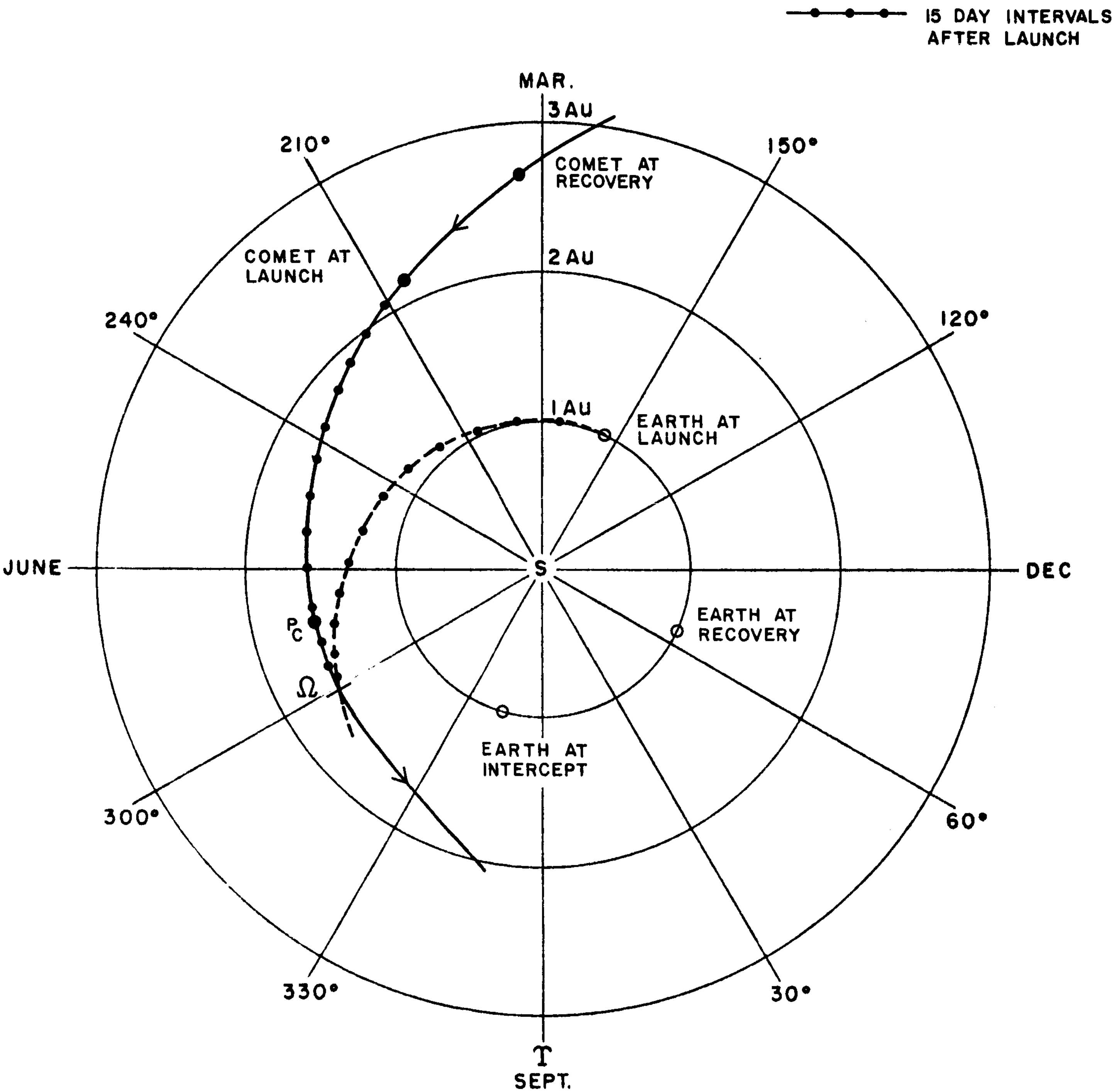
Mission Characteristics

Perihelion date	18 Aug 1983
Launch date	26 Feb 1983
Flight time (TF)	175-190 days
Communications distance (RC)	1 AU
Ideal velocity (ΔV)	43,000 ft/sec
Approach velocity (VHP)	8 km/sec
Recovery	60 days before launch
Expected miss distance	1000 km
Time passing through coma	1-1/2 hours for fly-by
Magnitude at intercept	12

Launch Vehicle Payload Capability

Tat-Kick	600 lbs.
Atlas-Centaur	1300 lbs.
SLV 3X-Kick	1600 lbs.
SLV 3X-Centaur F-Kick	4500 lbs.
Saturn 1B-Centaur	10,000 lbs.
Saturn 1B-Centaur F	12,000 lbs.

