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SPACECRAFT SYSTEM EVALUATION

VOL. 4

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COMET AND CLOSE-APPROACH ASTEROID MISSION STUDY

FINAL REPORT

CONTRACT JPL 950870

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FOREWORD

This document is the final report of work performed on System Requirements, Spacecraft Description, Mission Capability, and Mariner-C System Comparison by the WDL Division of the Philco Corporation during the Comet and Close-Approach Asteroid Mission Study for the Jet Propulsion Laboratory under Contract JPL 950870. The report covers work performed during the period 2 July 1964 to 2 January 1965.

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SPACECRAFT SYSTEM EVALUATION

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SECTION 1
ENVIRONMENTAL REQUIREMENTS

1.1 GROUND ENVIRONMENT

Spacecraft equipment, unless special provisions are made to isolate it from the external environment, may be subjected to these ambient conditions during ground handling and storage:

a. Temperatures between $0^{\circ}F$ and $120^{\circ}F$ for an indefinite period
b. Pressures from 90 to 810 Torr
c. Relative humidities of up to 96 percent
d. Vibration during transport and handling of 3 g's at 200 cps
e. Shocks during handling of 10 g's.

1.2 LAUNCH VEHICLE ENVIRONMENT

The launch vehicles under consideration are the Atlas-Agena and the Atlas-Centaur. The Centaur environment outlined in Table 1-1 has been a guide to spacecraft subsystem and configuration designs. The model environment should be updated when new test data become available.

1.3 SPACE ENVIRONMENT

In addition to the comet model, a model of the interplanetary medium between 1 and 2 A.U. during quiet-sun conditions has been generated from prior work on the Solar Probe Study [Philco, 1963] and from more recent literature [Anderson, 1964; Beard, 1964; Jones, 1963; Lees, 1964; Ogilvie and Bryan, 1964; Reid, 1964; Scarf and Noble, 1964]. See Table 1-2.

TABLE 1-1 CENTAUR ENVIRONMENT

This data is based on an environmental specification for the Centaur stage boostered by the Atlas launch vehicle.

Vibration

Throughout power flight phase:

Longitudinal

Frequency cps	G's (zero - peak)
5 - 40	2.5
40 - 1500	2.0

Lateral

Frequency cps	G's (zero - peak)
1 - 2.5	2.0
2.5 - 40	1.25
40 - 1500	2.0

Gaussian Vibration

Throughout power flight phase:

Longitudinal and Lateral

Frequency cps	G's (rms)
100 - 1500	2.0

Acceleration

Maximum value during flight (approximately 153 sec.) near separation:

6.25 G's Longitudinal

0.4 G's Lateral

Noise

145 db (over-all level in the payload environment).

Temperature

Maximum inside skin temperature of the Shroud = 300°F.

Table 1-2. Space Envirnoment

CORPUSCULAR RADIATION		
Galactic Cosmic Rays		3×10^{-9} w/cm^2-yr
Solar Cosmic Rays		3×10^{-6} w/cm^2-5 hr
Solar Wind		4×10^{-5} w/cm^2-5 hr
SOLAR CONSTANT		
	1 A.U.	0.140 w/cm^2
	2 A.U.	0.035 w/cm^2
SOLAR PRESSURE		
Solar Constant	1 A.U.	4.6×10^{-5} dynes/cm^2
	2 A.U.	1.15×10^{-5} dynes/cm^2
Solar Wind	1 A.U.	4×10^{-9} dynes/ cm^2
	2 A.U.	1×10^{-9} dynes/cm^2
MAGNETIC FIELD		
	1 A.U.	(2 to 1) 10^{-5} gauss
	2 A.U.	(0.1 to 5) 10^{-6} gauss
EXTERNAL IRRADIATION		
Solar Protons	1	10^8 erg/gm-yr
Cosmic Protons	1	10^5 erg/gm-yr
INTERNAL IRRADIATION		
Solar Protons		10^6 erg/gm-yr
Gammas		10^0 erg/gm-yr
Neutrons		10^5 erg/gm-yr

Collisions between cosmic ray protons and interstellar hydrogen nuclei will produce secondary electrons through a reaction chain, but the number and magnitude are low and can be neglected as a degrading factor on the vehicle. 4000 Mev protons in nuclear reactions with Al nuclei produce nuclides of Mg, Ne, Na, F, O, N, C and Be, which, in some cases, are radioactive and decay by gamma, electron, or positron emission. Bremsstrahlung gamma emission will expose external as well as internal components. Neutrons caused by proton interactions will expose external and internal components.

