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PARAMETRIC ANALYSIS OF MICROWAVE AND LASER SYSTEMS FOR COMMUNICATION AND TRACKING

Volume II - System Selection

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16. Abstract

Present and future space programs are requiring progressively higher communication rates. For instance, the Earth Resources Technology Satellite-A requires about 70 MHz total bandwidth in its S-Band downlink spectra, and it appears likely that future earth observation satellites will require more bandwidth because of the larger number of sensors and higher sensor resolutions. On the other hand, the frequency bands allocated via international agreements for space use are limited, and hence, the r-f spectrum is becoming crowded. However, the advent of the C-W laser systems offered a "new" and wide electromagnetic spectrum for use in space telecommunications. Although the laser systems offered this "new" capability, their technological development was also new. Therefore, this study was undertaken to make a comparative analysis of microwave and laser space telecommunication systems. A fundamental objective of the study was to provide the mission planner and designer with reference data (weight, volume, reliability, and costs), supplementary material, and a trade-off methodology for selecting the system (microwave or optical) which best suits his requirements. This report is the final report of that study. Because of the large amount of material, the report is presented in four volumes. This volume, Volume II, "Systems Selection," contains two major parts, "Mission Analysis and Methodology" and "System Theory." The first part is a review of mission constraints, history and plans. It is given as a foundation for understanding space communication goals. The methodology or design criteria developed under this contract is also described in this part and in pertinent appendices. "System Theory" describes the constraining equations used to determine deep space communications link performance. Special treatment is given to the determination of signal to noise ratios in optical communications systems.

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PARAMETRIC ANALYSIS OF MICROWAVE AND LASER SYSTEMS FOR COMMUNICATION AND TRACKING

VOLUME I	SUMMARY
VOLUME II	**SYSTEM SELECTION**
VOLUME III	REFERENCE DATA FOR ADVANCED SPACE COMMUNICATION AND TRACKING SYSTEMS
VOLUME IV	OPERATIONAL ENVIRONMENT AND SYSTEM IMPLEMENTATION

ACKNOWLEDGEMENT

"Mission Analysis and Methodology" was largely prepared by Mr. James R. Sullivan and Dr. William K. Pratt. "Systems Theory" was largely prepared by Dr. Pratt. Mr. Sullivan, formerly of Hughes Aircraft Company is currently with Systems Associates. Dr. Pratt, formerly at Hughes Aircraft Company, is presently Associate Professor of Electrical Engineering at the University of Southern California.

BRIEF INDEX OF VOLUME II

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PART 2 SYSTEM THEORY

Appendices

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PART 1 MISSION ANALYSIS AND METHODOLOGY

PART 2 SYSTEM THEORY

PART 1 MISSION ANALYSIS AND METHODOLOGY

INTRODUCTION

The purpose and topics of this part are introduced.

Mission analysis and methodology is divided into four sections. A brief description of each section and the topics they contain is given below.

An Analysis of Potential Mission Objectives

Clearly it is necessary to determine the type of space mission, the data requirements and time duration before a communication system can be designed. This section contains general background data on the solar system and on the type of manned and unmanned missions currently being planned. From this data typical payload and data rates are derived.

Analysis of Mission Requirements

Once a particular mission is selected, several design constraints are imposed upon the communication system. Those discussed in this section include constraints of data rate, acquisition and tracking, communication range, mission duration and communication system weight restrictions.

Methodology for Optimized Communication Systems

A goal of this study was to provide a means of impartially describing the optimum communication system for a particular mission. A methodology is given as are computer derived results. The methodology designs the least expensive or lightest communications system within the constraints of the range equation.

Methodology Examples and Conclusions

Computer results of the methodology are given which compare laser and microwave systems for a Mars mission.

SUMMARY

Mission goals have been documented and optimum communication analysis methods have been developed. Sample communication problems are given to illustrate optimum configurations.

The mission analysis documents potential missions and provides a communication methodology which allows the selection of the best communication implementation for a given mission.

Missions

In general, deep space missions can be divided into four classes: 1) deep space probes which simply pass through interplanetary space making scientific measurements of the space environment encountered, 2) fly-by missions which have as their objectives a specific planet, but which make scientific measurements of that planet only during the fly-by phase, 3) planetary orbiter missions in which the spacecraft is placed into orbit about the target planet, and 4) planetary entry and lander missions in which the spacecraft or capsule enters the planetary atmosphere and transmits data either directly back to Earth or relays it through the spacecraft bus back to Earth.

Mission and Type of Communication System

When the general capabilities of laser and microwave systems are compared with the Data Rate Estimates, certain conclusions may be reached, these are noted below.

- A radio communication system should be used for space probes operating at planetary distances. This is largely due to the low data rate which may easily be accommodated by existing radio systems.

- An optical communication system should be used for a planetary orbiting mission. This is due to the very large amount of data which may be gathered using imagery sensors at these long ranges and which will be gathered at high rates for extended periods of time. Thus, not offering an opportunity to store the data and transmitting it at a slower rate.

- An optical communication link is also appropriate for manned lander mission. Here the high data rate obtained from imagery sensors leads to the selection of optical communications.

- In flyby missions the data rate can be high for a short period of time. This allows the use of a storage and playback mode and a radio link. The radio link would also be necessary since, with a flyby mission, continuous communication coverage is usually required during the critical flyby time. This could not be obtained with an optical system unless the additional complexity of an earth orbiting optical receiving station is used to prevent blockage by clouds.

- For a manned orbiting mission a radio system is likely best even though high, long term data rates may be expected. The reason for this is the additional difficulty in decoupling man caused mechanical disturbances which are difficult and expensive (in terms of control system fuel (weight) to decouple from the optical pointing system.

An optical communication system can provide high data rates at planetary distances. Due to the specialized care required in pointing and tracking, this high data rate transmission becomes the principle features of laser communications. However this is not the only type of communication required by a spacecraft. In fact, there is generally a requirement for continual telemetry data which allows the earth stations to monitor the spacecraft performance and to determine the spacecraft's position. In addition to the transmission of telemetry data, the spacecraft must receive commands and beacon signals from earth. The two functions, commands and telemetry, are accomplished best, by far, with a radio system. Thus it is seen that any optical system is really a combination of laser/optical and microwave, with the microwave being a relatively low performance communication system (and thus much less costly and lighter than a link that transmits the high data gates) and the optical system being designed to transmit the high data rates.

MISSION ANALYSIS AND METHODOLOGY

Analysis of Potential Mission Objectives

CURRENT PROGRAMS

THE SOLAR SYSTEM

An examination of the major bodies in the solar system helps guide the selection of preferred deep space missions, and associated telecommunications requirements. The best way to fulfill these requirements is the theme of this report.

The choice of a space communication system for a particular mission must take into account

1. Probable objectives of the mission under consideration
2. Reflection of these mission objectives into communication system requirements.

This involves definition of communication range, system lifetime requirements, and total data goals. These in turn affect data transmission rate and data processing and storage facility requirements. The composite mission constraints must then be reconciled with the restrictions on communication system such as weight, volume and power which are imposed by technological limitations. It is the purpose of this Mission Analysis Section to present: 1) potential mission objectives, 2) the conditions of these missions which are pertinent to communications, and 3) the demands which these missions will impose on a communications system.

The solar system consists of the sun as center body and a great number of smaller bodies revolving about the sun with the solar mass representing about 99.2 percent of the total mass of the solar system.

The extrasolar matter can be divided into the following groups:

1. Planets and their satellites (see Table A)[1]
2. Minor planets (asteroids or planetoids)
3. Comets
4. Meteors and dust
5. Interplanetary gas

Aside from the sun, the presently known solar system consists of nine planets, more than 1500 catalogued asteroids, 31 satellites, and an unknown, but very large number of comets and meteors. The mean density of interplanetary dust in the vicinity of the earth cannot be estimated presently with greater accuracy than a factor of 1000. Interplanetary gas consisting mainly of ionized hydrogen, helium and electrons is thinly distributed throughout the solar system.

All planets of the solar system revolve about the sun in the same direction as the earth (counter-clockwise if seen from a point above the North Pole of the earth's orbital plane, the ecliptic plane). With

[1]Miluschewa, Sima, "The Solar System Environment," IEEE Transactions on Aerosapce and Electronic Systems, p. 758, September 1967.

the exception of Pluto and Mercury, the outermost and innermost planets known, all planets move very nearly in the plane of the ecliptic, that is in the earth's orbital plane (see Figure A).[2] These two facts make full utilization of the planets' orbital velocities for cotangential interplanetary transfer orbits possible.

The main factor in determining the motion of planets, asteroids, comets and meteors is the powerful gravitational field of the sun. Planetary distances extend by a factor of 100 into space, from Mercury to Pluto. Some comet orbits extend considerably beyond Pluto while most asteroidal orbits extend to 2.8 A. U.

Table A. Physical Characteristics of the Planets

Symbol	☿	♀	⊕	♂	♃	♄	♅	♆	♇
Planet	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
No. of natural satellites	0	0	1	2	12	9	5	2	
Equatorial radius (⊕ = 1)	0.379	0.956	1.00	0.535	11.14	9.47	3.69	3.50	1.1
Equatorial radius (10^3 km)	2.42	6.10	6.378	3.41	70.4	6.04	2.35	2.23	7.
Mass (including satellites) (⊕ = 1)	0.0546	0.81498	1 01230	0.1077	317.89	95.12	14 52	17.	0.8 ±0.1
Equatorial surface gravity (⊕ = 1)	0.380	0.893	1.00	0.377	2.54	1 06	1.07	1.4	0.7
Semimajor axis, a (AU)	0.387	0.723	1.00	1.52	5 20	9.53	19.18	30.06	39.52
Perihelion distance (AU)	0.308	0.718	0 983	1.381	4.951	9.008	18 277	29 80	29.69
Aphelion distance (AU)	0.467	0.728	1.017	1.666	5.455	10.07	20.09	30.32	49.34
Orbital eccentricity ($e \times 10^{-3}$)	206.	6.79	16.73	93.3	48.5	51.6	44.31	7.34	248.11
Mean orbital velocity (⊕ = 1)	1.607	1.176	1.00	0.807	0.438	0.324	0.228	0.182	0.159
km/s	47.90	35.05	29.77	24.02	13.05	9.64	6.797	5.43	4.73
10^3 ft/s	157.19	114.96	97.70	73.81	42.82	31 60	22.30	17.80	15.6
Period of revolution (⊕ = 1)	0.241	0.617	1.00	1.83	11.86	29.46	84.0	164.8	247.7
Orbital inclination, i, to ecliptic (deg)	7.00	3.39	0	1.85	1.31	2.49	0.77	1.77	17.16
Inclination of equatorial plane to orbit (deg)			23.4	25.2	3.12	26.7	98.0	29	
Axial rotational period	$88^d.0$	150^d to 280^d	$23^h 56.07^m$	$24^h 37.38^m$	$9^h 53^m$	$10^h 26^m$	$10^h 42^m$	$15^h 48^m$	
Excape velocity (10^3 ft/s)	13.6	33.5	36.7	16.5	197.5	119.5	72.5	82.4	31.3

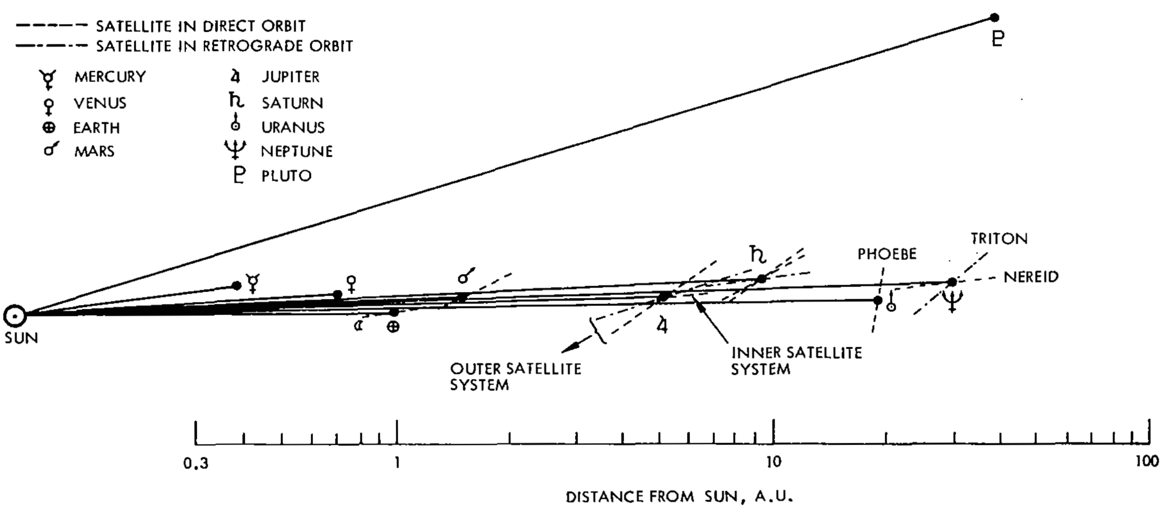


Figure A. Orbital Inclinations of Planets and Their Satellites in the Solar System

[2]Serfert, H.S., Space Technology, John Wiley and Sons, New York, 1959.

CURRENT UNMANNED PROGRAMS

Mission Goals, Status (as of January 1969), and Contractors are given for 29 current unmanned probes.

A variety of lunar and planetary missions are currently planned or under active consideration by NASA. Unmanned interplanetary missions under consideration are summarized in Table A. [1]

In 1969 a double fly-by mission to Mars is planned with an advanced version of the successful Mariner IV spacecraft. With these flights additional photographic coverage will be obtained and more detailed observations of the Martian atmosphere will be made preliminary to the subsequently planned Voyager mission in 1973. A comparison between the Mariner IV spacecraft and the proposed 1969 Mariner-Mars spacecraft is shown in Table B. Proposed experiments include IR, UV, and television scanning for atmosphere and planetary surface observations as well as measurements of interplanetary fields and particles.

The Voyager Program is directed initially toward the exploration of Mars and is geared to first flights during the 1973 opportunity. However, the Voyager, as a basic spacecraft system, is likely to serve as a vehicle for more detailed exploration of Venus and Jupiter. The current Voyager concept consists of three basic modules. The first is the spacecraft bus, houses the necessary electronics, attitude control, and communications systems for interplanetary and orbital operations as well as necessary support for the landing capsule. Second, a propulsion system which provides the necessary propulsion for midcourse correction and orbital insertion and thirdly the landing capsule. Preliminary Voyager spacecraft system designs are summarized in Table C.

[1] Space/Aeronautics, January 1969.

Table A. U. S. Unmanned Space Science Projects

	Missions, Technical Goals	Status, Milestones	Funding, Contractors
	PLANETARY AND LUNAR VEHICLES		
MARINER MARS	Mariner Mars '64: far flybys for atmospheric studies. Mariner Mars '69; near flybys for closer examination of ionospheric and atmospheric characteristics, shape of planet. Mariner Mars '71: to orbit planet, conduct topographical and thermal mapping, study atmospheric dynamics, seasonal environmental variations. Mariner Titan Mars '73: orbiter and soft-lander to study surface, biospheric, and entry characteristics. Mariner Mars '75-'77: large surface lab with return module to bring back soil samples. Boosters: MM '64, Atlas-Agena; MM '69 and '71, Atlas-Centaur; MTM '73, Titan 3D-Centaur; MM '75-'77, Saturn 5 or Saturn 5-Nerva. MM '64, '69, '71: *NASA-JPL.* MTM '73: *NASA-Langley.* MM '75-'77: *NASA-OSSA.*	MM '64 still responding to demand for signals from solar orbit. Two MM '69 satellites and experiments under test; missions scheduled for Feb. and Apr. '69. MM '71 mission approved by NASA; experiment selection underway; flights scheduled for spring and fall '71. MTM '73 (Viking) approved as line item for FY '70 budget; landing simulation late '68; two '73 flights planned. MM '75-'77 under study.	All Mariner projects through FY '68, est. $250m. FY '69: MM '69 and '71, $44m; MM '73, $9m; advanced missions, $2m.
PIONEER	Solar-orbiting probes of very high magnetic cleanliness for study of energy spectra and distribution of particles and fields during 11-yr solar cycle. First versions orbited 0.8-1.2 AU from sun; extended version, 0.4-0.6 AU; advanced version, 0.2-0.3 AU. Boosters: TAD, Atlas-Centaur-TE364 (Pioneers F, G). *NASA-Ames.*	Pioneer 6 launched '65 to 0.814 AU of sun. Pioneer 7 launched '66; lags earth in orbit of 1.13 AU aphelion, 1 AU perihelion. Pioneer 8 flew Dec. '67; Pioneer 9 on Nov. 15, '68. Pioneer E, F, G scheduled for '69, '72, '73; F and G may study Jupiter and asteroid belts.	Through FY '68, $70m; FY '69, $9m (excluding launch vehicles). TRW Systems (prime).
SURVEYOR	Soft lunar landing of unmanned instrumented spacecraft with tv camera, touchdown strain gage instrumentation. Surveyor 3, 4 carried surface sampler; 5, 6 conducted alpha backscatter analysis of lunar surface; 7 carried sample and backscatter analysis experiments. Booster: Double-burn Centaur. *NASA-JPL.*	Surveyor 1 soft-landed June '66; Surveyor 2 impacted Sep. '66 in out-of-control tumble; Surveyors 3, 5, 6 landed in '67, 7 on Jan. 9, '68.	Through FY '67, $508m; FY '69, $1m. Est. total: $488.9m (spacecraft), $103.3m (boosters). Hughes (prime).
MARINER VENUS	Mariner Venus '67: far flyby for preliminary atmospheric studies with modified Mariner Mars. Mariner Venus '73-'75: near flyby of atmospheric probes. Mariner Multiprobe Buoyant Stations: balloons in Venusian orbit, to launch probes for atmospheric studies. Boosters: MV '67, Atlas-Agena; MV '73-'75, Multiprobe, Atlas-Centaur. MV '67: *NASA-JPL;* MV '73-75, Multiprobe: *NASA-OSSA.*	MV '67 still responding to demand for signals. MV '73-'75 mission approved as line item for FY '70 budget. Preliminary designs of buoyant stations in '68; two planned but not approved for '75.	Funding: see Mariner Mars (above). Martin Marietta (preliminary design of buoyant stations).
PLANETARY EXPLORER	Low-cost, long-life Explorer-type craft (modified Imp design) for study of planetary environments; to orbit Mars in '73, '75, '77; Venus in '72, '73, '75, '77; Mercury in '73. Booster: TAT-Delta. *NASA-Goddard.*	Preliminary design work underway at Goddard by Imp project team.	Funded as part of Imp (see below).
	NEAR-EARTH STUDY		
AIR DENSITY, INJUN	Two jointly launched satellites. Air Density craft is 12-ft inflatable sphere similar to Explorer 9, 19, 24; measures air density changes in upper atmosphere. Injun measures downflux of radiation upon upper atmosphere, low-frequency ionospheric radio emissions. Booster: Scout. *NASA-OSSA, Langley.*	AD launches in '61 and '64. First AD/I launch (Explorer 24, 25) in '64, second (Explorer 39, 40) in Aug. '68.	Through FY '68, $9m; FY '69, $0.7m. Est. total: $4.6m (spacecraft), $4.4m (boosters). Injun: Iowa State (prime); Bendix (spacecraft assembly).
ISIS (INTERNATIONAL SATELLITE FOR IONOSPHERIC STUDIES)	Joint project of NASA and Canadian Defense Research Board to study ionosphere throughout solar cycle. Canadian Alouette swept-frequency topside sounder, U.S. Ionosphere Explorer fixed-frequency sounder, U.S. Direct Measurement Explorer measures electron and ion density, temperature. Boosters: Thor-Agena (early Isis), Delta (Isis A-C). *NASA-Goddard.*	Alouette 1 launched '62; Ionosphere Explorer 20, '64; Alouette 2, '65. Isis A planned for Jan. 22, '69 launch into low-altitude, nearly polar orbit. Isis B scheduled for '70, C for '71.	Through FY '68, $24m; FY '69, $1.4m. Est. total for 11 Isis: $25.6m plus $51.8m for boosters.