KOPFF



P_C = PERIHELION OF COMET

Figure 6 <u>190 DAY TRAJECTORY TO KOPFF</u>

Table 17

PAYLOAD FOR KOPFF FLY-BY MISSION (1983)

Experimental payload 3 (see page 26)	75 lbs.
Transmitter (10 watts 625 b/sec 210' DSIF)	10
Antenna (25 db 3' dia)	10
Data encoder, storage, etc. (10^7 bits storage)	30
Power supply (200 watts RTG)	200
Batteries	25
Comet seeker (duplicate)	30
Shielding	40
Structure	100
Guidance and attitude motors (less propellant)	30
Spacecraft weight at intercept	550 lbs.
Attitude propellant	50
Midcourse propellant (250 m/sec I_{SP} = 225 secs)	100
Spacecraft weight at start of trajectory	700 lbs.
Effective weight of shroud and adapter	100
Total effective payload weight	800 $^{-0}_{+5}$% lbs.

Launch Vehicle

Atlas-Centaur

Table 18

PAYLOAD FOR KOPFF MISSION 1983
WITH VELOCITY MATCHING

Experimental payload 2 (see page 25)	70 lbs.
Transmitter (2 watts 125 bits/sec 210' DSIF)	5
Antenna (25 db 3' dia)	10
Data encoder, storage, etc. (10^5 bits storage)	10
Power supply (100 watts RTG)	100
Batteries	30
Comet seeker (duplicate)	30
Shielding	60
Structure	100
Attitude motors (less propellant)	35
Spacecraft weight at intercept	450 lbs.
Attitude propellant	200
Midcourse propellant (250 m/sec I_{SP} = 380 secs)	625
Terminal propellant (I_{SP} = 380 secs and tankage = 5%)	8375
Spacecraft weight at start of trajectory	9650 lbs.
Effective weight of shroud and adapter (spacecraft only)	200
Total effective payload weight	9850 $^{-0}_{+1}$% lbs.

Launch vehicle

Saturn 1B-Centaur

7.5 Mission to Periodic Comet Halley (1986)

Halley's comet has been recorded at every passage since 239 B.C. but its last return in 1910 is by far the best documented. At that time it was the subject of world-wide study. The total mass of Halley has been calculated as 3×10^{19} gms (Bobrovnikoff 1931) which, if the density is 1.3 gm/cc, would give a nucleus diameter of some 20 km. An indirect estimate was obtained when Halley passed in front of the Sun without being noticeable indicating that its diameter is less than 50 km (Watson 1956).

Spectroscopic analysis of the coma has shown a strong continuum indicating a high dust content and CN, C_2, C_3, CH with the C_3 much stronger than CN (Swings and Haser 1961). Calculations on the tail spectra (Richter 1963) indicate a partial density for C_2 of 10^5 mols/cm^3. This leads to a total gas production for the comet of 10^{25} mols/sec and a total emitting gas content for the coma of 10^{35}-10^{36} mols at any instant. The coma diameter was greater than 3×10^5 km in 1910.

Liller (1960) and Whipple (1963) have suggested a meteoritic mass loss of some 5×10^{14}-10^{16} gm per passage, this contributing to the Orionid and Aquirid meteor showers. From this, a very approximate average dust density for the coma can be calculated as 10^{-3} gms/km^3. If the average mass of a dust particle is assumed to be 10^{-9} gms then the spatial density will be 10^6 particles/km^3. Assuming an approach velocity of 60 km/sec the flux intercepted by the spacecraft will be some

$60/m^2/sec$ as a very approximate estimate. Actually the density of the dust might be expected to vary inversely as the square of the distance from the nucleus. In the 1910 apparition, both a dusty and a gaseous tail were apparent. The maximum tail length was estimated as greater than 10^7 km.