SECTION 2
MISSION CHARACTERISTICS

2.1 MISSION CONSTRAINTS

Mission constraints for the design of conceptual spacecraft to acomplish the Comet Mission objectives are tabulated below in Table 2-1.

Table 2-1. Mission Constraints

Mission Period	1967-1975
Launch Vehicles	Atlas-Agena Atlas-Centaur
DSIF Capability	1964-1968
Injection Energy (C_3)	7 - 22.2 km^2/sec^2
Flight Time (to intercept)	160 - 300 days
Heliocentric Distance (at intercept)	1.25 - 1.80 A.U.
Geocentric Distance (at intercept)	$(92\text{-}294) \times 10^6$ km
Closing Velocity	8 - 15 km/sec
Corrected Miss Distance (3σ)	5000 - 10,000 km
Payload Capability	
Atlas-Agena	578 - 630 lbs
Atlas-Centaur	900 - 1400 lbs

2.2 SEQUENCE OF EVENTS

A sequence of events for the photovoltaic-configuration spacecraft is tabulated in Table 2-2, using a mission to Pons-Winnecke to time-key the events. The sequence is the same for the isotopic configuration

Table 2-2. Mission Sequence of Events - Photovoltaic Configuration

PHASE		EVENT	TIME	SOURCE	DESTINATION	COMMENTS
Launch	1	Lift-off (T)	0	Event	---	---
	2	RF Power Up, Cruise Science On	5 min	Centaur timer	Power	At shroud separation
	3	Injection (I)	45 min	Centaur	---	---
Acquisition	4	Separation (S)	48 min	Agena D timer	---	---
		a. RF Power Up, Cruise Science On, Data Mode II	---	Separation connector	Power	Back-up to #2.
		b. Enable CC&S	---	Separation connector	CC&S	---
		c. Arm Pyro-technic	---	Pyro-arming switch	Pyro	Switch parallel with timer.
		d. Attitude Control Subsystem On	---	Pyro-arming switch	A/C	Start sun acquisition.
		e. Timer On	---	---	---	---
	5	Arm Pyrotechnics	48.3 min	Timer	Pyro	See #4c.
	6	Deploy Solar Panels and Solar Vanes, Unlatch Scan Platform	49.6 min	Timer	Pyro	---
		a. Deploy, unlatch	53 min	CC&S	Pyro	Back-up DC Back-up
	7	Deploy Science Boom	54 min	Timer	Pyro	---
		a. Deploy Boom	58 min	CC&S	Pyro	Back-up. DC back-up.
	8	Roll S/C to calibrate magnetometer	---	---	---	---
	9	A/C On	63 min	CC&S	A/C	Back-up to #4d. Direct command back-up (DC).
	10	Sun Acquisition Complete	70 min	---	---	---
	11	Canopus Sensor and Solar Vanes On. Start Roll Search about z-axis.	997 min (16.62 hr)	CC&S	A/C	DC Back-up. Stop Magnetometer calibration roll signal.
	12	Canopus Acquisition complete	1060 min (17.67 hr)	---	---	---