CURRENT UNMANNED PROGRAMS

Table A. U. S. Unmanned Space Science Projects (Continued)

INTER-PLANETARY MONITORING PLATFORM	Study of radiation environment of cislunar space throughout a solar cycle, as well as of interplanetary magnetic fields and earth's magnetosphere; development of solar-flare prediction method; assessment of radiation hazard for Apollo. Satellites earth-anchored (135 lb) or lunar-anchored (181 lb). Booster: TAD. *NASA-Goddard.*	Explorer 18 launched '63; Explorer 21 ('64) had perigee of only 60,000 mi (upper-stage failure). First Lunar Imp (D, Explorer 33) failed to achieve planned lunar orbit in '66 (perturbed 2nd-stage firing), went into 450,000-km earth orbit. Imp E (Explorer 35) into lunar orbit and Imp F (Explorer 34) into elliptical earth orbit in '67. Imp G planned for '69 earth orbit with 128,000-mi apogee; Imp I, H, J approved for '70, '71, '72.	Through FY '68, $43m; Fy '69, $7m. Est. totals: $56m (10 spacecraft), $33.3m (boosters). In-house program.
BIOSATELLITE	Study of biological system responses to effects of weightlessness, radiation, lack of earth's periodicity. Experiments at cellular, tissue, organ, and organism levels aimed at study of embryological development, growth, and physiological functions in organisms such as primates. Three missions required to accommodate payloads. Booster: TAD. *NASA-Ames.*	Biosatellite 1 launched Dec. '66; scientific failure (capsule was not recovered). Biosat 2 made successful but shortened flight in '67. Biosat D and backup Biosat F to carry primates on 30-day flights in '69, '70. Biosats C and E for 21-day flights canceled Dec. '68. Studies being considered for follow-on Biosat, improved Biosat, Biopioneer, manned orbiting biotechnology laboratories (Bio A-F), Advanced Biosat.	Through FY '68, $120m; FY '69, $21m. Est. totals: $136.5m (6 satellites), $21.5m (boosters).
UNIVERSITY EXPLORER	Owl Explorers to study near-earth atmospheric phenomena (e.g., aurora and airglow) as they correlate with trapped radiation belts and precipitated radiation. Satellites designed for university use. Booster: Scout. *NASA-Wallops.*	Two identical Owl satellites to be launched 1 month apart in '70 or earlier.	FY '69, $7m, total: $9m. Rice U. (prime).
SMALL SCIENTIFIC SATELLITE	To provide group of experimenters with opportunities to fly single or dual sensors for synoptic and related studies; may be launched in clusters. Booster: Scout. *NASA-Goddard.*	SSS-A scheduled for launch in '70, -B in '71.	FY '69, $2m. In-house program.
	OBSERVATORIES		
ORBITING ASTRONOMICAL OBSERVATORY	Study of spectral regions invisible from earth because of atmospheric absorption. In 35-deg-inclined circular orbit at 500 mi, OAO carries 1000 lb of instruments, weighs 4000 lb. Limited payload available for secondary missions. Booster: Atlas-Centaur. *NASA-Goddard.*	OAO-A1, launched '66, suffered power failure on second day, rendered no data. OAO-1 launched successfully Dec. 7, '68. OAO-B and -C scheduled for '69 and '70.	Through FY '68, $292m; FY '69, $37m. Est. total: $440m (spacecraft), $107m (boosters). Grumman (prime), GE-MSD (stabilization and control), Kollsman Instruments (star trackers), Westinghouse Research Lab (tv).
RADIO ASTRONOMY EXPLORER	Measurements of frequency, intensity, direction of radio signals from celestial sources in 0.25-9.2-MHz range. Mapping of radio sources on all-sky basis with two satellites. Booster: TAD. *NASA-Goddard.*	RAE-A (Explorer 38) launched Jul. '68 into 3700-mi circular orbit with 58 deg retrograde inclination; each of four 750-ft antenna booms successfully extended. RAE-B scheduled for '69 to complete mapping of radio sources in sky.	Through FY '68, $40m; FY '69, $1.5m. Total: $46m for in-house program.
SMALL ASTRONOMY SATELLITE	Detect x-rays and gamma rays from planetary and solar sources on all-sky basis from 300-mi orbit with 30-deg inclination to ecliptic. Booster: Delta. *NASA-Goddard.*	SAS-A (x-ray) being built for launch in '70, SAS-B (gamma ray) for '71.	plus $1.5m per booster. FY '69, $5m. American Science & Engineering (SAS-A x-ray experiment, $3.4m).
ORBITING SOLAR OBSERVATORY	Stabilized space platforms in earth orbit to study solar phenomena from outside distorting effects of atmosphere through 11-year solar cycle. Fan-shaped stabilized section connects to rotating wheel containing instruments. Booster: Thor-Delta. *NASA-Goddard.*	Oso 1 ('62) collected 2000 hr of data; Oso 2 ('65) made 4100 orbits in 9 months; Oso C ('65) lost due to launch vehicle failure; Oso 3, 4 launched '67. Oso F and G planned for '69, H for '70.	Through FY '67, $71m; FY '69, $12m. Est. total: $95m (spacecraft), $25m (boosters). Ball Bros. (prime).
ORBITING GEOPHYSICAL OBSERVATORY	Series of 3-axis-stabilized spacecraft to study particle activity, aurora and air-glow, geomagnetic fields, upper atmosphere composition, ionizing and heating energy sources. Orbits: highly eccentric (Ego) and polar circular (Pogo). Boosters: Ego, Atlas-Agena; Pogo, TAT. *NASA-Goddard.*	Ego 1 launched '64, still operating intermittently. Ego 3 ('66) performed for scheduled 46 days. Ogo 4 launched '67; Ogo 5 (Ego), Mar. '68. Ogo F (Pogo) scheduled for early '69.	Through FY '68, 260m; FY '69, $13m. Est. total: $219.1m (spacecraft), $47.1m (boosters). TRW Systems (prime). Ogo 5: American Standard (horizon scanners), Hoffman Electronics solar cells).

Table A. U. S. Unmanned Space Science Projects (Continued)

	SERVICE SATELLITES		
	Missions, Technical Goals	**Status, Milestones**	**Funding, Contractors**
ATS (APPLICATIONS TECHNOLOGY SATELLITE)	Satellites to develop cloud surveillance, communications, stabilization, and navigation technology in synchronous orbit. Several scientific experiments included. Weights: 800-1600 lb (ATS-1 through -E), 1600-2000 lb (ATS-E, -G). Booster: Atlas-Agena (ATS-1, -2, -3), Atlas-Centaur (ATS-4, -E through -G). *NASA-Goddard.*	ATS-1 and -3 providing communications and cloud cover mapping; high-resolution color from ATS-3. Launch vehicle failures on ATS-2 ('67) and -4 (Aug. '68) have delayed gravity gradient stabilization tests. ATS-E launch scheduled for early '69.	ATS-1 through -4, -E, -F: through FY '68, $127.63m; FY '69, $10.2m. ATS-F, -G: through FY '68, $3.5m; FY '69, $13.5m; est. FY '70, $30m; Primes: Hughes (ATS-1 through -4, -E), GE-MSD (ATS-F), Goodyear (ATS -G). Antennas: Fairchild Hiller (ATS-F), Convair (ATS-G).
NAVIGATION SATELLITE	Provide worldwide, low-cost, accurate navigation data to wide variety of airborne and marine vehicles. Booster: Delta class. *DOD, NASA-OSSA, Comsat Corp.*	Navy's Transit navigation satellite declassified in mid-'67, 11 more to orbit by early '70s. Wide commercial usage expected. ATS-3 Opie (Omega Position Location Experiment) demonstrated 1-2 nm accuracy ('68). Nimbus B-2 and D's IRLS experiment will further technology options. ATS-F and -G also to contribute to navsat arts.	NASA expenditures through FY '68, $2m; FY '69, $3m; est. FY '70, $3.5m. Johns Hopkins APL (prime); RCA-AED (spacecraft); Magnavox (receivers); GE-MSD, Philco, RCA-AED, TRW, Westinghouse (advanced studies).
INTELSAT 3	Third-generation commercial comsat. Coverage of Atlantic, Pacific, and Indian Oceans with 6-7 satellites. Started in late '68. 290-lb satellite providing 1200 two-way voice circuits, 450 MHz bandwidth, 6-GHz uplink and 4-GHz downlink. Booster: Thor-Delta. *Comsat Corp.*	Contract calls for 6 operational flight articles; option for 12 additional spacecraft. First commercial satellite with mechanically despun antenna. Anticipated '70 ground station total: 43. Sep. '68 launch failure; successful launch Dec. 18, '68.	Satellite contract cost: $32m plus orbital performance incentive. Through '68, $32m; '69, $33m; est. '70, $22m (including launch cost). TRW (prime); ITT; Sylvania; Aerojet-General; LMSC.
ESSA (ENVIRONMENTAL SURVEY SATELLITE)	First operational metsat system. Based on Tiros wheel-mode configuration in 750-nm circular sun-synchronous orbit. Global readout from Essa-AVCS series, local readout from Essa-APT series. Primary sensors in visual band with daily daytime coverage. Booster: Delta. *ESSA, NASA.*	Provides cloud cover maps to over 400 APT local-readout stations, operated by weather services around the world, and to a large number of ham-built receivers. Nine satellites; Essa 1-8 launched '66-68, Essa 9 to be launched early '69.	Through FY '68, $24.3m (for satellites); $36m (for launch vehicles and services); FY '69, $4.5m (launch cost of Essa 9). RCA-AED (prime).
ADVANCED ASSA	Provide visual-ir (day-night) cloud cover surveillance with local and global readout; 700-lb rotor-stabilized platform using Tiros M design; 750-800-nm polar, sun-synchronous orbit; will carry solar flux monitor and heat balance sensor on operational basis. Booster: Delta. *ESSA, NASA-Goddard.*	In system test. Launch goal mid-'69. One R&D model on order by NASA; 5 operational vehicles on order by ESSA. Satellite will carry dual redundant AVCS and APT systems to halve replacement launch requirements.	NASA: through FY '68, $16.5m; FY '69, $4.3m; est. FY '70, $2.6m. ESSA: through FY '68, $31m; FY '69, $6.5m; est. FY '70, $5m, RCA-AED (prime).
PILOT DOMESTIC COMSAT	Provide domestic tv, voice, and teletype communications for continental U.S. on trial basis. Pair of 2000-lb synchronous-orbit satellites spaced 6 deg apart. ERP: 38 dbw. Stabilization: ±0.2-deg. Capability: 12 color tv channels, 21,600 trunk channels, 9600 multipoint message channels, or any combination thereof. Booster: Atlas-Agena or Titan-Agena. *Comsat Corp.*	In advanced study stage; depends on congressional response to wide-ranging national policy recommendations of Presidential Task Force on Communications Policy, which suggests go-ahead with Comsat Corp. as "trustee." Opposition expected from domestic carriers. Two educational tv channels included in 12-channel capacity. Launch goal '70.	Projected cost: $35.7m for R&D, satellites, launch services plus $20m for ground stations. Hughes (most likely prime on basis of Intelsat 4 contract).
INTELSAT 4	Fourth-generation spin-stabilized, 1075-lb commercial comsat with mechanically despun antennas. Design to include 2 horns for earth coverage, pair of steerable dishes for 4.5 deg spot coverage. Capacity: 5000+ 2-way phone circuits or 12 color tv channels. ERP: 36 dbw/channel. Booster: Titan 3B-Agena or Atlas-Centaur. *Comsat Corp.*	Four spacecraft to be delivered by Sep. '70. European participation will be extensive; 10 Intelsat member nations will share subcontracts; assembly of third and fourth spacecraft in England.	Contract cost: $72m. Hughes (prime); British Aircraft Corp. (major subcontractor).

CURRENT UNMANNED PROGRAMS

Table A. U.S. Unmanned Space Science Projects (Continued)

	Missions, Technical Goals	Status, Milestones	Funding, Contractors
AERONAUTICAL COMSAT	Provide ATC and airline operational communications over North Atlantic and Pacific traffic lanes. Spin-stabilized 375-lb satellite with vhf aircraft-to-satellite link and microwave ground-to-satellite link. Four operational, 4 backup channels; 25-kHz channel spacing; 250 wats ERP/channel. Est. life: 5 yr. Booster: Long-Tank Delta. *Comsat Corp.*	Techniques in development with ATS-1 through -3. Some technology spillover possible from Tacomsat and Les 5. Pan Am Boeing 707 now testing Digicom vhf system with FAA support. All domestic agencies involved in favor of satellite; agreement on funding firming up. International (IATA) approval being pursued. Launch possible '71 or '72.	Through FY '68, $1m (primarily from NASA but including $0.25m for Philco studies for Intelsat). In-house funding by RCA, TRW. Projected cost for 2-satellite system (1 Atlantic, 1 Pacific), $50m. Likely funding: U.S. 70 percent (FAA, 50%; domestic carriers, 20%), foreign 30%.
SYNCHRONOUS METSAT	Advanced meteorological satellite to provide continuous day and night cloud cover mapping from synchronous orbit. Real-time surveillance of special weather phenomena. Also vertical sounding for H_2O and temperature profiles in tropical oceanic areas; transponder for horizontal sounding; balloon tracking at 10,000-40,000-ft altitudes; readout of instrumented oceanic buoys. Booster: Atlas-Centaur. *NASA-OSSA, Langley, Goddard, ESSA-NESC.*	Program limited to system studies and technology development on Nimbus and ATS; pressure building up for early ('71-'72) deployment. ATS-F may carry a high-resolution ir radiometer for nighttime cloud mapping. Vertical profiling (to be tested with Nimbus B-2 and D ir radiometers) may be impossible from synchronous orbit unless microwave radiometers (to fly on Nimbus E and F) are used. Balloon and buoy interrogation from synchronous orbit successfully tested with ATS-3's Ople system.	Through FY '68, $0.5m; FY '69, $0.3m. NASA and ESSA in-house studies.
DIRECT BROADCAST SATELLITE	Direct broadcast of voice and tv to tv center receivers in underdeveloped countries. Studies cover vhf, L-band, S-band, vsm, fm. Orbits may vary from 5000 to 22,300 mi. Booster: Atlas-Centaur, *NASA-OSSA.*	Program sound technologically but impeded by economic and political considerations. Broadcast to private homes from synchronous orbit economically unlikely, feasible to tv centers where audience size might justify larger antennas, low-noise receivers. Tests of 30-ft ATS-F antenna in Indian tv experiment will advance direct broadcast technology. Possible '73 orbit.	Through FY '68, $0.5m; FY '69, $0.2m. GE-MSD, TRW (studies).
	SURVEY SATELLITES		
GEODETIC SATELLITE	Active (Geos) and passive (Pageos) satellites with complementary ground instrumentation for precise geodesy. To measure earth's gravitational field within 0.05 ppm; link local and continental geodetic datums within 10 m. Geos has 5 onboard measuring systems, including a corner reflector for laser ranging. Pageos (100-ft-dia balloon), in 2250-mi circular orbit, uses photographic tracking to compensate for atmospheric scintillation. Booster: Geos-TAD; Pageos-TAT-Agena. *NASA-OSSA, Langley, Commerce.*	Geos 1 launched '65; Pageos 1, '66; Geos 2, Jan. '68. 110 ground stations participating. Success of tests with initial network of 6 laser trackers (ranging accuracy: 1-1.5 meters) suggests future experiments will be able to determine magnitude and rate of continental drift. Geos C, ('70) will attempt to measure shape of oceans with X-band radar altimeter.	Through FY '68, $14.5m; FY '69, $2.4m; est. FY '70, $3.8m. Johns Hopkins APL (prime, Geos) and Schjeldahl (prime, Pageos).
ORBITING DATA RELAY	*Synchronous-orbit communications relay-repeater* to relieve time, bandwidth and radiated-power constraints of 200-600-nm orbiters. Could lighten telemetry load on Stadan network expected in '70s from meteorological and earth resource satellites. Voice relay to MSFC on post-Apollo manned flights. 2-3 satellites in 1500-3500-lb range. Booster: Atlas-Centaur or Titan 3-Burner 2. *NASA-Goddard.*	*In conceptual study phase,* with emphasis on voice link for post-Apollo manned flights. Requirements: maintain contact with two lower-orbit target satellites; 4 two-way channels, each 1 MHz from ground station to repeater to target, 10 MHz in opposite direction. Studies concentrating on antenna techniques, gain margins, multipath, modulation. X-band (repeater to ground and S-band (repeater to target). 60 gHz a possibility for wide-band link.	Through FY '68, $0.2m; FY '69, $0.55m; est. FY '70, $0.5m. RCA-AED (studies); also in-house studies at Goddard, JPL.
ERTS (EARTH RESOURCE TECHNOLOGY SATELLITE)	Stabilized 750- to 1200-lb platform in low-to-medium orbit (500 nm max) to perform wide variety of agricultural, hydrological, geologic, geographic remote sensing with high-resolution tv, multispectral ir, radar mappers. Booster: Delta, Atlas-Agena. *NASA-OSSA, Interior, Agriculture, Commerce, Navy Oceanographic Office.*	Aircraft flight testing of sensors over wide variety of ground truth sites in progress. Spacecraft (Erts A and B) likely to employ high-resolution tv for cartographic and geologic mission, ir spectrometer and microwave sensors for agriculture, hydrology. Program also linked to Orbital Workshop (in spite of Congressional disapproval). Governmental policy direction required; current Planning Research payoff study will have impact on program evolution.	Through FY '68, $29m; FY '69, $20.5m; est. FY '70, $35-45m. GE-MSD, Lockheed-MSD, TRW (spacecraft); IBM-FSD, McDonnell Automation (data processing studies); U. of Kansas, Michigan, Purdue, RCA-AED, TRW Systems (sensor development); Planning Research (economic benefit analyses).