The characteristics for a fly-by mission to Halley's comet are summarized in Table 19. Early recovery and a relatively low ideal velocity are the attractive features. The approach velocity is very high (69 km/sec) due to the retrograde orbit of the comet. The trajectory is shown in Figure 7.

There is a large scientific interest in Halley's comet and it will be bright enough at intercept to obtain spectroscopic data from the Earth. However an important function of the mission will be to obtain data on the nucleus of the comet. Thus a miss distance of 1000 km has been suggested, which will be difficult but not impossible to attain. The high approach velocity will also make it difficult to obtain a good spatial resolution for measurements in the coma. Table 20 lists a suggested payload which includes the full experimental package with an unrestricted data rate. A suitable launch vehicle will be a SLV 3X -Centaur.

An alternative approach to the Halley mission is to use a low thrust stage on a Saturn 1B-Centaur. It is not possible at this time to estimate the characteristics of the thrusted stage nor therefore whether the required system could be available by 1985. However two possibilities exist:

a) an intercept mission using a low thrust trajectory may have a considerably smaller approach velocity than the ballistic trajectory and b) a low thrust rendezvous mission may be far more feasible than in the ballistic case. There is clearly a requirement for further study of low thrust trajectories for comet missions.

Table 19

SUMMARY OF CHARACTERISTICS FOR MISSION TO HALLEY (1986)

Orbital Parameters for Halley (1986)

Period	75.9	Eccentricity	0.967
Semi-major axis	17.9	Long. of asc. node	58°
Inclination	162.2°	Arg of perihelion	111.7°