Cruise	13	Set Roll and Pitch Turn Duration and Polarity	25 days	Quantitative Command (QC)	CC&S	---
	14	Set Motor Burn Duration	25 days	QC	CC&S	---
Maneuver	15	Start Maneuver Sequence (M)	30 days	DC	CC&S	---
		a. Gyro Warmup	---	CC&S	A/C	---
		b. Switch to Data Mode I	---	A/C	Data Encoder (D/E)	DC Back-up
	16	Start Maneuver	M + 60 min	CC&S	A/C	First midcourse
		a. S/C to Inertial Control (all axes). Star-Sensor Auto-pilot Off	---	---	---	---
	17	Stop Roll and Pitch Turns.	M + 90 min	CC&S	A/C	---
	18	Ignite Midcourse (M/C) Motor	M + 103 min	CC&S	Pyro	---
	19	Stop M/C Motor	M + 105 min	CC&S	Pyro	---
Acquisition	20	Start Reacquisition of Sun & Canopus	M + 110 min	CC&S	A/C	---
		a. Switch to Data Mode II	---	A/C	D/E	DC Backup.
	21	Sun Reacquisition Complete	M + 120 min	---	---	---
	22	Canopus Reacquisition Complete	M + 180 min	---	---	---
	23	Maneuver Counter Off	M + 199 min	CC&S	CC&S	Permits 2nd maneuver.
Maneuver; Acquisition	24	Arm 2nd Maneuver	---	DC	Pyro	---
	25	Repeat Events 13-23	116 days ($E - 40^d$)	---	---	Second midcourse
Cruise	26	Update Canopus Sensor Cone Angle	126 days ($E - 30^d$)	CC&S	A/C	DC Back-up.
	27	Transmit via High Gain, Receive via Omni	136 days ($E - 20^d$)	CC&S	Radio	DC Back-up.

Encounter	28	Start Encounter Sequence	---	DC	CC&S	---
	29	Start Comet Acquisition	126^d ($E-30^d$)	CC&S	A/C (CT)	DC Back-up.
	30	Comet Acquisition Complete	154^d ($E-2^d$)	Comet Tracker (CT)	Data Automation System (DAS)	---
		a. Switch to Data Mode III or IIIa	---	DAS	D/E	Option depends on data rate capability.
	31	Intercept Science On	154.5^d ($E-1.5^d$)	CC&S	Power	DC Back-up At $1.3x10^6$ km away from comet.
		a. Instrument Cover Off	---	CC&S	Pyro	---
		b. Tape Recorder On	---	Power	Recorder	---
	32	Start Recording	155^d ($E-1^d$)			
		a. Start Tape Recorder	---	DAS	Recorder	Recorder on for either Data Mode III or IIIa.
	33	Closest Approach (E)	156 days	---	---	---
	34	Tape Recorder Stop	157^d ($E+1^d$)	Recorder Recorder	Recorder DAS	Automatic Stop.
		a. Switch to Data Mode II	---	DAS	D/E	DC Back-up.
		b. Inhibit Start Tape Commands	---	DAS	DAS	---
	35	Intercept Science Off	157.5^d ($E+1.5^d$)	CC&S	Power	DC Back-up. At $1.3x10^6$ km away from comet.
Playback	36	Tape Playback	158^d ($E+2^d$)	CC&S	D/E	DC Back-up.
		a. Switch to Data Mode V	---	---	---	---
		b. Cruise Science Off	---	D/E	Power	---
		c. Playback Twice	---	---	---	---
Cruise	37	Switch to Data Mode II	186^d ($E+30^d$)	DC	D/E	Optional after all recorded data received and if power and gas permit
		a. Cruise Science On	---	DC	Power	

except for the solar deployment events.

2.2.1 Data Modes

Data modes referred to in Table 2-2 are as follows:

- I: Sampling of only engineering data during maneuvers and during cruise.
- II: Transmission of alternating engineering and science data block during launch, initial acquisition and cruise.
- III: Sampling of only science data during intercept. (No engineering data.)
- IIIa: Transmission of science data during intercept, except TV at maximum bit rate.
- IV: Transmission of stored science data and of real-time Mode I engineering data during post-intercept.