Table B. Mariner Mars Mission Comparisons

	1964	1969
LAUNCH	260 KG with Atlas-Agena	400 KG with Atlas-Centaur
MISSION	Fly By	Fly By
SCIENTIFIC CAPABILITY	20 KG of Experiments	30 KG of Experiments
	4 KG on Scan Platform	15 KG on Scan Platform
	5 million Data Bits	10 million Data Bits

Table C. Preliminary Design Results, Voyager Spacecraft System

	Boeing	GE	TRW	JPL
Hi Gain Antenna Size	2.45 m x 3.65 m	2.3 m circular	2 m x 1.68 m	2.15 m circular
Data Storage	2×10^8 Bits	6×10^8 Bits	2×10^8 Bits	1×10^8 Bits
Solar Panel Area	22.5 m^2	18.3 m^2	17.6 m^2	16.2 m^2
Battery Power	2460 watt-hr	2280 watt-hr	2000 watt-hr	3300 watt-hr
Preferred Propulsion	Solid	Liquid	Solid	Liquid
Relay Link Power and Frequency	14 watts - 100 MHz	20 watts - 200 MHz	20 watts - 137 MHz	20 watts - 400 MHz
S-Band Encounter Data Rate	8000 bps	8500 bps	5000 bps	5000 bps

DEEP SPACE MISSIONS

Deep space missions may be classified by their ultimate termination point and by the type of measurements made.

In general, deep space missions can be divided into four classes: 1) deep space probes which simply pass through interplanetary space making scientific measurements of the space environment encountered, 2) fly-by missions which have as their objectives a specific planet, but which make scientific measurements of that planet only during the fly-by phase, 3) planetary orbiter missions in which the spacecraft is placed into orbit about the target planet, and 4) planetary entry and lander missions in which the spacecraft or capsule enters the planetary atmosphere and transmits data either directly back to Earth or relays it through the spacecraft bus back to Earth. It would, of course, be extremely useful if all four of these general types of missions could be embodied in a single spacecraft concept since the use of a spacecraft proven on the earlier, simpler missions would enhance the probability of success of later, more complex systems.

Each of these types of missions is, in fact, constrained by the actual target objective of the mission, and it is obvious that a fly-by mission to Jupiter is different from a fly-by mission to Pluto. The most obvious difference, of course, is the difference in flight time. However, if the flight time is flexible due to a wide choice of booster vehicles, a 2-year mission to Jupiter could be performed using a relatively small booster and also perform a 2-year mission to Pluto using a much larger booster. If the communication system can be made compatible with both missions, but with a substantially reduced data rate for the Pluto mission (the thermal control and electrical power systems can be made compatible), then with the exception of the boost environment, these missions could be conceived of as essentially the same. Indeed, with the boosters available within the next 10 years, this approach is completely feasible. Thus, a spacecraft concept with a sufficiently high data rate capability at Jupiter can also be used for the Pluto mission with a low but acceptable data rate. Thus, by designing a spacecraft to meet the change in booster requirements, one of the critical elements needed for a multipurpose, solar system exploratory vehicle will be achieved.

The scientific objectives of deep space missions can be considered in terms of the spectrum of measurements to be made and the required position for making these measurements. These may be generally divided into three broad fields: the measurement of gross particles such as micrometeoroids; the measurement of atomic and molecular particles, electrons, protons, etc.; and measurements over the electromagnetic spectrum.

Gross particles (micrometeoroids) can only be measured effectively at the location of the particles since there is no method for making such measurements from Earth. A knowledge of the gross flux of such particles throughout the solar system is important, and the mass/velocity distribution as well as the direction can provide data concerning the history of the solar system.

Low-energy particles must also be measured _in situ_ since there is no known method of measuring their characteristics from Earth. On the other hand, many of the important characteristics of high-energy particles can be measured as well in near-Earth solar orbit as they can in deep space; therefore, such experiments are only valuable in the region where the solar influence terminates and for measuring trapped high-energy particles near a planet. Magnetic field measurements also require local measurements. With respect to neutral particles, measurements should be made outside the region of influence of the Sun and therefore, such a scientific objective can only be carried out on a very deep space probe.

Measurements throughout the electromagnetic spectrum are not valuable to pure deep space missions since these can best be made in the vicinity of the Earth. However, near a planet such as Jupiter or Saturn, high resolution measurements made over the entire spectrum are vital.

DEEP SPACE PROBE OBJECTIVES

Deep space exploration objectives include measurement of the sun's influence, of cosmic ray variation, of galactic magnetic field of low energy cosmic mass abundances, and of micrometeoroid densitites.

The first set of scientific objectives of all missions of concern relate to deep space experimentation, since for all of the missions the largest portion of the flight is associated with the transit phase. Of course, in a pure deep space probe there will be no terminal phase; hence, deep space experiments will be the sum total of the mission. The Table summarizes a typical set of scientific objectives for a deep space probe. Most of these will be a part of all deep space missions, whether or not there is a planetary target.

Perhaps the most important of these scientific objectives is to determine the extent of the influence of the Sun. Various theories exist as to the extent of the solar influence (in particular, the termination of the solar wind) and an accurate determination of its extent and the characteristics of the transition region are of great scientific interest. Low energy particle measurements along with magnetic measurements will provide much of this data.

Another related scientific objective is to determine the variations in the cosmic rays, both solar and galactic, with distance from the Sun. These measurements should be corrected with solar activity measured at the Earth and with effects observed in Jupiter, and in tails of comets.

In regions of space largely free of the influence of particles and fields from the Sun, measurements concerning the galaxy could be made. An obvious measurement concerns the existence of a galactic magnetic field which is predicted to be no more than one gamma. The determination of the existence and magnitude of this field would be of fundamental importance in evaluating other extra solar system effects.

Another important scientific objective would be to determine, through mass spectrometry of neutral particles, low energy cosmic mass abundances. A measurement of those abundances beyond the solar wind termination boundary would be of great relevance to current cosmological ideas.

During transit through the solar system, measurement of micrometeoroid densities would be of great value and could be performed relatively easily. Finally, once beyond the orbit of Neptune (40 AU) possible determination of the existence of a belt of material, such as that postulated by Whipple, as a source of comets could be determined. There are many other specific scientific objectives, but most can readily be defined within these broad objectives.

Deep Space Probe Objectives

Objectives	Sensors
Measurement of variations of solar wind with time and distance from Sun; verify transition region theories (2-40 AU). Measure relationship between plasma and magnetic fields.	Plasma probe
Measure interplanetary fields (0. 1γ). Determine existence of ordered galactic magnetic field (postulated $< 1\gamma$).	Magnetometers
Measure variations of cosmic rays (solar and galactic) with time and distance from Sun. Correlate Jupiter radio emission and cometary tail variations with cosmic ray measurements.	High-energy charged particle detectors
Measure variations in density with time and distance from Sun. Investigate cometary material source regions (20-40 AU).	Micrometeoroid detectors
Measure cosmic isotopic abundance.	Neutral mass spectrometry

DEEP SPACE PROBE INSTRUMENTATION

Typical instrumentation is given for 50 pound and 500 pound instrumentation packages. Typical interface problems are noted.

The size, weight, and data requirements of the experimental equipment for any mission can obviously vary greatly, depending upon the accuracy and dynamic range desired. But to make a realistic comparison of choices two weight categories have been selected. The first is a 23 kg (50-pound) set of experiments with modest objectives, such as that carried on Pioneer or Mariner missions, and the second is a considerably expanded set of 228 kg (500 pounds), typical of the kind of equipment that may be carried on a Voyager mission.

The Table lists a typical set of experiment equipment for deep space missions. As can be seen, there are six basic types of experiment equipment which can provide most of the desired data. Table B presents weights for the 228 kg (500-pound) payload representing not only different sensors, but also redundancy. However, the weights assume that the electronics use integrated circuits, thus the balance between electronics and sensors is much different from that in current experiments. For example, typical flux gate magnetometer sensors weigh 0.27 kg (0.6 lbs) while the electronics may weigh six times as much. With integrated circuits, the weights of the sensors and the electronics would be about the same. Thus, for the same total weight at least three magnetometers could be carried. The dynamic range for measurement of interplanetary fields and those near a planet, that is from 0.1 gamma in space to about six gauss around Jupiter, is 60,000. This range may be better calibrated using a set of three or four magnetometers, each of which is highly accurate within a specific portion of the band. As another example, on a typical plasma detection experiment, the Pioneer, the sensors weigh two pounds while the electronics weigh 1.8 kg (four pounds). With the use of integrated circuits, the electronics would be less than 0.23 kg (half pound), allowing the use of two detectors.

As can be seen, in general these experiments require very little power and place essentially no substantial data burden on the spacecraft system. These experiments will also have other important requirements such as position of the experiments with respect to the body attitude in space. If the vehicle is fully attitude-controlled and it is desired to scan in the plane of the ecliptic and perpendicular to the ecliptic, a large number of sensors must be provided or else the spacecraft must go through a roll maneuver at regular intervals. On the other hand, if the spacecraft is spin stabilized with its spin axis pointed toward the Earth, the sensors perpendicular to the spin axis will scan a plane perpendicular to the ecliptic each resolution. Even a spin-stabilized spacecraft will require additional sensors mounted at various angles to insure complete sky coverage. Spin cycle sky coverage requires angular resolution which is, however, easy to implement. None of the experiments studied require a fully stabilized spacecraft, although some imaging systems demand a fairly low rate, on the order of 1 rpm.

There is, of course, a variety of interface problems associated with these experiments. Some of the most obvious include reducing the background magnetic fields within the spacecraft itself to sufficiently lower levels so that unambiguous measurements of the magnetic fields can be made. Again, plasma sensors which have a window requirement must also be carefully evaluated for their interface with thermo-controlled systems since these windows are subject to heat leaks.

Deep Space Probe Experiments

Instrumentation	Weight kg	Weight lbs	Power (watts)	Range	Resolution	Bits/Sample	Typical Sample Rate
22.7 Kg (50-Pound) Payload							
Plasma detector	1.8	4.0	1.0	0.5 - 20 kev	10 samples	70	Variable as a function of available data transmission rate
Magnetometers	2.3	5.0	2.0	0.2 - 20γ	0.25%	8	
Radiation particle detector	3.6	8.0	3.0	100 - 500 mev	5 samples	750	
Micrometeoroid detectors	2.3	5.0	1.0	particle counts	-	6	
Neutral mass spectrometer	9.1	20.0	5.0	mass and unit charge	1:25	7	
Radio propagation (electron density)	3.2	7.0	2.0	f (one way)	-	7	
230 Kg (500-Pound) Payload							
Plasma detector	23.0	50.0	5.0	0.1-50 kev and particle discrimination	100 samples	700	Variable as a function of available data transmission rate
Magnetometers	13.8	30.0	6.0	0.1-100γ	0.25%	8	
Radiation particle detectors	11.4	25.0	9.0	10-1,000 mev and particle discrimination	20 samples	700	
Micrometeoroid detectors	45.5	100.0	3.0	M and V	0.25%	8	
Neutral mass spectrometer	6.8	150.0	20.0	M and e	1:100	7	
Radio propagation (electron density)	18.2	40.0	90.0	f (two way)	-	7	

PLANETARY FLY-BY AND ORBITER MISSION OBJECTIVES

Fly-by and orbiter mission objectives are largely oriented toward imagery data and atmospheric measurements. The orbiter mission provides a much larger amount of data.

There are many scientific objectives for missions with a planetary target. The more prominant objectives are summarized in the Table. In general, those for the fly-by and orbiting missions will be roughly similar. Phototelevision of the target is probably most important. Such a scientific objective can vary from the relatively modest mission used in Mariner Mars '64, which obtained a few images of Mars, to elaborate orbiter missions mapping the entire surface of a planet. Such an imaging experiment provides a great deal of data, not only about the surface characteristics of the planet and the weather, but also can measure seasonal effects through the use of polarimetry and colorimetry.

Infrared microwave radiometry can provide thermal mapping of the planetary surface, identifying specific areas of interest. Infrared spectral measurements could detect the presence of organic chemical compounds and be used to observe topographic variations in critical spectrum regions such as that near 3.5 microns. These measurements can also detect the height profile distribution and circulation of specific atmospheric constituents as well as the content of trace constituents. The opacity and reflectivity of the atmosphere in the ultraviolet spectrum can alternatively provide a more sensitive determination of the atmospheric composition.

Fly-by Missions

On a fly-by mission it will be desirable to pass over the terminator. In general, such trajectory is possible. On a fly-by mission it is also desirable to measure the attenuation of sunlight observed through the planetary atmosphere, in broad and narrow spectral bands, to obtain estimates of the height profile of atmospheric constituents. A similar occultation experiment using the spacecraft RF transponder would provide data regarding atmospheric density profile from the comparison of the apparent trajectory with the actual trajectory. It should be noted, of course, that many of the scientific measurements made during the transit phase, such as particle, plasma, magnetic field, and possibly micrometeoroid, will also be useful during the fly-by mission.

Another desirable objective to derive information regarding the upper atmosphere is to measure the Aurorea and airglow which will also establish a background against which meteor flashes may be observed. When this experiment is coupled with photometry, the micrometeoroid flux can be measured.

Those measurements related to planetary thermal balance, height and characteristics of clouds, and the particle matter in suspension will provide weather and wind data.

Orbiter Missions

Orbiter missions will have the same basic objectives as the fly-by mission, but the instrumentation balance should be different because of the increased time near the target. Photo-television will be largely used as a mapping mission, as will the UV and IR spectrographic measurements. The occultation experiments, whether at RF or using the Sun as a source, can be performed repeatedly, providing greater accuracy and confidence. All the equipment must be designed to measure seasonal changes as well as even smaller variations caused by diurnal effects, etc.

Fly-By Mission Objectives

Objectives	Sensors
To obtain high resolution images of surface and clouds.	Phototelevision
To obtain albedo characteristics as a function of wavelength, topography and phase angle. To determine limb effects as a function of wavelength; to count meteor entry flashes. To determine the polarization of visible to ultra-violet energy as a function of wavelength, topography and phase angle; to determine the solar absorption spectrum.	Photometry
1900 Å- 3000 Å To determine opacity of atmosphere to UV in the region of 1900 Å to 3000 Å, to measure the CO content; To detect N_2 and Lyman α glow (H), H_2,and N at wavelength <1900 Å. To determine the solar absorption spectrum.	UV spectrometry
To map atmospheric temperatures.	IR radiometry Microwave radiometry
To measure the content of NH_3, CH_4, N_2O, to determine the combined absorption of N_2O- CH_4; to determine the solar absorption spectrum.	IR spectrometry
To measure aruorea and airglow; to detect N_2, Na	IR-UV spectroscopy
To measure planetary mass; to measure planetary atmospheric properties from RF osculation experiment.	Spacecraft Tracking
To measure local effects at the target planet, such as a possible radiation belt, etc.	Plasma, magnetic fields, high-energy charged particles and micrometeroid

PLANETARY FLY-BY AND ORBITER INSTRUMENTATION

The imagery sensors and particle sensors are the most prominent used in fly-by and orbiter missions. Possible instrumentation payloads are described.

The Table lists a typical set of fly-by experiment equipment. The most critical item on this list is clearly the phototelevision system, since the optics associated with such a system may vary greatly, depending upon the desired resolution. An optical system for a mission such as Mariner or Voyager will, in general, be fairly heavy, both since high resolution is desired and since the spacecraft is not allowed to fly close to the planet. The desire to keep the planet Mars biologically pure until a satisfactory biological exploratory mission can be performed, currently constrains the minimum fly-by distance. However, for Jupiter or Saturn missions sterilization considerations are of a different nature, and a fly-by mission might well be allowed to come as close as system accuracy will allow. Current accuracy estimates indicate that with DSIF tracking alone, a fly-by mission to Jupiter with a distance of closest approach of 7000 km is possible, and that with a fairly simple terminal sensor this might be reduced by a factor of 3 or 4. But even at a distance of 7000 km, a simple lens with 10.2 cm (4-inch) focal length could provide a resolution of 2 km, which is 5000 times better than is presently achievable from the Earth using 508 cm (200-inch) Mount Palomar telescope. In the light of present knowledge of Jupiter's circulation and cloud structure, such high resolution might not be as valuable as a synoptic view, but would be desirable on later missions.