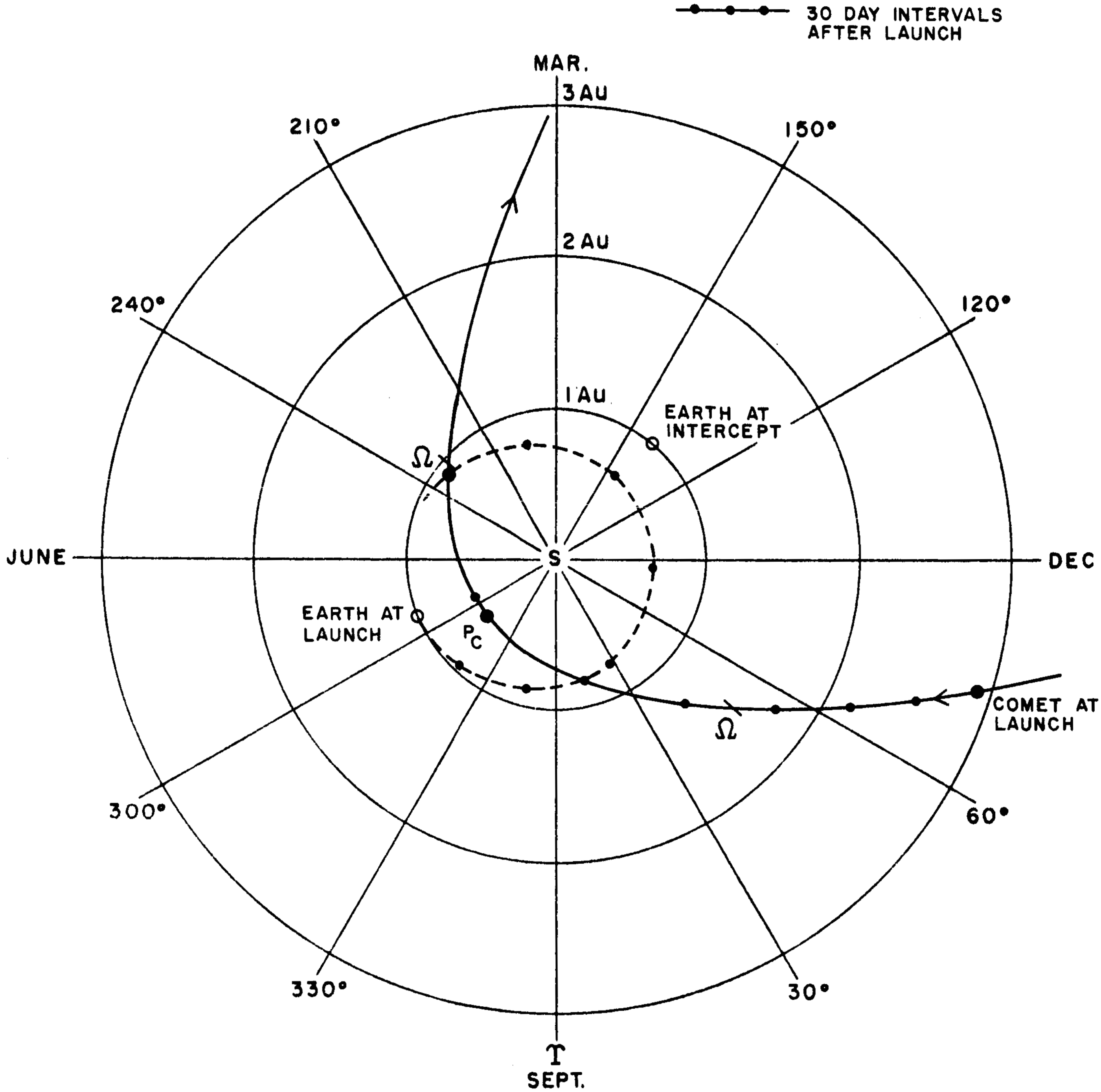
Mission Characteristics

Perihelion date	8 Jan 1986
Launch date	July 1985
Flight time (TF)	210 days
Communications distance (RC)	1.25 AU
Ideal velocity (ΔV)	42,500 ft/sec
Approach velocity (VHP)	69 km/sec
Recovery	200 days before launch
Expected miss distance	1000 km
Time passing through coma	1 hour
Magnitude at intercept	5

Launch Vehicle Payload Capability

Atlas-Centaur	1500 lbs.
SLV 3X-Kick	1700 lbs.
SLV 3X-Centaur	2100 lbs.
Titan III-C	2300 lbs.
SLV 3X-Centaur F	3100 lbs.

HALLEY



P_C = PERIHELION OF COMET

Figure 7 <u>210 DAY TRAJECTORY TO HALLEY</u>

Table 20

PAYLOAD FOR FLY-BY MISSION TO HALLEY (1986)

Experimental Payload 3 (see page 26)	75 lbs.
Transmitter (10 watts 625 bits/sec 210' DSIF)	10
Antenna (25 db 3')	10
Data encoder, storage, etc. (10^7 bits storage)	30
Power supply (200 watts RTG)	200
Batteries	30
Comet seeker (duplicate)	30
Shielding	50
Structure	10
Guidance and attitude motors (less propellant)	100
Spacecraft weight at intercept	635 lbs.
Attitude propellant	200
Midcourse propellant (2 km/sec I_{SP}=225 secs)	800
Spacecraft weight at start of trajectory	1635 lbs.
Effective weight of shroud and adapter	250
Total effective weight of payload	1885 $^{-0}_{+2}$% lbs.