2.2.2 Events

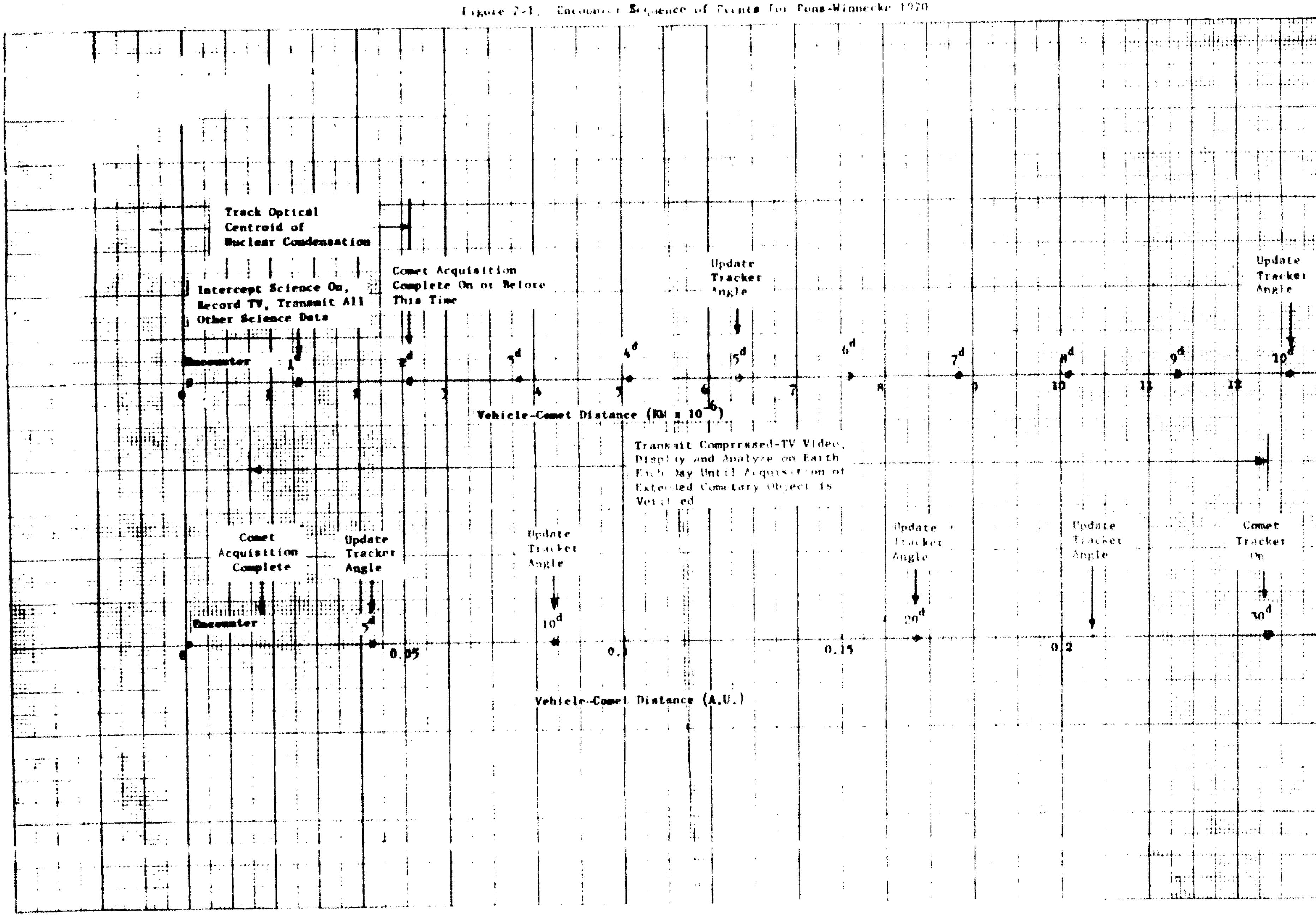
If the science boom for extending the sensitive magnetometer and ionizatin chamber is obviated by very low residual spacecraft magnetism, the low-gain antenna waveguide can be used to mount these instruments and Event 7, deploy science boom, is deleted.

On a mission to Brooks (2) at 1.8 A.U. heliocentric distance, Event 31, intercept science on, occurs before the scheduled encounter in order to offset the cold temerature of the tracking assembly and science platform at this large distance.