For the 227 kg (500-pound) payload it is expected that the great increase in weight will be devoted to a large optical system which should increase the resolution by about two orders of magnitude requiring the same increase in the picture transmission for the same area coverage. But with a data transmission rate of 10,000 bits/sec, reasonable for this system at the orbit of Jupiter, a month of transmission is required.

By comparison with the phototelevision system requirements, the rest of the experiments appropriate for a fly-by mission are modest in terms of weight, power, and required bandwidth. The equipment is itself quite standard and presents no difficulty to the spacecraft interface requirements. The pointing accuracy requirements of the phototelevision system is in general higher than the requirements of the other experiments, with the exception that long integration time may be required for infrared radiometers if measurements at various depths in the atmosphere are to be achieved. However, all of the requirements of these experiments are contingent upon the fly-by distance achievable and the amount of time spent in the vicinity of the planet.

Orbiter Mission Instrumentation

The orbiter experiments will be to a large extent similar to those for the fly-by mission, but presumably with modifications desirable for the mapping function which will be grossly performed from orbit. A very desirable phototelevision measurement would be time lapse photography at fairly low resolution in order to determine the motion of the gases at the surface of the planet. The relatively high rates of rotation of the planets, 10 hours for Jupiter and 10-1/2 hours for Saturn, as compared with the period of the highly elliptical orbits (selected to minimize propulsion requirements) will make it difficult to accomplish such photography effectively at periapsis. However, since low resolution pictures appear to be desirable, these could be accomplished at apoapsis with the same camera used to provide high resolution pictures at periapsis. The configuration of the vehicle could be substantially constrained by the requirement to achieve both of these objectives with a single camera system, especially since the selection of a precise orbit and appropriate characteristics of the phototelevision system are necessarily linked to the booster system capability and the system accuracy. Nevertheless, the spacecraft system discussed appears capable of achieving a set of orbiter mission objectives with reasonable booster vehicles.

Fly-by Experiments

Instrumentation	Weight kg	Weight lbs	Power (watts)	Range	Resolution	Bits/ Sample	Typical Sample Rate	
23 Kg (50-Pound) Payload								
Phototelevision	6.8	15.0	5.0	-	10.2 cm (4 in.) focal length	4×10^5	30/minute	
IR radiometer	1.36	3.0	3.0	3.7 μ	0.25%	8	1/minute	
Meteor photometer	0.68	1.5	1.5	visible	-	20	1/minute	
Photometer	0.68	1.5	1.5	visible	3%	5	1/10 sec	
VLF planetary sensing	0.91	2.0	2.0	10 - 25 kc	5 filters	7	1/sec	Data Stored
Plasma detector	1.8	4.0	1.0	0.5 - 20 kev	10 samples	70		
Magnetometer	2.3	5.0	2.0	0.2 - 20 γ	0.25%	8		
Radiation particle detector	2.3	5.0	2.0	100 - 300 mev	3 samples	750	1/sec	
Micrometeoriod detector	2.3	5.0	1.0	particle count	-	6		
Radio Propagation	3.2	7.0	2.0	-	-	7		
228 Kg (500-Pound) Payload								
Phototelevision	12.5 (w/telescope)	275.0	30.0	-	1.9 m (75 in.) f/4	4×10^5	2/sec	
UV spectrometer	15.9	35.0	25.0	$1\text{-}3.5 \times 10^3$ Å	10 Å	5×10^3	1/sec	
IR spectrometer	20.5	45.0	15.0	2-5 μ	200 Å	5×10^3	1/sec	
IR radiometer	4.6	10.0	10.0	5-15 μ	0.25%	8	1/sec	
Meteor photometer	2.3	5.0	5.0	visible	-	12	1/sec	
Spectrometer (airglow and aurorae)	18.2	40.0	20.0	UV-IR	20 Å	3×10^3	1/sec	
Photometer	2.3	5.0	5.0	visible	0.8%	7	1/sec	
Microwave radiometer	11.4	25.0	4.0	1-10 cm	-	10	1/sec	
VLF planetary sensing	4.6	10.0	12.0	1-100 kc	100 filters	7	1/sec	
Plasma detector	1.8	4.0	1.0	0.5-20 kev	10 samples	70	1/sec	
Magnetometer	6.8	15.0	2.0	0.2 γ-10 gauss	0.25%	8	1/sec	
Radiation particle detector	3.6	8.0	2.0	100-500 mev	5 samples	750	1/sec	
Micrometeoroid detector	2.3	5.0	1.0	particle count	-	7	1/sec	
Radio propagation	3.2	7.0	2.0	-	-	7	1/sec	

ENTRY MISSION OBJECTIVES AND INSTRUMENTATION

Entry missions are designed to examine the atmosphere of planets, instrumentation is oriented toward atmospheric measurements.

For entry missions to such planets as Jupiter and Saturn, the density and the generally hostile characteristics of the atmosphere make a survivable impact, at best, improbable. Indeed, at this time no useful definition of the surface of such planets exists. However, a mission which transmits data even during a small portion of the entry would be extremely useful and could provide altitude profiles of temperatures, pressure, density, mean molecular mass, specific heat ratio, scattering power and attenuation of the atmosphere in the blue UV and near IR, and the momentum spectra of the galactic and solar cosmic ray induced nucleonic showers. Table A summarizes these objectives. Although all of these objectives are very desirable, it is clear that they are not easily achieved, not only in terms of experimental equipment, but also because of the entry trajectory characteristics.

Entry Mission Instrumentation

A capsule entry mission to planets such as Jupiter clearly requires a great deal of detailed study. However, a list of typical measurement instruments for a lightweight capsule is shown in Table B. The design of these instruments for the wide range of entry conditions possible will clearly present great problems, but if a lightweight, low W/D_CA capsule can be used and a meaningful relay link established, it appears that very valuable data can be gathered. Analysis of a number of trajectories has shown that this capsule can be launched from a spacecraft without reorienting the spacecraft at separation and that communication gain can be provided for the spacecraft-to-capsule link throughout the reentry phase, at the same time maintaining communications with earth.

Table A. Entry Mission Objectives

Objectives	Sensors
To determine the atmospheric deceleration profile.	Accelerometers and gyros
To measure temperature, pressure, density, and velocity of sound over the entry profile.	Aerometeormeters
To determine the atmospheric composition over the entry profile.	Mass spectrometer
To measure primary radiation particles and atmospheric-induced secondary radiation.	High-energy charge particle detectors
To determine atmospheric properties (ionosphere depth, ionization blackout, etc.).	RF tracking (2 frequencies)
To measure ionosphere characteristics.	Langmuir probe

Table B. Entry Mission Instrumentation

23 Kg (50-Pound) Payloads							
Instrumentation	Weight kg	Weight lbs	Power (watts)	Range	Resolution	Bits/ Sample	Typical Sample Rate
Accelerometers (8 redundant)	1.5	3.25	4.0	0 - 500 g's axial ± 20 g's axial	2% 2%	8 8	every 305 m (1,000 ft)
Gyro	0.4	0.87	3.0	roll rate	2%	8	
Aerometeormeter							
temperature	0.14	0.3	0.07	100 - 300°k	1%	7	
pressure	0.14	0.3	0.1	100-15,000 newtons/m^2	±50 newtons/m^2	-	
density	0.68	1.5	2.0	$2 \times 10^5 - 2 \times 10^4$ gmcm^{-3}	1%		
velocity of sound	0.32	0.7	0.3	250 - 380 m/sec	1%		
Mass spectrometer	2.7	6.0	6.0	5 - 12 amu	-	1,100	

MANNED MISSIONS

Manned space missions include Apollo and Apollo Applications which are based on earlier Mercury and Gemini flights and form the base for future, more advanced missions.

The objectives of manned space flight missions beyond Apollo and their present status are summarized in the Table. Beyond the present Apollo program is envisioned a several-year Apollo Applications program, (APP). It is intended to utilize the capabilities of the Apollo-Saturn hardware for exploring near-Earth space out to a distance of about 90,000 KM (50, 000 miles). The purpose of Apollo Applications is to provide information about man's capabilities in space in order to define and carry out future phases of manned space flight which will consider missions such as permanent orbital and lunar bases and interplanetary missions. The specific goals of Apollo Applications are to demonstrate three mission capabilities with crews of two or three: at least 14 days and perhaps as long as 90 to 135 days in earth orbit, 28 days in lunar orbit, and 14 days on the moon. During this time it is expected that the crew will:

- Perform synchronous and high inclination orbit operations
- Demonstrate orbital assembly and resupply
- Demonstrate personnel transfer in orbit
- Develop 3-month orbital flight capability
- Conduct extended duration lunar exploration
- Conduct operational, scientific, and technological experiments.

Chronologically Apollo Applications can be divided into two phases:

1. In 1970 and 1971, seven earth orbital flights of at least 14 days each including several in polar and synchronous orbits. The booster for the earlier of these launches will be Saturn 1B; for the later ones, Saturn V. The spacecraft will be a Command and Service Module (CSM) and a Lunar Module (LM).
2. Beginning in 1970, nine earth orbital missions of 45 days each and three lunar orbital missions of 28 days each. The launch vehicle will in all cases be a Saturn 1B.

No definite plans have yet been announced for a post-Apollo Applications manned space program. A likely course, however, is a comprehensive evolutionary program aimed at concurrently advancing the national space capability in three areas:

1. Earth orbital operations including research, communications, meteorological, and other activities.
2. Lunar exploration leading to a permanent research base.
3. Planetary exploration involving fly-by and landing missions to Mars and Venus with fly-bys of more distant ones.

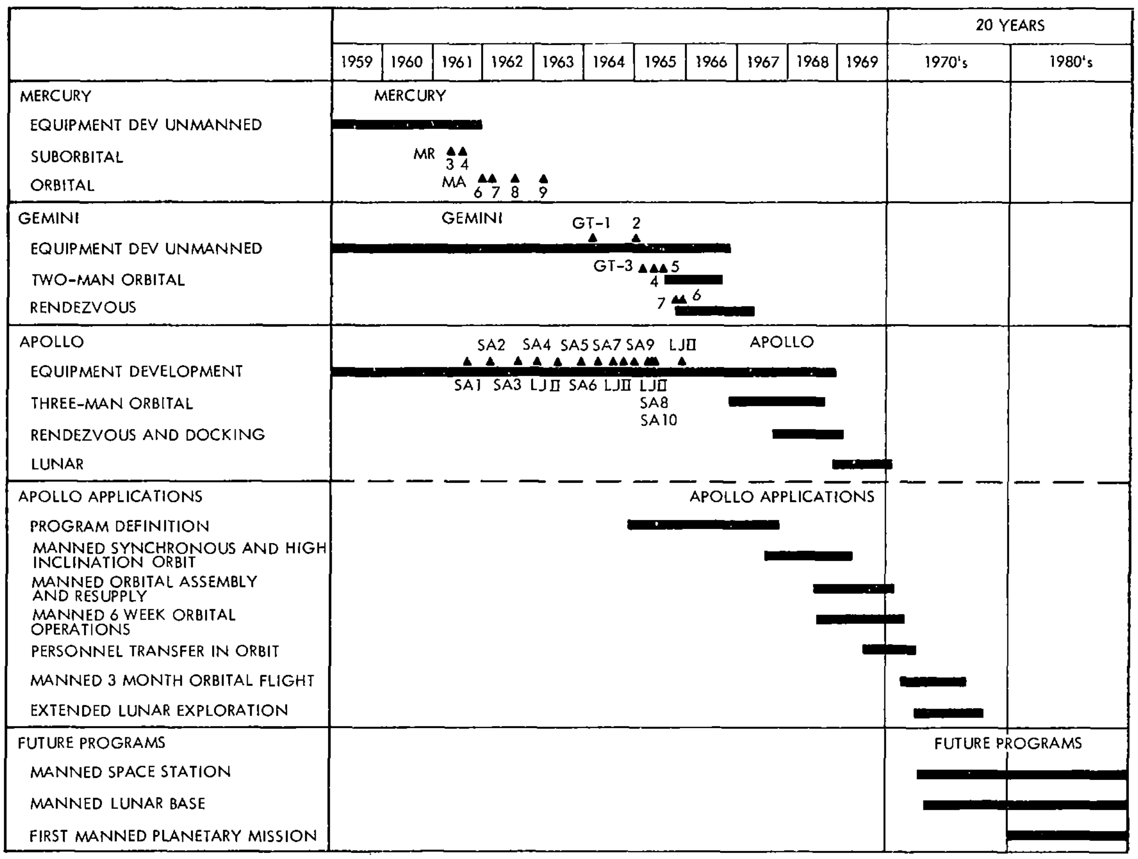
The projected schedule of the manned missions is summarized in the Figure.

U. S. Manned Space Missions[1]

	Missions, Technical Goals	Status, Milestones	Funding, Contractors
APOLLO	Manned landing on moon, initially for less than 1-day stay, including 3-hr surface excursion. Spacecraft: 3-man Command and Service Module (CSM), 2-man Lunar Module (LM). CSM to remain in lunar orbit; LM to land on and take off from moon, rendezvous with CSM; CM alone to reenter. Boosters: Saturn 1 and 1B for early earth-orbital test flights; Saturn 5 for current earth-orbital and lunar tests and lunar landing missions. *NASA-MSC* (spacecraft), *MSFC* (booster).	Considerable redesign and reorganization followed fatal fire during pad test in Jan. '67. Launch of first unmanned Saturn 5 and first full-speed reentry, Nov. '67; first unmanned test of LM on Saturn 1B, Jan. '68; second unmanned Saturn 5/CSM flight (Apollo 6), Apr. '68. First manned CSM launched by Saturn 1B Oct. '68 (Apollo 7) on 11-day earth-orbital mission, first manned Saturn 5 launch Dec. 21, '68 (Apollo 8) on 6-day lunar-orbit mission; both flights highly successful. Probable '69 launch sequence: first manned LM flight in earth orbit, Mar. '69 (Apollo 9); flight to moon with LM descent to 50,000 ft above lunar surface, May '69 (Apollo 10); lunar landing (Apollo 11), Aug. '69. If successful, perhaps 2-3 more landing missions could go in '69-'70.	Total cost now estimated at $23.9b through completion of basic program in FY '71. $21.4b already spent, including $2b for FY '69. Est. FY '70, $1.849b; est. FY '71, $618m. NAR (CSM, Saturn S-2 stage); Grumman (LM); McDonnell Douglas (S-4B); Boeing (S-1C, launch vehicle integration, spacecraft test integration and evaluation); IBM (Saturn Instrument Unit); GE (electric and electronic support and checkout equipment); RCA checkout computers).
APOLLO APLICATIONS (AAP)	Program reduced to five flights, three of them manned; possibility of three more flights with backups. All flights to be launched by Saturn 1B. First dual mission (AAP-1, -2) planned for Aug. '71: unmanned S-4B Orbital Workshop to be launched into near-earth orbit; to be followed next day by 3-man crew in CSM for setting up Workshop, after venting of residual fuel, as habitable work area for 28-day stay. Revisit for 56-day stay (AAP-3A) planned for late '71. Then AAP-3, -4 dual launch of unmanned Apollo Telescope Mount (for solar observation) and three-man crew in CSM, followed by rendezvous and dock with AAP-1 Workshop for 56-day stay. Prototype Workshop, ATM and CSM could be used as backups or for repeat missions. *NASA-MSFC* (Workshop, ATM), *SFC* (CSM).	Test hardware being built for Workshop, connecting airlock, Multiple Docking Adapter (MDA); fabrication of flight hardware not yet begun. ATM in final design phase; test hardware being built; no flight hardware yet. Contracts out for all ATM experiments, most Workshop experiments. CSM modifications still in preliminary design phase; no contractor selected yet.	Through FY '69, $483m; est. FY '70, $300m; est. FY '71-'72, $500-600m. McDonnell Douglas (Workshop, airlock), Martin (experiment integration), probably NAR (CSM).
EXTENDED LUNAR EXPLORATION	Gradual extension of lunar surface exploration, possibly beginning in '72, using Saturn 5s remaining from Apollo and modified LMs for 3-14 day stays. Flying platforms favored for lunar surface mobility role. Establishment of semipermanent bases; scientific experiments beyond Alsep level; use of unmanned lunar satellites in conjunction with surface experiments. Program may become known as Lunar Exploration Operations (Leo); has absorbed lunar surface missions previously planned for AAP. *NASA-OMSF.*	Plans to award study contracts in FY '70 for modified LM configurations. Perhaps some early development work in FY '70 on space suit, life support system, flying platform, solar cells or fuel cells for extended lunar stays.	Through FY '69; $5m+; some Apollo funds for FY '70 expected to be applied to Leo studies.
EXTENDED MANNED ORBITAL OPERATIONS	Nine-man, 80,000-150,000-lb space station under serious consideration as minimal major post-Apollo program. Station would be modular for compatibility with DOD missions, have minimum 2-yr lifetime in nominal 200-nm earth orbit. Objectives include earth resource surveys, meteorological, astronomical, medical and perhaps zero-g manufacturing experiments plus military missions. Modules could be placed in synchronous or polar orbit separately or from earth orbit. Could also be staging base for broadcast satellites, etc. Plans for station to serve as model for planetary craft have been set aside. For resupply, system would use low-cost launch vehicle in 100,000-lb-to-earth-orbit class and reusable spacecraft. *NASA-OMSF.*	Phase B studies of entire space station and resupply system expected to start early '69. Detailed phase C design work could begin late in FY '70, development in FY '71. Several launch vehicles under study. Large 6-9-man Gemini is leading candidate for reusable spacecraft, might have parawing for controlled land landing, include launch and ascent electronics section.	FY '69, ~$10m (for initial phase B work by two contractors). Est. cost of development of station, launch vehicles, and logistic spacecraft, plus 3-yr operation, <$5 billion.