Launch Vehicle

SLV 3X-Centaur

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Appendix 1

MEDIAN PARAMETERS OF COMETS
WITH PERIODS LESS THAN 100 YEARS

Appendix 1

MEDIAN PARAMETERS OF COMETS WITH PERIODS LESS THAN 100 YEARS

Positional Elements	Value
Mean number of appearance	4
Median period	7 years
Median inclination	15° (11° for $P < 10$ years)
Median eccentricity	0.56 (lowest = 0.135)
Median perihelion distance	1.3 AU
Median Aphelion distance	5.5 AU
Median semi-major axis	3.6 AU
Orbital direction	Direct (exception Halley)
Physical Elements	
Diameter of coma	20,000 - 2,000,000 km
Diameter of central condensation	2000 km
Ion densities in coma	$10^4 - 10^6$ ions/cm^3
Diameter of nucleus	1 - 10 km
Length of tail (visible to eye)	10×10^6 km (up to 150×10^6 km)
Solar distance at which tail appears	1.7 AU
Upper limit of mass for large comets	6×10^{18} gm
For faint small comets	6×10^{14} gm
Average density of coma or head	10^{-12} gm/cc
Average density of tail	10^{-24} gm/cc
Median absolute magnitude at $r = 1$, $\Delta = 1$	
First appearance	9 magnitude
Last appearance	10 magnitude
Faint comets	18 - 19 magnitude
Change of magnitude with solar and terrestrial distances r and Δ	$m = m + 2.5\, n \log r + 5 \log \Delta$, where $n = 4.5 \pm 1.5$ (n not necessarily constant for any comet)

Spectra (atoms, molecules, ions, continuum)

Nucleus

Strong solar continuum with Fraunhofer lines, CH, CH_2 (tentative)

Coma

Solar continuum also usually present, C_2 (swan bands), CN (violet and red bands), CH (3900 bands), OH (3064 system), NH (3360 system), C_3 (4050 group), OH^+ (tentative), CH^+ (fairly well established), NH_2 (?), Na-D lines (the sodium D-doublet appears in emission in the central part of the head. Some observers have reported Fe and Ni lines also.)

Tail

Solar continuum may be present at small heliocentric distances. Only molecular ions are found at large distances from the head. CO^+ major constituent (Baldet-Johnson band), N_2^+ major constituent (comet tail band), CH^+ minor constituent, OH^+, CO_2^+, some unassigned emission.

Appendix 2

GUIDANCE AND CONTROL FOR COMET MISSIONS

Appendix 2

GUIDANCE AND CONTROL FOR COMET MISSIONS

1. INTRODUCTION

The scientific experiments and measurements expected to be made on future comet missions may require that the space probe penetrate the coma to within 10,000 km, and in some cases to 1,000 km of the comet nucleus. The most important guidance constraint for missions of this type is the miss distance. Accordingly, the factors that influence the miss distance, its measurement and correction are considered here. A detailed error analysis of guidance systems and trajectory error is beyond the scope of this study, and this appendix attempts to define an average set of guidance and control constraints which can be applied to all missions considered in this study. Miss is defined in the usual manner as being the components of heliocentric position error lying in the "target" or "impact" plane which is centered at the target body and normal to the relative intercept velocity direction.

Following the launch of a comet probe there will be errors in the trajectory due to uncertainty in the position and velocity of the probe and the position of the target comet. These errors should be corrected as soon as possible after launch to minimize the velocity increment required. It is assumed that a typical residual error in miss distance following a post-injection correction effected within 10 days of launch will be of the order 100,000 km.

Unlike planetary orbits, the orbits of even the best known comets are not at present determined to a high degree of accuracy. An error of up to one day in the time of perihelion passage is not uncommon. A midcourse velocity correction based on several months of DSIF spacecraft tracking and ground-based comet observations corrects for comet orbit determination errors to the extent that they have been resolved since recovery. It is further assumed that at least one order of magnitude reduction in miss can be expected from the midcourse correction. Thus the residual error in miss distance following the midcourse correction should be of order 10,000 km. This correction is typically performed 3 months following launch and is likely to require about the same velocity increment as the injection guidance correction.