2.2.3 Encounter Sequence of Events

The series of events during the encounter phase is illustrated in Figure 2-1 for an Atlas-Centaur boosted spacecraft from AMR to

Figure 2-1. Encounter Sequence of Events for Pons-Winnecke 1970



Pons-Winnecke in 1970, and is detailed below:

Event 29: Start Comet Acquisition

(i) The comet tracker, pre-set before launch at an angle determined by the planned approach trajectory, is turned on by direct command 30 days before encounter after the second maneuver has been executed.

(ii) The comet tracker is a TV-tracker whose scanned image is compressed and telemetered through a buffer storage to Earth.

(iii) The received video on the Earth is reconstructed for display and analysis to verify that the target in the field of view is the comet and not bright stars radiating through the coma. The intensity and its time change is also recorded.

(iv) Transmission and analysis of the compressed TV images continues until ground analysis verifies the detection of the comet as an extended object in the star field.

(v) The angular position of the comet tracker is updated every 5 days either by direct command or by a clock-actuated signal (with DC back-up) based upon the planned approach velocity vector. The former option is exercised after acquisition in the field of view has been established. The latter option is excercised only during the period of compressed-TV transmission and analyssi.

(vi) Cruise science and engineering data are sequenced for transmission between a series of TV pictures.

Event 30: Comet Acquisition Complete

(i) The auto-track mode is initiated by direct command in order to track the optical centroid of the verified cometary object (nuclear condensation).

(ii) The nucleus-oriented intercept science ("Advanced-Mariner" TV, photometers, and spectrometers) is slaved to the comet tracking assembly.

Event 31: Intercept Science On

All cruise science remains on for measurements of cometary phenomena during the intercept; the ion-mass spectrometer, science TV, etc. are turned on; the tape recorder is turned on.

Event 32: Start Recording

At Pons-Winnecke, the tape recorder records mass-spectrometer and science-TV data, while all other science is transmitted in real time. With an increase in transmitter power from 10 to 25 watts and the use of the 210-foot DSIF receiver, all data but the science TV can be transmitted, as indicated by Event 30a of Table 2-2 (Switch to Data Mode IIIa)

Event 36: Tape Playback

All data is played back twice. With real-time transmission of most of the intercept science data, it is necessary to record and playback only the TV. The option exists for recording and thus playing back all the data up to 30 days after encounter (point of closest approach), as indicated by Event 37 in Table 2-2.

SECTION 3

SPACECRAFT SYSTEM EVALUATION

3.1 PERFORMANCE MODEL

The criteria established for evaluating system capability are the following key system parameters:

1. Weight of science. The weight of the instrument payload is a measure of the number and sophistication of experiments that can be performed to satisfy the mission objectives.

2. Aiming error. The 3-sigma aiming-point error is a measure of the results of an early, pre-acquisition orbital determination investigation for determining the uncertainty in time of perihelion passage; the guidance system, injection, and DSIF tracking errors; and the velocity-correction fuel capability to control a given spacecraft weight.

3. Bit rate. The telemetered bit rate is a measure of the total data registered by the instruments; the effective radiated power of the telemetry subsystem; the capacities of the data compression and storage subsystems; and, after the second maneuver, the number of compressed pictures that can be analysed to confirm the detection of the comet, to measure its intensity, and to determine the direction of the comet tracker relative to the optical centroid of the comet. A higher value is assigned to real-time transmission of data during intercept than to post-intercept playback only.

These three parameters form the basis for the following simple formulation of system capability:

$$M = \frac{W_{sci}}{71} \cdot \frac{\left(1 - \frac{3\sigma}{dm}\right)}{0.4} \frac{\Delta V}{80} \frac{W_{s/c}}{565} \cdot \frac{B}{10} \qquad (3\text{-}1)$$

where

$W_{sci}/71$ = weight (lbs) of scientific instruments and ancillary scan platform relative to 71-db reference

3σ = 3-sigma error about aiming point (km)

dm = miss-distance from center of nuclear condensation (km)

0.4 = aiming-error function reference

$\Delta V/80$ = total midcourse velocity correction capability (m/sec) relative to 80 m/sec reference

$W_{s/c}/565$ = weight (lbs) of spacecraft relative to 565-lb reference

B/10 = bit rate transmitted during intercept (bps) relative to 10-bps reference

The reference values are Mariner-C capabilities. Table 3-1 tabulates the system capabilities (M) of Atlas-Centaur and Atlas-Agena comet probes. The Centaur probes assume a 25-watt spacecraft transmitter and a 210-foot low-temperature ground receiving antenna. The Agena probes assume 10 watts and the 210-foot receiving system.