[1] Space/Aeronautics, January 1969.

MANNED MISSIONS



Timetable of Manned Space Missions[2]

[2]Advances with Astronautical Sciences, 21, p. 123.

MISSION ANALYSIS AND METHODOLOGY

Analysis of Mission Requirements

REQUIREMENTS

DATA TRANSMISSION REQUIREMENTS

Dominant data transmission requirements are due to imagery data. Possible improvements in data transmission can be made using spacecraft data storage and processing.

Data transmission requirements depend on the number and type of experiments to be carried, the time interval during which information must be returned, and the available information storage capacity. Typical instrument payloads for an unmanned planetary fly-by spacecraft and their associated data outputs are listed in Table A. The optimum transmission rate for returning this data must be determined by a trade-off between transmitter power, transmitting and receiving aperture size, information storage capacity and reliability considerations which is the subject of the methodology of this study. Typical maximum data rate requirements for various types of information are listed in Table B. Real-time television data rate requirements versus bandwidth are shown in Figure A. Figure B shows the anticipated data rates for various communication tasks.

Communication research activities are aimed at advancing capability in microwave, millimeter, sub-millimeter, and optical frequencies. In the microwave region, presently used by the DSIF, increased tube power and efficiency, larger antennas and lower noise temperatures in ground receivers are expected to increase data rates at Mars distance to 10^6 bits/sec. Depending on the data rate requirements of a particular mission, it may be preferable from a systems viewpoint to provide sufficient data storage capacity to permit transmission at rates far lower than the acquisition rate.

For most deep space missions, the minimum acceptable data rate can be relatively low (the minimum bit rate on both Pioneer and Mariner Mars is 8-1/3 bits/sec.). Although the bits per sample can be large when very high resolution is desired, in general the number of samples per unit time will be small. It is obvious that quantities that vary with distance from the Sun will be measured as slowly as the flight time itself. Time-varying events will in general be coupled with solar events, but significant ones are not very frequent, and hence only short-term resolution during such events is, in general, required. An obvious case is the number of samples gathered from micrometeoroid detectors. All flights to date have experienced a very small number of impacts, and if even as many as 10,000 bits per sample are obtained, the amount of time over which such data can be transmitted prior to a second impact is enormous. As another example, the changes in magnetic fields are generally both small and slow, and a large change, as in the event of a solar flare, occurs infrequently. This means that much time is available between events to transmit all of the information gathered and stored during that event. In addition, if effective data processing is used on the spacecraft and most redundant data eliminated, the transmission requirements can readily be reduced by two orders of magnitude, even for a very high resolution experiment.

Planetary fly-by and relay entry missions will gather a great deal of information at planetary encounter. But unless real-time transmission data is required, the average data requirements will not be much higher than those for deep space probes. For example, 1000 high resolution

Table A. Planetary Fly-by Scientific Payload

Interplanetary Measurements				
	Sample Rate	Bits Per Sample	Total Bits	Measurement Time
Solar magnetic field	2/hr	32	1.7×10^6	3 yrs.
Solar wind	1/hr	200	5.1×10^6	3 yrs.
Cosmic dust	1/hr	100	2.5×10^6	3 yrs.
Lyman α line intensity	1/hr	8	0.2×10^6	3 yrs.
X-ray flux	1/hr	24	0.61×10^6	3 yrs.
Cosmic ray flux	3/hr	72	5.1×10^6	3 yrs.
Solar flare proton flux	1/hr	24	6.1×10^6	3 yrs.
			21.21×10^6	
Planetary Fly-By Measurements				
Magnetic field	60/hr	16	1×10^4	10.4 hrs.
Trapped radiation	66/hr	56	3×10^4	8.1 hrs.
Atmospheric composition	612/hr	256	1.6×10^4	0.1 hrs.
Surface features	300/hr	2.5×10^6	14000×10^4	0.19 hrs.
			1.4×10^8	

Table B. Typical Data Requirements

Pulse Code Modulation				
Type	Signal Bandwidth	Representation, bits/sample	Maximum Bit Rate	Tolerable Error Rate
Scientific data	0-1 kHz	9	18 kilobits/sec	10^{-3}
Engineering data	0-1 kHz	7	14 kilobits/sec	10^{-3}
Command data			50 bits/sec	10^{-5}
Teletype			75 bits/sec	10^{-5}
Speech	0-4 kHz	3	20 kilobits/sec	10^{-3}
Real-time television (500 x 500-element picture)	15 Hz-4 mHz	6	48 megabits/sec	10^{-3}
Pictorial transmission (500 x 500-element picture in 12.5 seconds)	15 Hz-10 kHz	6	120 kilobits/sec	10^{-3}

DATA TRANSMISSION REQUIREMENTS

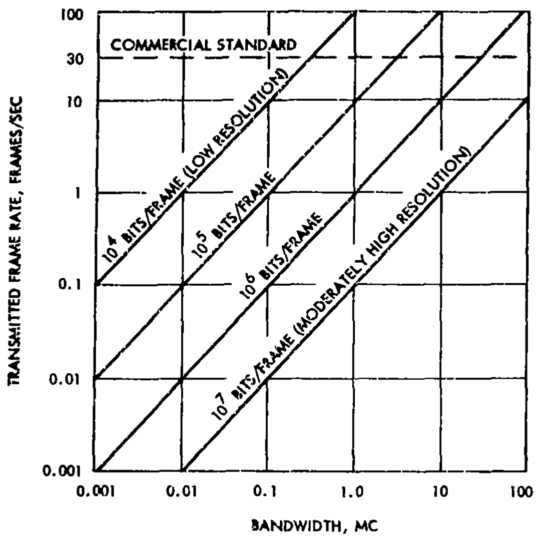


Figure A. Bandwidth requirements can be reduced by reducing the number of frames transmitted per second. However, the nature of the analog signal puts an effective lower limit on frame rate.

pictures (500, 000 bits/sec) and 8 grey levels transmitted with 1 sync bit/resolution element, there will be a total of 2 million bits per picture. The total number of bits for 1000 pictures will be 2×10^9. If the transmission rate is 2000 bits/sec, the required time to transmit 2×10^9 bits is only 2×10^6 seconds or about 15 days. If we assume that ground stations are available only one-third of the time, a total of 45 days is required to transmit 2×10^9 bits, a very small portion of the total flight time. Of course the key tradeoff which must be made is that of weight/ cost for transmission capability compared to weight/cost of data storage capability.

Spaceborne recorders are available with speed capabilities ranging from 1 bit/sec to 5 megabits/sec. Recorders with write/read speed ratios of 100:1 have been used in space, although higher speed ratios of 10, 000 or more would be desirable for some applications. In general, recorder system weight is a direct function of the capacity for a given storage mode (e. g. , tape), plus a fixed weight which is a function of the data rate. As an example, the Mariner 4 data tape recorder and its data encoder weighed 17. 9 KG and stored 5.25×10^6 bits of data. Actual operating mean times between failure are on the order of 1000 hours, although recorders have survived a primarily quiescent existence in the space environment for as long as one year.

Data handling requirements may be as small as 10 to 100 computational cycles per day during midcourse on a planetary fly-by mission, then rise to 100, 000 per second during encounter. A typical aerospace computer having an add time of 2 to 5 microseconds and a capacity of 4096 16-bit words, occupies about 0. 05m^3, weighs about 10 kg and consumes 80 watts. Compact computers with capacities of over 16, 000 36-bit words each are within the present state-of-the-art. It is expected that space computers of the mid-1970s, having a memory capacity of 32, 000 36-bit words, would weigh less than 1 kg and displace less than 0. 005m^3 based on the present promises of thin film and integrated circuitry electronics. Mean times between failure of present computers are on the order of 10, 000 hours; mean times between failure on the order of 50, 000 to one million hours are predicted by the mid-1970s.

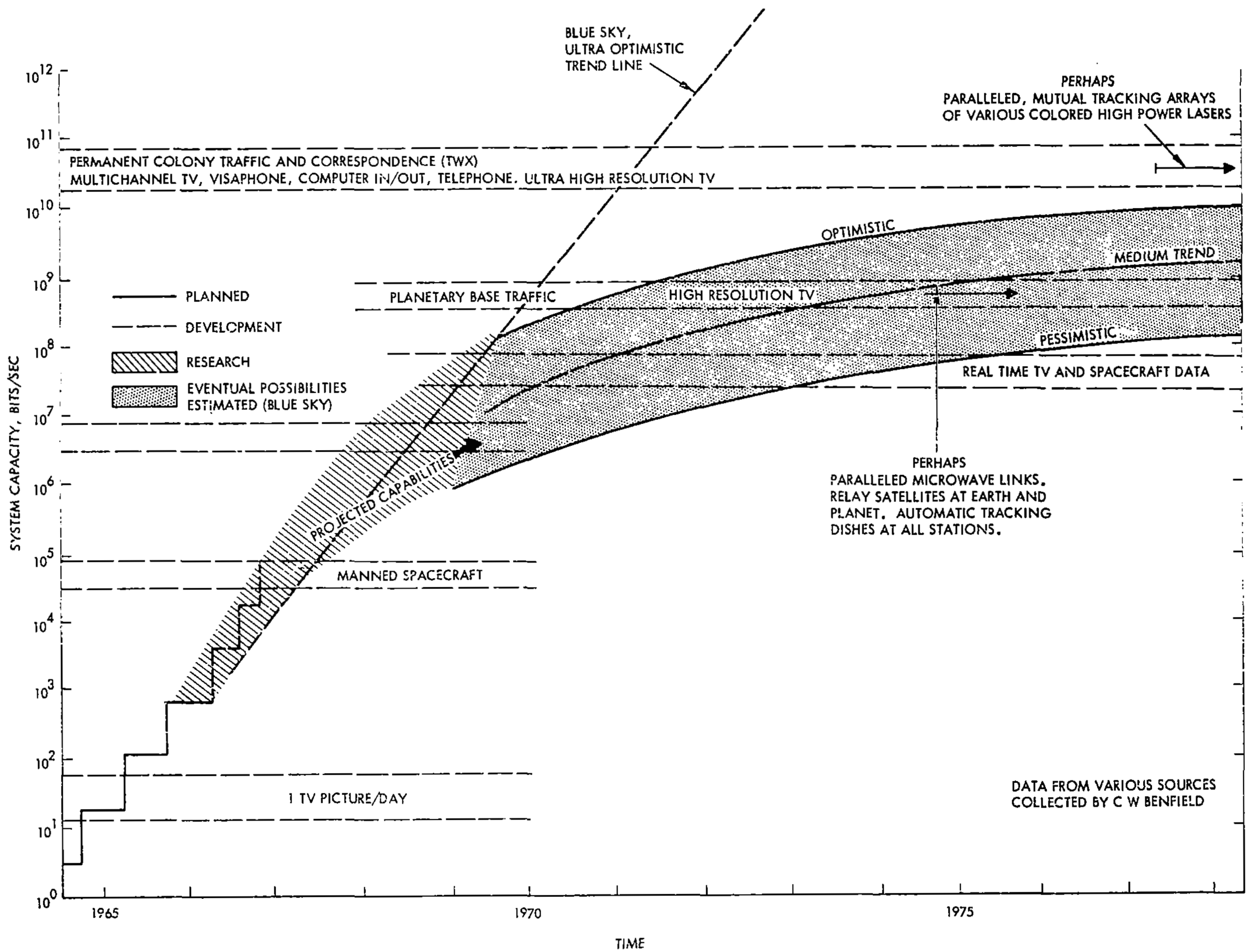


Figure B. Projected communication requirements for near planets. Message time, or data rate, can be improved by technological advances. Data rate appears as bits/second for a typical planetary distance of 463×10^6 km, with mission capabilities represented by various bit rates.

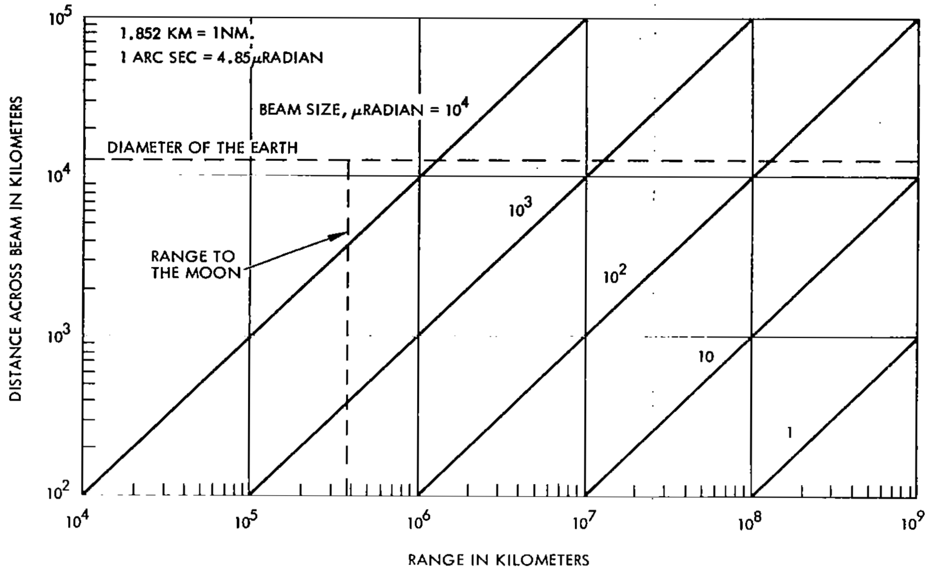
ACQUISITION AND TRACKING REQUIREMENTS

Acquisition and tracking requirements increase with decreasing beamwidth, such as are possible using an optical communication system.

Acquisition and tracking are not new functional requirements for space vehicles. However, with the advent of laser beams, the tracking accuracy and the acquisition requirements have become much more severe. An appreciation of the requirements imposed upon acquisition and tracking by narrow beams are given in the Figure. In this figure, the range between the spacecraft and the receiving site is plotted against the transmitter beam diameter. The parameter used in this diagram is the transmitter beamwidth measured at the half power points. Also noted in the diagram is the diameter of the earth. It is seen from this figure that the tracking systems must not only point at the earth itself but at a particular spot on the earth and that this spot must be tracked as the earth rotates. This will be a requirement for virtually all tracking systems which have a beamwidth less than 100 microradians (20 arc seconds); since a 100-microradian beam illuminates only a portion of the earth at the closer ranges.

An alternate receiving site is an earth satellite in near polar orbit. However, the same pointing requirement remains. That is, the deep space communication system must accurately point at the receiving site as it (in this case a satellite) rotates about the earth.

From these considerations, it may be seen that the acquisition and tracking are an extremely complicated and important part of a communications system, especially for laser systems where the very narrow beamwidths are possible.



Acquisition and Tracking Requirements

COMMUNICATION RANGE

Communication range for planetary probes is related to the birth of Christ, the planet being investigated, and the type of trajectory taken to the planet.

If all other factors remain constant, the information capacity of a communication link decreases as the inverse square of the transmission distance. Thus, the Mars-to-Earth transmission capacity is of the order of 10^{-6} that of the Moon-to-Earth capacity. Maintaining a given data rate transmission capability over increased range requires increases in transmitter power, transmitter aperture, receiving aperture, etc., or some combination of these.

Communication range for a given space mission depends on the launch date and the injection energy expended as well as the objective. The Figures show communication distance at encounter versus launch date with C_3, the injection energy of the escape hyperbola, as a parameter for Mercury, Venus, Mars, and Jupiter missions. The terms Type I and Type II refer to the two possible elliptical interplanetary transfer orbits. For Type I, the heliocentric central transfer angle is less than 180 degrees and for Type II it is greater than 180 degrees. Class I or II refers, to planetary encounter at the first or second intersection of the spacecraft trajectory with the planetary orbit.