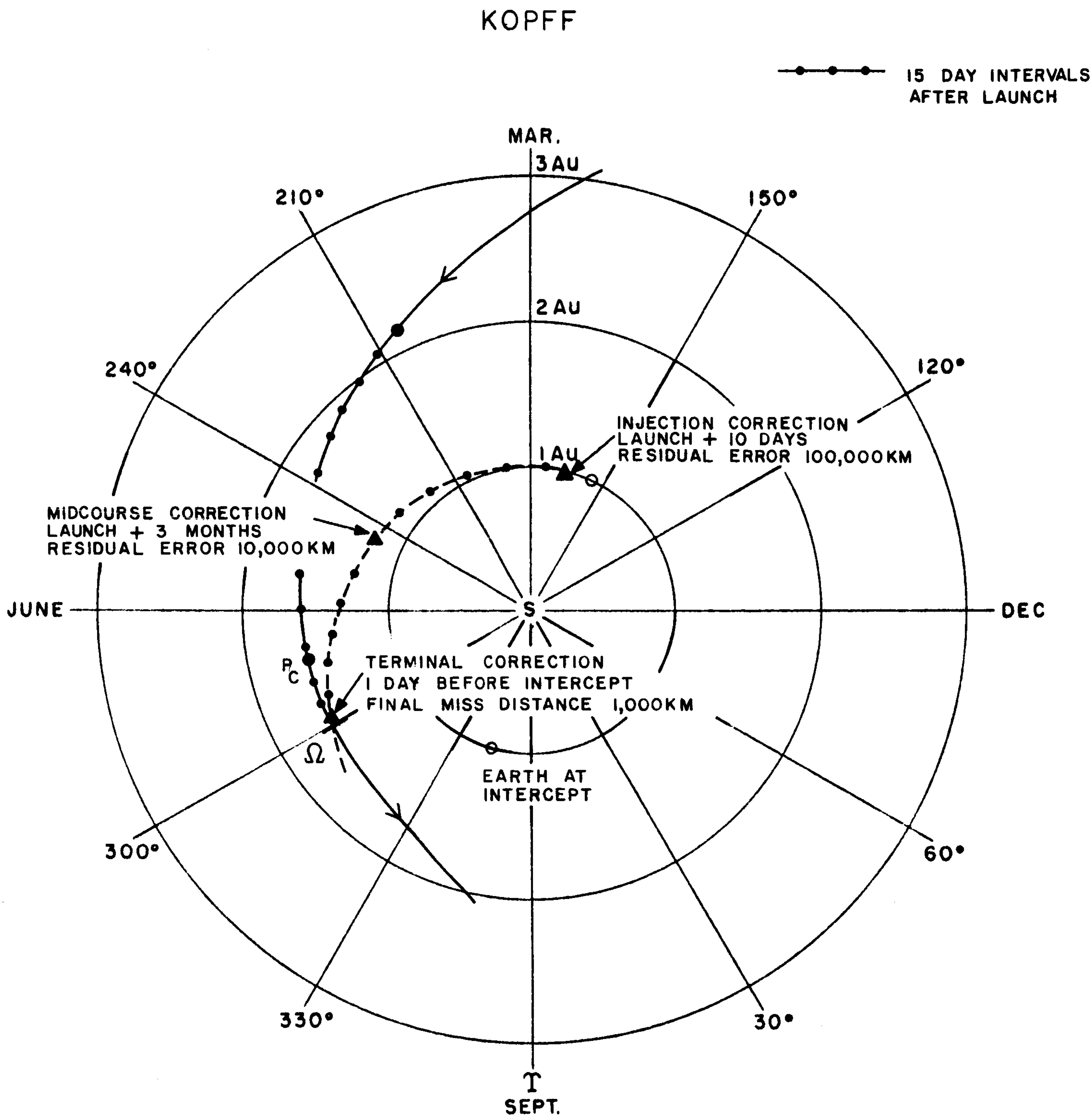
In order to finally approach the comets' nucleus within 1,000 km, on-board guidance will almost certainly be required. Terminal maneuvers can be performed within the last few days of the mission and achieve the desired miss distance at intercept. The fuel requirement for this maneuver is by far the largest of the corrections involved in comet fly-by missions.

A typical mission profile showing post-injection, mid-course and terminal guidance corrections is presented in Figure A-1 for a 190 day mission to Kopff.

2. POST-INJECTION GUIDANCE CORRECTIONS

One rigorous way of determining injection (launch) errors is to conduct a detailed error analysis of the injection guidance system. This involves designating each source of hardware error and generating launch trajectories for each mission. This type of complete simulation is not within the scope of the present study. A simpler method is to assume errors in the hyperbolic excess velocity components at launch. Two alternatives are suggested. The first assumes error magnitudes proportional to the magnitude of the hyperbolic velocity for a given mission. The second assumes constant error magnitudes for all missions. Obviously, neither alternative is truly representative of the actual case. It was decided that there was no strong justification for assuming the first alternative to be more representative than the second, but at least the designation of constant errors yields results which are akin to basic error sensitivities, and since the analysis is linear, the results can be easily modified or adjusted. For this reason, the second alternative was chosen.