3.2 MISSION SUCCESS FACTORS

The success of the mission depends primarily upon the following critical subsystems and cometary factors:

1. Attitude control system reliability to establish or maintain Sun and Canopus references affects available power from photo-voltaic panels, thermal control, high-gain antenna pointing,

Table 3-1 System Capabilities of Atlas-Centaur and Atlas-Agena Comet Probes

MISSION	W_{sci}	$3\sigma/dm$	ΔV	B	$W_{s/c}$	M
Atlas/Centaur Pons-Winnecke 1969	152	0.5	200	2840	737	2470
Atlas-Agena Mariner Mod. '69 (Pons-Winnecke)	77	0.5	120	1135	573	232
Atlas-Agena Mariner Mod. '70 (Pons-Winnecke)	123	0.5	80	1135	623	270
Atlas-Centaur Kopff 1970	152	0.5	200	248	750	221
Atlas-Centaur Brooks (2)	152	0.5	200	284	800	270
Mariner-C 1964	71	0.6	80	10	565	1

and science platform pointing.

2. The conduct of a thorough analysis of comet observational data reduces cometary orbital uncertainties and thus increases the probability of intercept and reduces the velocity-correction requirements.

3. Midcourse propulsion reliability to execute velocity corrections accurately affects the miss distance and probability of intercept.

4. The biasing of the miss-distance for the spacecraft to pass on the sunlit side of the nuclear condensation determines science platform pointing, science resolution, and the ability to observe the nucleus from a given position on the spacecraft.

5. Comet observability after the second maneuver determines the accuracy with which encounter instruments can be pointed at the nucleus, and determines the required sensitivity of the comet tracker and science TV.

6. Comet tracker reliability to acquire and track the optical centroid of the comet determines whether television and spectrophotometric data on the nucleus can be collected.

Partial success can still be realized with the spectrophotometric instruments aboard the tracking assembly, especially if the pointing angle relative to the spacecraft and comet centroid is known. DSIF spacecraft tracking and Earth-based comet tracking data can be used in conjunction with either the preset tracker position (in the event the comet tracker does not acquire and lock onto the moving target) or the last telemetered comet tracker position (in the event of control failure).

7. Shock loading on spacecraft during entry into the cometary atmosphere at the high relative velocities is negligible.

8. Dust damage to solar cells and optical trackers during flight through the coma is unknown.

9. Communication blackout of command, ranging and telemetry signals due to electrons in the coma is absent at frequencies above the HF range.

3.3 PAYLOAD CAPACITY

The comet probe system weight now totals 700 to 800 lbs. Since the Atlas-Centaur payload capability for comet missions is 900 to 1300 lbs., it is advisable that the weight difference be appropriated in ways that will enhance the scientific value of the mission, assure a high probability of success, and introduce higher performance components. Thus, heavier components including structural materials can be used; redundant components and assemblies can be accommodated.

For example, on some missions another tracking assembly could be accommodated, and on others added spectrophotometric or television subsystems could be added to the one tracking assembly now specified. In thermal control, change-of-phase passive control techniques for battery temperature can be used rather than active shutters, redundant active control assemblies can be incorporated, and solid-slab insulation can be used rather than multifoil insulation for ease of fabrication and simplicity of attachment. In telecommunication, redundancy in the telemetry and command assemblies can be accommodated, and high-power amplifiers (e.g., 50 watts) can be supported to increase the data transmission rate during intercept (e.g., 300 bps)

In power, higher power demands mean fitting increased solar panel area within the Surveyor shroud (e.g., 90 sq. ft.). In guidance and control, higher performance components (e.g., gyros) that weigh more than those presently used can be mounted.

SECTION 4

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