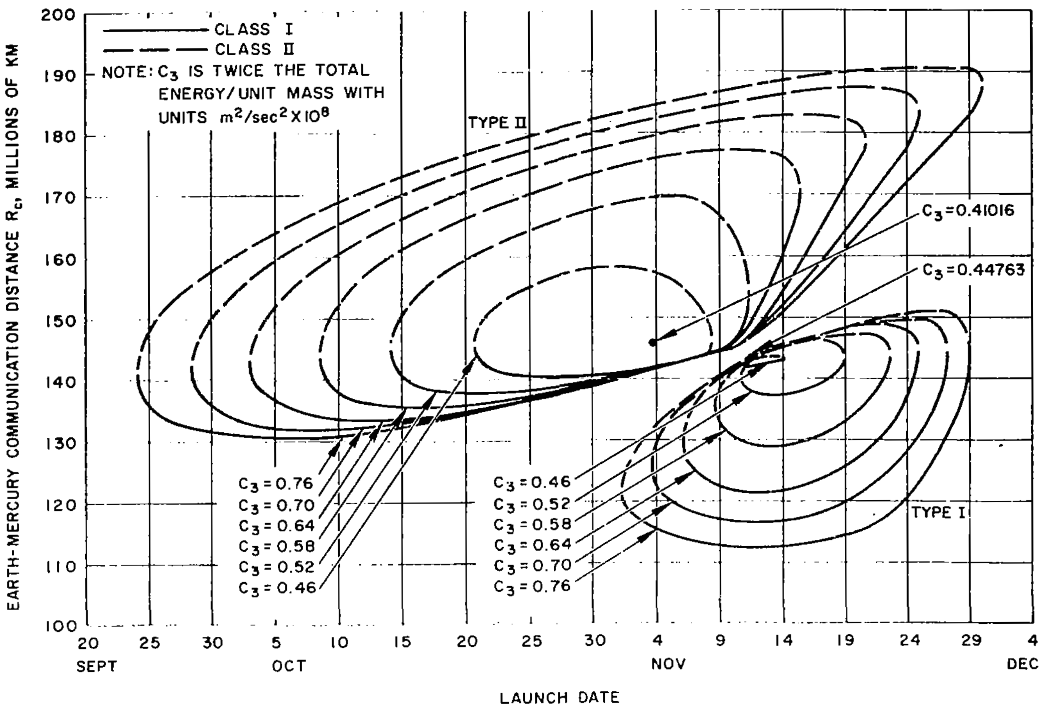


Figure A. Mercury 1968: Earth-Mercury Communication Distance Versus Launch Date

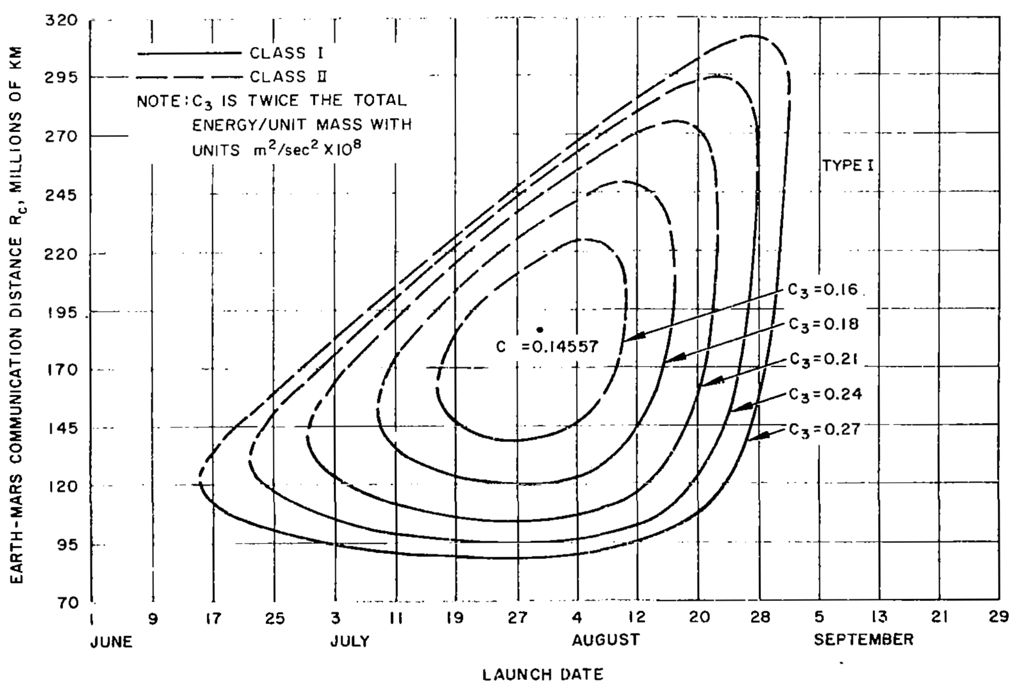


Figure C. Mars 1973: Earth-Mars Communication Distance Versus Launch Date

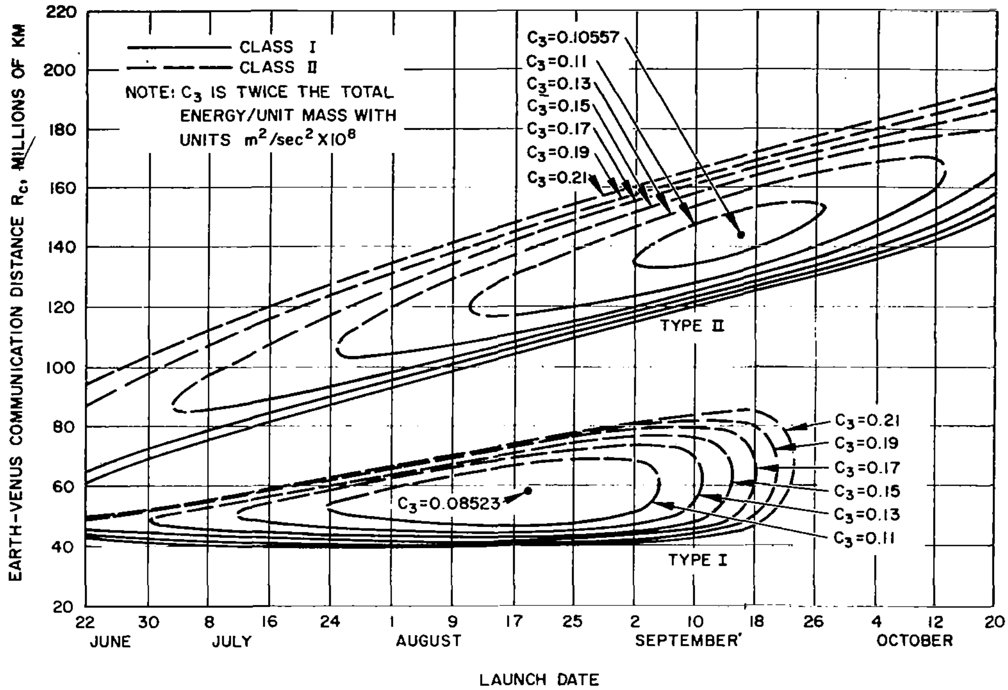


Figure B. Venus 1970: Earth-Venus Communication Distance Versus Launch Date

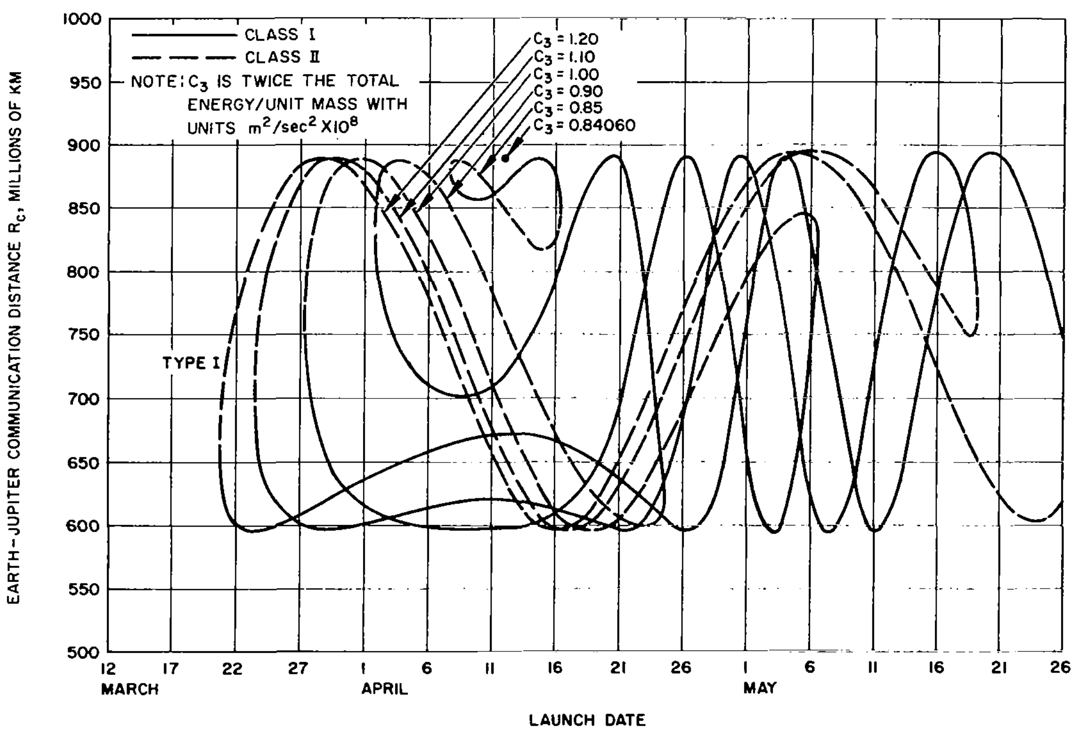


Figure D. Jupiter 1973: Earth-Jupiter Communication Distance Versus Launch Date, Type I

MISSION DURATION

Mission duration to planets is measured in years. Several possibilities exist to reduce this time but it still remains 10 times as large as proposed Apollo Application missions.

Mission duration affects the design of communications systems for unmanned excursions primarily by imposing equipment reliability and/or lifetime requirements. For manned missions the time constraint may be psychologically and physiologically limited by the crew rather than equipment reliability. There is a tradeoff between interplanetary orbit injection energy and flight time to reach a given target body in space if a ballistic trajectory is used. Interplanetary (Mercury, Venus, Mars, and Jupiter) flight times versus launch date for ballistic trajectories are given in Figures A through D with twice the interplanetary orbit injection energy and mass as a parameter. Figure E shows approximate transfer times as a function of solar distance. Because of the very long flight times to the outer planets via ballistic trajectories, considerable thought has been given to two alternate trajectories: Gravity assistance trajectories using the gravitational attraction of one or more intermediate bodies to impart energy to the vehicle as illustrated in Figure F and continuous thrust trajectories, possibly using nuclear or solar electric propulsion. Figure G compares flight times for Saturn, Uranus, Neptune, and Pluto missions using ballistic, continuous thrust, and gravity assisted trajectories. Figure G shows, for a 273 kg (600-lb) payload and a Saturn V-Center launch vehicle, the appreciable savings in flight time achievable with constant thrust nuclear electric propulsion and with Jupiter gravity assistance as compared to a ballistic trajectory.

Duration of manned missions is further increased by the length of the return trip. A summary of the durations of various types of manned and unmanned missions is shown in the Table. It is apparent that the shortest missions, whether fly-by orbital or landing missions are considered, require on the order of one year and the longest missions as long as two to three years. These flight times are longer than the proposed Apollo Applications Earth-orbital mission capability by a factor of ten. Mission life beyond flight time may vary from hours in the case of planetary fly-by to years in the case of a communication satellite.