Constant errors of 10 m/sec in each of three mutually orthogonal velocity components are assumed in the desired injection velocity. This yields a root mean square velocity



P_C = PERIHELION OF COMET

Figure A1. GUIDANCE REQUIREMENTS FOR MISSION TO KOPFF increment of 17.3 m/sec. This value has been assumed as the post-injection guidance correction required for all missions.

3. MIDCOURSE GUIDANCE CORRECTIONS

Following the post-injection correction, the residual error in the miss distance is assumed to be $\sim$100,000 km due mainly to the uncertainty in the position of the target comet in its trajectory. Additional Earth-based comet observations, with the possibility of data from the on-board comet seeker, should allow a reduction of the error in the intercept location by about one order of magnitude. Allowing 3 months of observation after launch, the comet's position should, on the average, lie resolved to within 10,000 km. For a 6 month mission, this allows 3 months to convert a 100,000 km error to a 10,000 km error, i.e., a reduction of 90,000 km. This correction should therefore involve a velocity increment of about 12 m/sec.

4. TERMINAL GUIDANCE CORRECTIONS

In order to obtain the close approach to a comet's nucleus (1,000 km) required for some of the proposed missions discussed in this study, it seems clear that terminal guidance corrections will be required, and that an on-board comet seeker will be necessary.

Following the midcourse correction executed at about 3 months after launch, a total rms error of $\sim$10,000 km should exist. In order that a miss distance of 1,000 km can be achieved with a single terminal maneuver, the required terminal velocity increment can be taken as (Friedlander 1964)

$$DV_{term} = 2\sqrt{\frac{2}{\pi}}\,(VHP)\,\sigma_\theta\,\left(\frac{\sigma_o}{\sigma_f}\right)$$

where VHP is the approach velocity; σ_θ is the accuracy, in radians, of the assumed on-board comet seeker; σ_f is the final tolerable miss distance and σ_o is the positional error following midcourse correction. Taking an average VHP of 20 km/sec and assuming a comet seeker with an accuracy of 1/10th degree of arc, we obtain

$$DV_{term} = 560 \text{ m/sec} .$$

Such a terminal correction would be executed 8 hours before intercept and at a distance of 5.75×10^5 km from the comet, a distance at which the comet seeker would be effective.

Since 30 m/sec are required for the post-injection and midcourse corrections, a total velocity increment of about 600 m/sec will be required to provide a 1,000 km miss distance at intercept.

Assuming a storable propellant with I_{SP} = 225 sec, the guidance corrections require 24 percent of the total weight of the spacecraft. For I_{SP} = 350 sec, only 16 percent is necessary.

5. VELOCITY MATCHING CAPABILITY

This section discusses the propellant requirements for the spacecraft to rendezvous with the target comet. We assume that a 600 m/sec injection, midcourse and terminal guidance correction will bring the spacecraft within an acceptable miss distance (say 1,000 km) of the comet nucleus prior to the rendezvous maneuver which consists simply of removing the excess hyperbolic approach velocity from the spacecraft.

If the total increment in velocity (which may include the midcourse correction) is DV then the rocket equation gives

$$\rho = \rho_o \exp \frac{-DV}{g\ I_{SP}}$$

where ρ_o = weight of (spacecraft + rocket tankage + fuel) and ρ = weight of (spacecraft + rocket tankage). If the tankage, which includes the structure and adapter for the terminal rocket is assumed to be a fixed proportion of the total weight, $\alpha\ \rho_o$, where α is typically between 0.05 and 0.1, then the weight of the spacecraft payload ρ_p will be

$$\rho_p = \rho_o \left(\exp \frac{-DV}{g\ I_{SP}} - \alpha\right),$$

and the payload fraction is

$$\frac{\rho_p}{\rho_o} = \left(\exp \frac{-DV}{g\ I_{SP}} - \alpha\right) .$$

This equation has been used to compile Table 8.

REFERENCE

Friedlander, A. L. 1964, Multiple Correction Approach Guidance Policies with Minimum Average Fuel Criterion, IITRI Technical Note GCTN-106