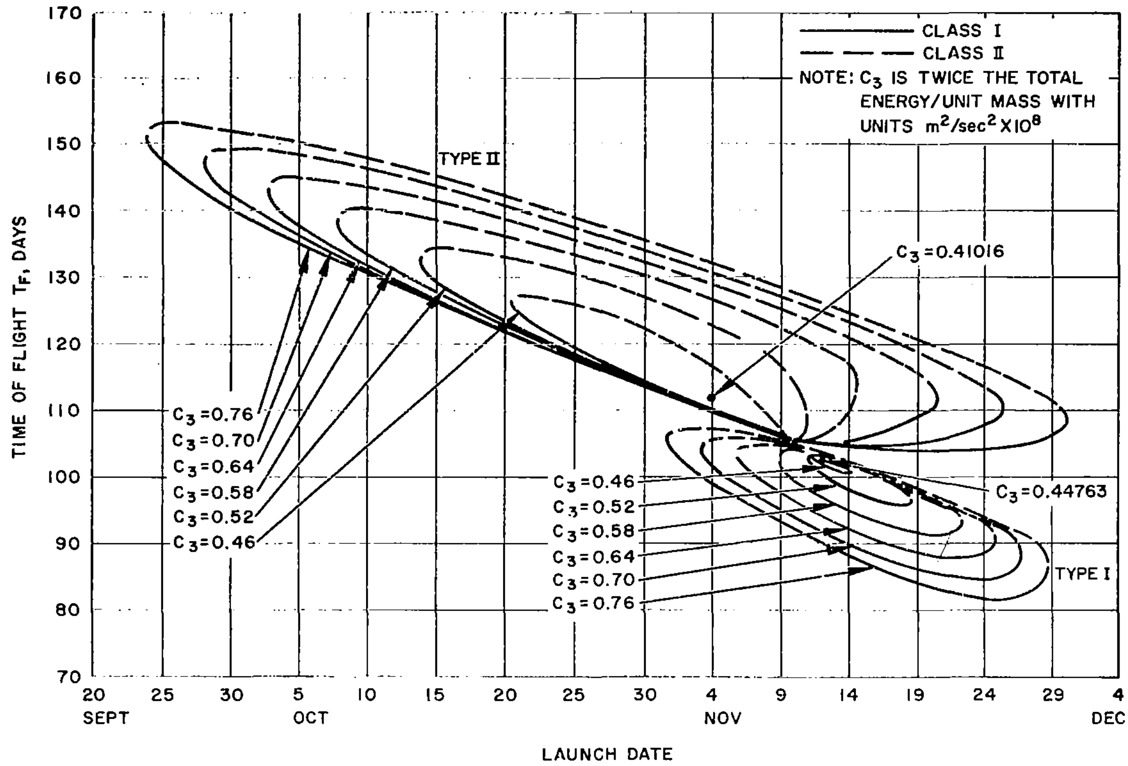


Figure A. Mercury 1968: Time of Flight Versus Launch Date

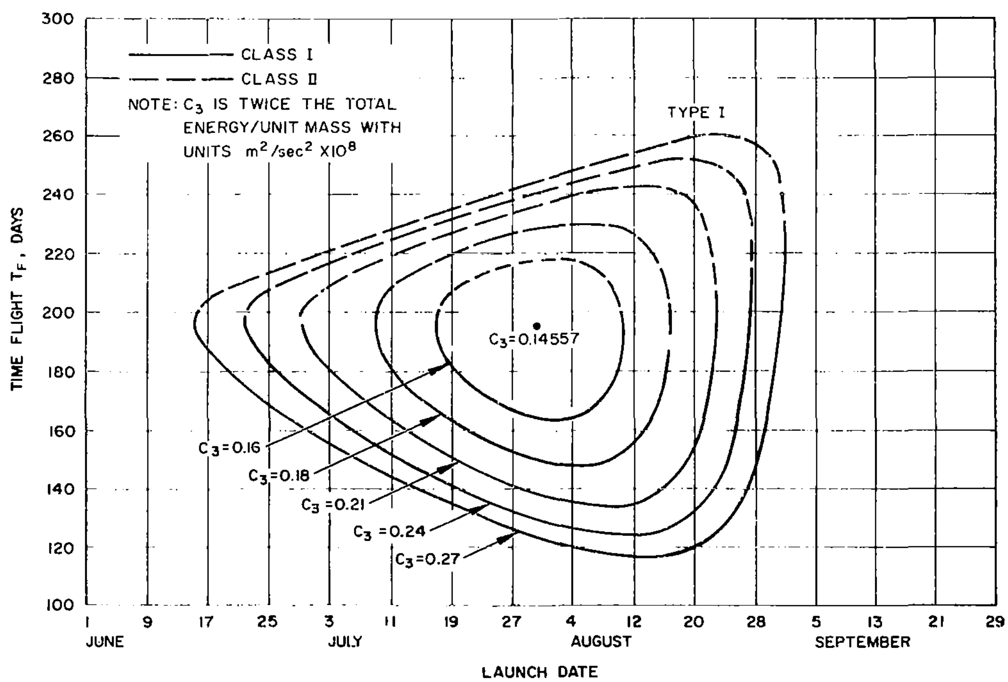


Figure C. Mars 1973: Time of Flight Versus Launch Date

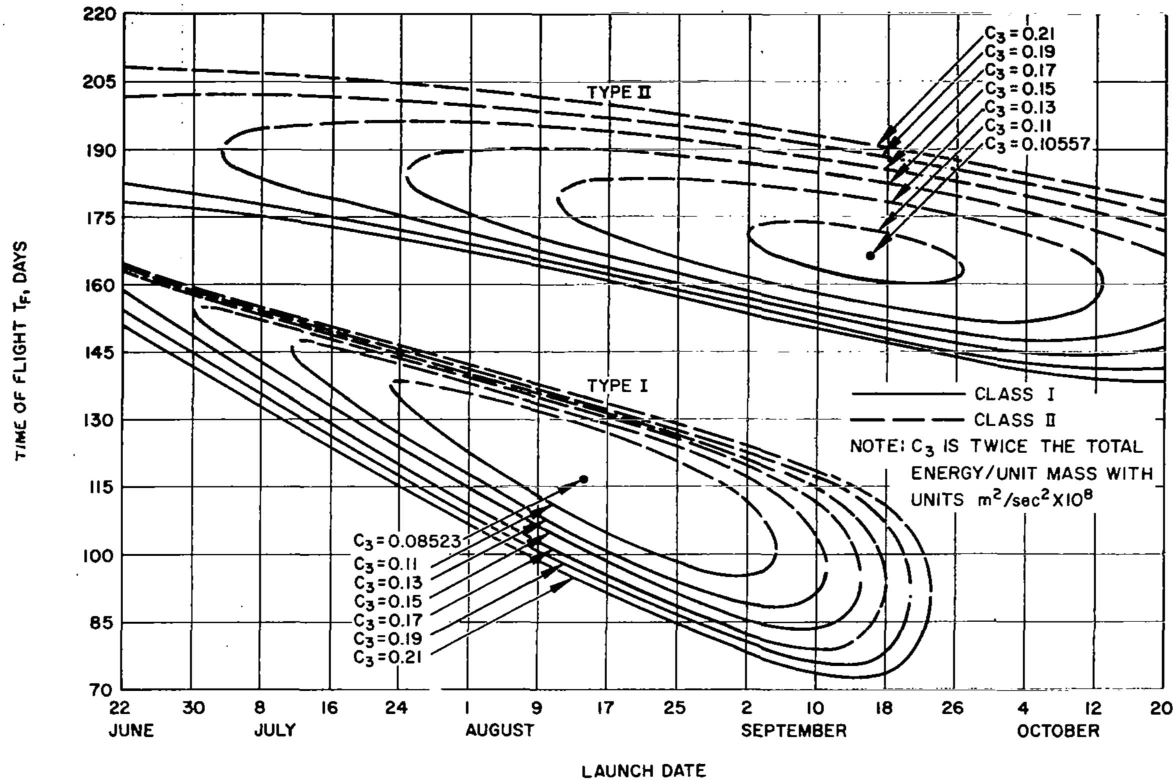


Figure B. Venus 1970: Time of Flight Versus Launch Date

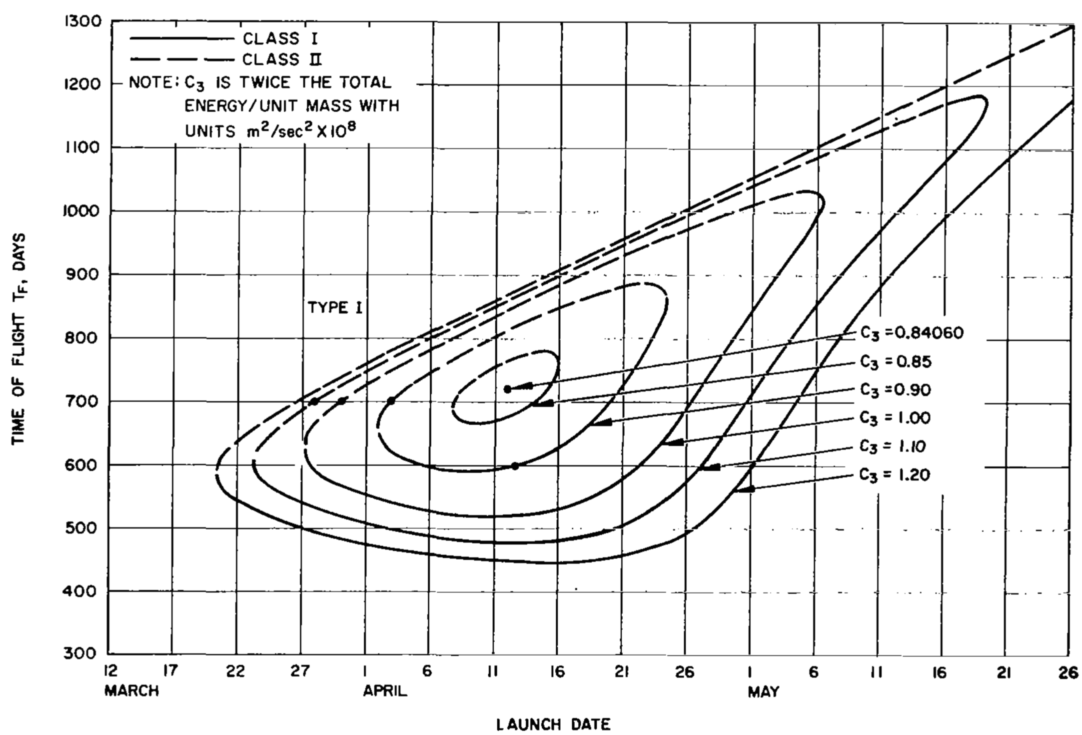


Figure D. Jupiter 1973: Time of Flight Versus Launch Date, Type I

MISSION DURATION

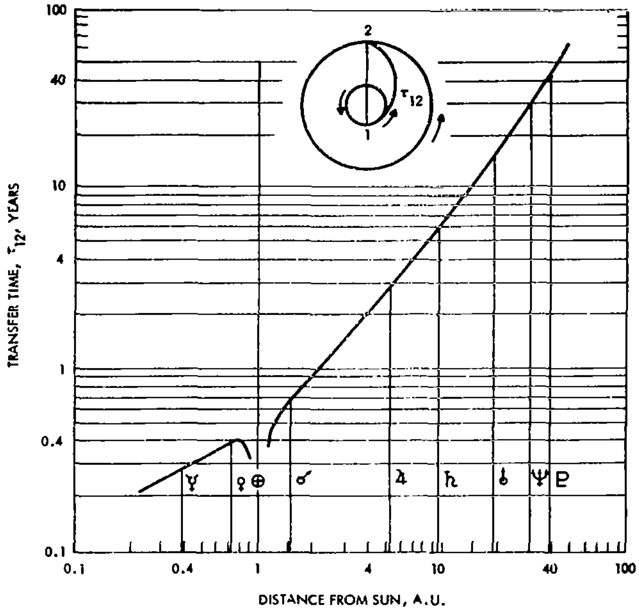


Figure E. Transfer Time for One-Way Missions to Planets Using Minimum-Energy Transfer Orbits

Typical Mission Durations

Manned Missions*	Time Period	Probable Duration
Orbital:		
Apollo Applications	1970-1972	up to 56 days
Manned Orbiting Research Laboratory	1970	1 - 5 years
Apollo	1968-1969	5 to 10 days
Lunar:		
Semi-permanent Base	1976-1980	6 months
Apollo	1970	1 - 2 days
Planetary:		
Mars or Venus Fly-by	1976-1980	15-20 months (typical opposition class mission)
Unmanned Missions	**Time Period**	**Probable Duration**
Planetary:		
Voyager	1973-1975	8 - 12 months
Deep Space:		
Advanced Pioneer	Post 1972	Several years

*Only Apollo and Apollo Applications are approved manned programs. The others are given here for study purposes only.

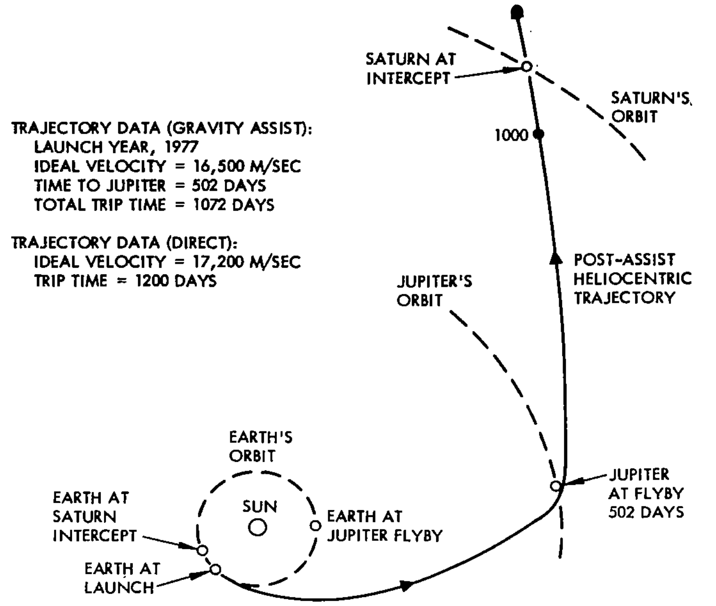


Figure F. Jupiter Gravity Assisted Saturn Fly-By Mission

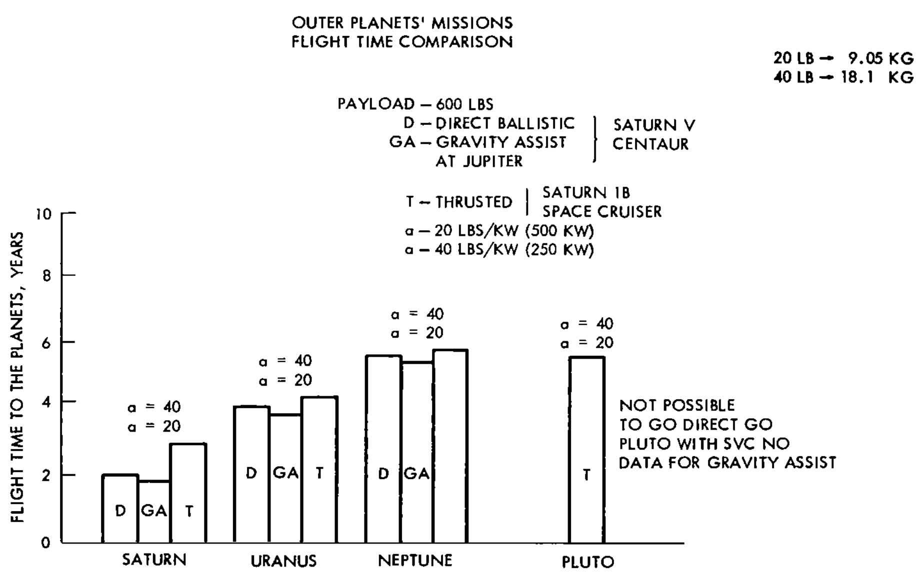
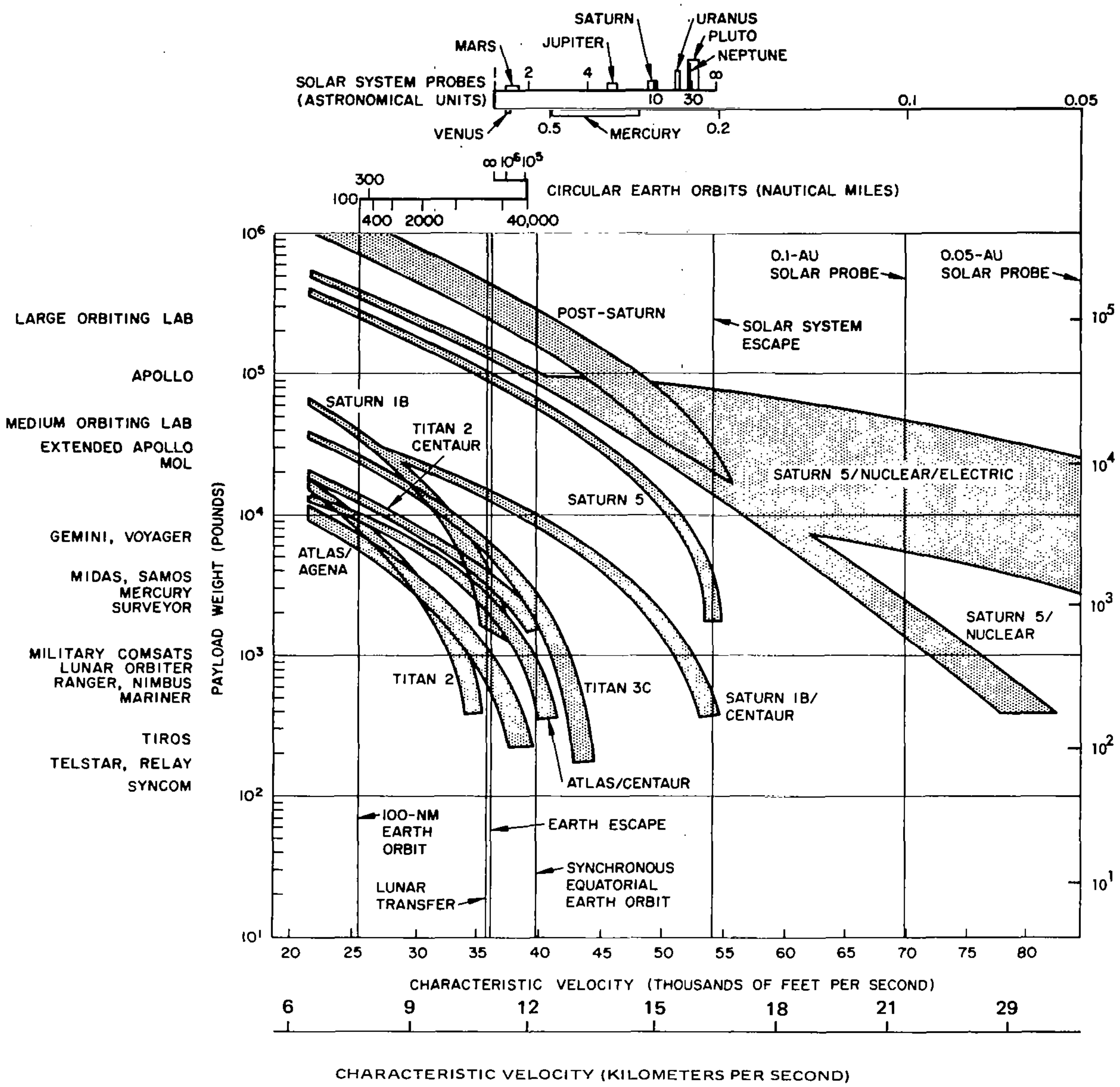


Figure G. Comparison of One-Way Flight Times to the Outer Planets Using Ballistic Gravity Assisted, and Thrusted Trajectories

COMMUNICATION SYSTEM WEIGHT RESTRICTIONS

Communication system weight restriction is a compromise between the system performance requirements and the available weight which is in turn dependent upon the type of booster used.

Permissible payload for a given mission is dictated by launch vehicle capability and allocation of that payload among the various spacecraft systems is determined by mission objectives. The fractional part of the payload comprised by the communication system will vary depending on the required data rates and transmission range. Payload capabilities of present and projected launch vehicles are depicted in the Figure. It can be seen that the payload weight which may be launched on a given mission (i.e., at a specified characteristic velocity) is a discrete rather than a continuous function. Hence vehicles having weights intermediate between the payload capabilities of two launch vehicles may be increased in weight to the payload of the next largest launcher without penalty. Thus for some payload weights, additional weight may be a non-critical burden. An example of such payload weight quantization is the rather wide gap in payload capability between Saturn 1B/Centaur and Saturn V.



Launch Vehicle Capabilities - Payloads and Destination

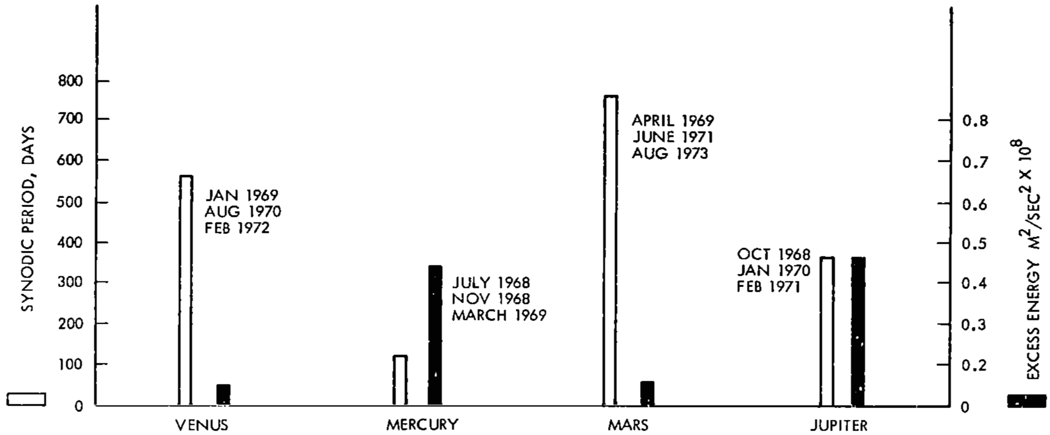
The horizontal characteristic velocity scale shows velocity a vehicle needs at 185 Km altitude (not orbit) to reach destination, assuming a minimum energy trajectory.

MISSION OPPORTUNITIES

Planetary mission opportunities depend upon the synodic period of the planet and have acceptable durations of 1 to 3 months.

In reality, feasible launchings can occur only for small time intervals (1-3 months) when the relative positions of Earth and the target planet are such that the velocity requirements for ballistic transfers can be reasonable achieved by modern boost vehicles. These intervals occur once during each synodic period of the planet. A synodic period is the time interval required for the Earth and target planet to attain the same heliocentric longitude.

Thus, favorable launch opportunities occur approximately every 1.6 years for Venus, every 2.1 years for Mars, every 0.3 year for Mercury and every 1.1 years for Jupiter. The Figure shows the opportunity periodicity for these planets along with the approximate injection energy requirements. Also listed in the figure is the next few opportunity dates for each of these planets.



Period of reoccurring opportunity and injection energy requirement for the various planets. Approximate launch windows for the next several years are also shown.

MISSION ANALYSIS AND METHODOLOGY

Methodology for Optimizing Communication Systems

THE PURPOSE FOR A COMMUNICATIONS METHODOLOGY

A comprehensive communications methodology has been developed to provide impartial evaluation of communication systems using weight and cost as criteria.

The previous two sections have described scientific objectives and communications requirements for deep space missions. These requirements must be related to communications systems in a logical and impartial manner in order to evaluate fairly the several communication system choices available. In particular, it is desireable to evaluate both laser and radio communications systems using optimum configurations for each. The importance of determining optimum systems for comparison is clearly required, otherwise system designs may be formulated which lead to unfair comparisons.

A means for generating such comparison has been developed during this contract. It is based upon two criteria, that of determining the lightest weight system to provide a given performance and that of providing the least expensive system to provide a given performance. This has been called a "Communications Methodology". It has been programmed for a computer to provide optimum values for all the key design parameters of a communications link.

Subsequent topics describe the salient features of the Communications Methodology and give examples of its use. The Methodology then forms a basis of analysis which uses as gross inputs 1) mission objectives and requirements and 2) detailed descriptions of communication constraints and components. The communications constraints are discussed in this Volume, Volume II in the form of Communication Theory, and in Volume IV in terms of Atmospheric Limitations and Existing Ground Facilities. Communication components are discussed extensively in Volume III. These include such components as transmitter power sources, antennas, detectors, etc. Communications constraints and components are described for both radio and optical systems.

The topics which follow in this section illustrate how the methodology is formed, the rationale it uses, the practical data it required (burdens) and examples of its use.

MAJOR SYSTEM PARAMETERS USED IN THE METHODOLOGY

Four major system parameters are defined which may be used to express the weight or cost of an entire communication link. These parameters are: The transmitter power, the transmitter antenna gain, the receiver antenna gain, and the receiver field of view.

The complex relationships between the design parameters of communication systems and their fabrication cost, weight, volume, power requirement, etc., create the need for a unified approach to the optimum design of communication systems. An optimization methodology is needed which provides the system designer with the optimum values of the major parameters of a communication system. Major system parameters have the characteristic that all communications link parameters may be expressed in terms of one of them. The major system parameters are:

Transmitter antenna diameter (or gain)
Receiver antenna diameter (or gain)
Transmitter power
Receiver field of view

The optimization methodology is applicable for optical as well as radio systems. In principle, any type of modulation or demodulation can be handled if some suitable performance criterion is available. The optimization procedure for the most common and practical combinations of digital modulation and detection techniques are documented in this report. For these systems the performance criterion is the probability of detection error.

Basically, the optimization procedure is to develop system cost relationships as a function of the values of the system parameters. These cost relationships include the fabrication cost of the system components, the cost of placing the components aboard a spacecraft, and any other pertinent system costs. This phase of the optimization procedure is, in many respects, the most difficult since in many cases it requires technological predictions. However, a great amount of parametric cost burden data has been gathered for many system components (See a subsequent topic in this section on burdens). With the cost relationships developed, the total system cost is minimized as a function of the values of the major system parameters under the constraint that the performance criterion is achieved.

The communication component burden relationships employed in the optimization procedure may be modeled by power series or be specified numerically. The only requirements are that the burden relationships be monotonic, single-valued, piece-wise differentiable functions of the system parameters. These conditions are usually fulfilled for the four major system parameters listed previously. The conditions are generally not met when attempts are made to express burdens as a function of transmission wavelength.

As an introduction to the relationships between communication parameters and weight or cost, the following paragraphs are given.

Transmitter Antenna. The weight and fabrication cost of a transmitter antenna system are dependent upon the transmitter antenna diameter. A transmitter antenna is usually designed to operate as close to the diffraction limit as possible to achieve the greatest spatial power density at the receiver for a given transmitter aperture diameter. For small transmitter apertures, the weight is proportional to the antenna area, and hence to the square of the aperture diameter. For larger size apertures, as structural supports are added to maintain the rigidity required for diffraction limited operation, the weight dependence becomes volumetric.

Receiver Antenna. The weight and fabrication cost of a receiver antenna system are dependent upon the receiver antenna aperture diameter. At optical frequencies receiver antennas are not normally designed to be diffraction limited, and hence construction and mechanical support tolerances need not be as stringent as for a transmitter antenna.

Transmitter Antenna Pointing System. The transmitter antenna pointing system consists of a gimballed support unit, which points the transmitter antenna toward the receiver. The weight of the transmitter antenna pointing system is relatively insensitive to the transmitter pointing accuracy. Its weight is proportional to the weight of the transmitter antenna, which in turn has a weight dependent upon the transmitter antenna diameter. The fabrication cost of the transmitter pointing equipment is inversely proportional to the transmitter pointing accuracy. The pointing accuracy is usually specified as a fixed percentage of the transmitter beamwidth. Since the transmitter antenna is diffraction limited, the fabrication cost is proportional to the transmitter aperture diameter. The electrical power requirement for the transmitter antenna pointing system is primarily dependent upon the weight of the transmitter antenna.

Receiver Pointing System. The weight of the receiver pointing system is relatively insensitive to the receiver pointing accuracy. Its weight is proportional to the weight of the receiver antenna, which is itself dependent upon the receiver aperture diameter. The fabrication cost of the receiver pointing equipment is inversely proportional to the receiver pointing accuracy, which is a fixed percentage of the receiver field of view. The power supply requirement for the receiver pointing system is primarily dependent upon the weight of the receiver antenna.

Transmitter. For a given transmission wavelength, within limits, the weight and fabrication cost of a transmitter are dependent upon the transmitter power. The electrical input power requirement is directly proportional to the transmitted power.

Transmitter System Power Supply. The fabrication cost and weight of the electrical power supply and conversion equipment at the transmitter are dependent upon the electrical power requirements of the transmitter antenna pointing system, transmitter, and modulator.

Receiver System Power Supply. The fabrication cost and weight of the electrical power supply and conversion equipment at the receiver are dependent upon the power requirements of the receiver pointing system and communications receiver equipment.

TYPES OF SYSTEM CLASSIFIED IN THE METHODOLOGY

Communication systems are classified by: transmission wavelength, modulation method, demodulation method and dominant noise in the detector.

The communications methodology developed is intended to be comprehensive, so that a great variety of systems may be examined. The systems which may be considered are taken from the following classifications.

- Transmission wavelength
  - radio
  - optical
- Modulation method
  - PCM amplitude modulation
  - PCM polarization modulation
  - PCM frequency modulation
  - PCM phase modulation
- Demodulation method
  - direct
  - heterodyne
  - homodyne
- Types of noise
  - thermal
  - background radiation
  - shot

A division between optical and radio systems is commonly taken at a wavelength of 100 microns. For wavelengths shorter than 100 microns the transmitter is usually a laser, the antennas are made of polished reflectors or transparent lenses, and the carrier demodulator is a photodetector. At the radio wavelengths a variety of transmitter oscillators are available, the antennas are generally metal reflectors, horns, or wire assemblies, and the detector is a nonlinear electrical element.

Not all combinations of modulation and demodulation methods are feasible at all transmission wavelengths but rather sets usually results from practical considerations. For instance, polarization modulation is limited to the optical region because of difficulties in constructing radio frequency polarization modulators. Also radio frequency phase modulation systems must employ a homodyne receiver to perform optimum demodulation.

At radio frequency, noise is principally caused by two physical sources, thermal noise at the antenna load and background radiation from external sources. Both types of noise may be modeled by Gaussian statistics. However, optical receiver noise is caused by two sources: 1) thermal noise of the photodetector load resistor and resistive elements within the detector, 2) by detector shot noise which is caused by the randomness of electron emissions induced by laser carrier radiation, background radiation, and detector dark current. Shot noise is modeled by Poisson statistics. In an optical direct detection receiver, if the photodetector has an internal current gain mechanism, detector shot noise is usually dominant, otherwise thermal noise predominates. In a heterodyne or homodyne optical receiver the local oscillator power can be made large to achieve shot noise limited operation even without photodetector gain.

For the Communication Methodology optimization analysis, communication systems have been divided into four types which are described below.

ROPS - Radio communication OPtimization system with Stops. This system is thermal and background radiation noise limited and uses Gaussian detection statistics.

TOPS - Thermal noise optical OPtimum communication system with Stops. This system uses direct detection, is thermal noise limited and has Gaussian detection statistics.

SOPS - Shot noise optical OPtimum communication system with Stops. This system uses direct detection is shot noise limited and has Poisson detection statistics.

HOPS - Heterodyne optical OPtimum communication system with Stops. This system uses heterodyne or homodyne detection, is shot noise limited and has Poisson detection statistics.

These four types of communication systems have been incorporated into the computer implementation of the optimization procedure. They are conveniently implemented as separate parts since the detection processes differ.

KEYSTONE OPTIMIZATION PROCEDURES USED IN THE METHODOLOGY

The heart of the optimization procedure consists of partially differentiating the functional relationships describing the four major system parameters and solving for optimum values by use of Lagrange multipliers.

Let x, y, z, w represent a set of four physical parameters of the communication system to be optimized, e. g., transmitter antenna gain or diameter, receiver antenna gain or diameter, transmitter power, and receiver field of view. The probability of detection error, P, may then be expressed in terms of the system parameters as

$$P = f_1 (x, y, z, w) \qquad (1)$$

Likewise, the total system cost, C, is another function of the system parameters.

$$C = f_2 (x, y, z, w)$$

Let P^R be the required probability of detection error. Then, by the method of Lagrange multipliers, to minimize the total system cost and achieve P^R, the dummy function C' is formed

$$C' \equiv C + \Lambda (P^R - P)$$

Where Λ is the Lagrange multiplier. Now, setting the partial derivatives of C', with respect to the system parameters, equal to zero yields.

$$\frac{\partial C'}{\partial x} = \frac{\partial C}{\partial x} - \Lambda \frac{\partial P}{\partial x} = 0$$

$$\frac{\partial C'}{\partial y} = \frac{\partial C}{\partial y} - \Lambda \frac{\partial P}{\partial y} = 0$$

$$\frac{\partial C'}{\partial z} = \frac{\partial C}{\partial z} - \Lambda \frac{\partial P}{\partial z} = 0$$

$$\frac{\partial C'}{\partial w} = \frac{\partial C}{\partial w} - \Lambda \frac{\partial P}{\partial w} = 0$$

Equating the Λ's gives a set of six characteristic equations.

$$\frac{\partial C}{\partial x} \frac{\partial P}{\partial y} - \frac{\partial C}{\partial y} \frac{\partial P}{\partial x} = 0$$

$$\frac{\partial C}{\partial x} \frac{\partial P}{\partial z} - \frac{\partial C}{\partial z} \frac{\partial P}{\partial x} = 0$$

$$\frac{\partial C}{\partial x} \frac{\partial P}{\partial w} - \frac{\partial C}{\partial w} \frac{\partial P}{\partial x} = 0$$

[1]Schechter, R. S., The Variational Method in Engineering, McGraw-Hill, New York, 1967.

$$\frac{\partial C}{\partial y}\frac{\partial P}{\partial z} - \frac{\partial C}{\partial z}\frac{\partial P}{\partial y} = 0$$

$$\frac{\partial C}{\partial y}\frac{\partial P}{\partial w} - \frac{\partial C}{\partial w}\frac{\partial P}{\partial y} = 0$$

$$\frac{\partial C}{\partial z}\frac{\partial P}{\partial w} - \frac{\partial C}{\partial w}\frac{\partial P}{\partial z} = 0$$

Any subset of three of these equations solved simultaneously with equation (1) for the required probability of detection error gives the optimum solution of the system parameters. In a particular optimization problem, one or more of the system parameters may be held fixed, either by desire or because of technological limitations. In this situation the characteristic equations containing the fixed parameters are merely deleted from the simultaneous solution. For some optimization problems it is possible to solve the characteristic equations analytically, but usually recursive digital techniques are required.

For many communication systems the probability of error is related monotonically and uniquely to the signal-to-noise ratio, S/N, measured at some point in the communication receiver.

$$P = f_3\left(\frac{S}{N}\right)$$

The signal-to-noise ratio can then be written as a function of the system parameters

$$\frac{S}{N} = f_4\,(x,\ y,\ z,\ w) \qquad (2)$$

The characteristic equations, for such systems, then reduce to

$$\frac{\partial C}{\partial x}\frac{\partial(S/N)}{\partial y} - \frac{\partial C}{\partial y}\frac{\partial(S/N)}{\partial x} = 0$$

$$\frac{\partial C}{\partial x}\frac{\partial(S/N)}{\partial z} - \frac{\partial C}{\partial z}\frac{\partial(S/N)}{\partial x} = 0$$

$$\frac{\partial C}{\partial x}\frac{\partial(S/N)}{\partial w} - \frac{\partial C}{\partial w}\frac{\partial(S/N)}{\partial x} = 0$$

$$\frac{\partial C}{\partial y}\frac{\partial(S/N)}{\partial z} - \frac{\partial C}{\partial z}\frac{\partial(S/N)}{\partial y} = 0$$

$$\frac{\partial C}{\partial y}\frac{\partial(S/N)}{\partial w} - \frac{\partial C}{\partial y}\frac{\partial(S/N)}{\partial w} = 0$$

$$\frac{\partial C}{\partial z}\frac{\partial(S/N)}{\partial w} - \frac{\partial C}{\partial w}\frac{\partial(S/N)}{\partial z} = 0$$

A simultaneous solution of these equations with equation (2) for the required value of S/N (to achieve the desired probability of detection error) gives the optimum system parameters.

STRUCTURAL DETAIL OF METHODOLOGY IMPLEMENTATION

Typical equations for the detailed methodology are given. A complete listing of these equations is given in Appendix A.

Previous topics have illustrated the purposes and approach used to develop an optimized communication methodology. It is the purpose of this topic to illustrate the level of detail required in this implementation. Since this implementation contains a considerable amount of repetition, the majority of the detail is relegated to Appendix A of this volume.

The communication methodology optimizes the communication parameters such that either the lightest or least expensive communication system is derived, within the constraints imposed. It is therefore necessary to represent the various component parts of a communication system in terms of the weight and cost. (Additionally relationships for power have also been formulated.)

The following communication systems components have been represented in terms of weight and/or cost: transmitter antenna, receiver antenna, transmitter acquisition and pointing system, receiver acquisition and pointing system, the transmitter modulator, the receiver demodulator, the receiver power conditioning, the transmitter, and the spacecraft heat rejection system. These several relationships have been combined, the net result relates the complete communications system to four major system parameters which are: the transmitting and receiving antenna diameters, the transmitted power and the receiver field of view.

As an illustration of the equations used, the relationships of the transmitter antenna are listed below as is one of the four composite equations which illustrates the detail and format of the equations given only functionally in prior topics.

Transmitter Antenna Burdens

The weight and fabrication cost of a transmitter antenna are proportional to the transmitter aperture diameter. The transmitter antenna weight is

$$W_{d_T} = W_{KT} + K_{d_T} (d_T)^{n_T}$$

and the fabrication cost is

$$C_{\theta_T} = C_{KT} + K_{\theta_T} (d_T)^{m_T}$$

where

d_T = transmitter aperture diameter

K_{d_T} = constant relating transmitter antenna weight to transmitter aperture diameter.

K_{θ_T} = constant relating transmitter antenna fabrication cost to transmitter aperture diameter.

W_{KT} = transmitter antenna weight independent of transmitter aperture diameter.

C_{KT} = transmitter antenna fabrication cost independent of transmitter aperture diameter.

n_T = constant

m_T = constant

The total cost associated with transmitter antenna includes the fabrication cost and the cost of placing the weight, W_{d_T}, aboard a spacecraft. Thus,

$$C_{d_T} = K_{\theta_T} (d_T)^{m_T} + K_S K_{d_T} (d_T)^{n_T} + C_{KT} + K_S W_{KT}$$

where

K_S = cost per unit weight for spaceborne equipment

The cost, C_T, of the transmitter antenna and associated tracking equipment which is dependent upon the transmitter aperture diameter is as follows.

$$C_T \equiv \underbrace{\frac{K_{AT}}{(\lambda)^{q_T}} (d_T)^{q_T}}_{\substack{\text{fabrication}\\\text{cost of}\\\text{transmitter}\\\text{tracker}}} + \underbrace{K_{\theta_T}(d_T)^{m_T}}_{\substack{\text{fabrication}\\\text{cost of}\\\text{transmitter}\\\text{antenna}}} + \underbrace{K_S K_{d_T}(d_T)^{n_T}}_{\substack{\text{weight cost}\\\text{transmitter}\\\text{antenna}}} + \underbrace{K_S K_{d_T} K_{W_{AT}}(d_T)^{n_T}}_{\substack{\text{weight cost of}\\\text{transmitter}\\\text{tracker}}}$$

$$+ \underbrace{K_S K_{W_{ST}} K_{P_{QT}} K_{W_{AT}} K_{d_T}(d_T)^{n_T}}_{\substack{\text{weight cost of}\\\text{transmitter}\\\text{tracker power}\\\text{supply}}} + \underbrace{K_{ST} K_{P_{QT}} K_{W_{AT}} K_{d_T}(d_T)^{n_T}}_{\substack{\text{fabrication cost}\\\text{of transmitter}\\\text{tracker power}\\\text{supply}}}$$

In simplified form

$$C_T = K_{q_T}(d_T)^{q_T} + K_{m_T}(d_T)^{m_T} + K_{n_T}(d_T)^{n_T}$$

STRUCTURAL DETAIL OF METHODOLOGY IMPLEMENTATION

where

$$K_{q_T} \equiv \frac{K_{AT}}{(\lambda)^{q_T}}$$

$$K_{m_T} \equiv K_{\theta_T}$$

$$K_{n_T} \equiv K_{d_T} \left\{ K_S \left[1 + K_{W_{AT}} \right] + K_{P_{QT}} K_{W_{AT}} \left[K_{ST} + K_S K_{W_{ST}} \right] \right\}$$

where:

K_{AT} = constant relating transmitter tracking equipment fabrication cost to transmitter beamwidth

λ = transmitted wavelength

g_t = a constant

$K_{W_{AT}}$ = constant relating transmitter tracking equipment weight to transmitter antenna weight

$K_{W_{ST}}$ = constant relating transmitter power supply weight to power requirement.

$K_{P_{QT}}$ = constant relating transmitter acquisition and track equipment power requirement to equipment weight.

K_{ST} = constant relating transmitter power supply fabrication cost to power requirement.

SYSTEM BURDEN PARAMETERS

System "burdens" are the constants which are used to relate communication parameters e. g. the transmitter antenna diameter, to weight or cost. Numerical values for these burdens are given.

Associated with each major component of the various communication systems considered in the study are two equations that express the component weight and cost, respectively, as functions of the most appropriate communication system variable, d_T, d_R, P_T, or θ_R. For example, spacecraft prime power supply weight and cost are expressed as functions of transmitter output power, P_T; transmitter antenna weight and cost are expressed as functions of transmitter antenna diameter, d_T. These burden relations relate communication system configuration specified by a set of values of the system variables) to the corresponding system weight and cost. The optimization program incorporates these burden relations and the appropriate expressions relating the four major system variables, d_T, d_R, P_T, and θ_R to the data transmission rate, R_B. Using these relations, the computer calculations determine the set of values of d_T, d_R, P_T, θ_R that correspond to a minimum weight or minimum cost system at each specified data transmission rate, R_B. Thus it may be seen, that the efficacy of the computerized procedure for determining an optimum system configuration and the sensitivity of that configuration to variations in the cost or weight burdens depends critically on the correctness of the assumed burden relationships.

Confidence in the burden relationship presently being used varies, depending strongly on the component in question. As a general rule, cost burdens are considerably more nebulous than weight burdens. For some components such as photovoltaic power supplies, space radiators, launch costs, and perhaps antennas and optical apertures; the relationships can be expressed with reasonable certitude. On the other hand, burden relations for space qualified transmitting sources (both optical and higher power microwave) and the precise pointing systems required with the narrow laser beamwidths are known with less confidence.

The difficulties associated with accurately assessing these relationships stem primarily from two considerations:

1. Component complexity or configuration that does not lend itself to expressing the associated burdens as functions of a single system variable.

2. Failure of existing technology to provide space qualified components of the requisite performance with the result that burdens must be based on a time extrapolation.

The component burden relations presented here will continue to evolve in the path of technological advance and fuller understanding of the many diverse technologies represented.

The component burden relationships presently used are summarized in Tables A and B. Table A shows components for which the burden constants are relatively independent of mission destination. For each component, the assumed equations relating the associated variable system parameter and the component weight or cost burden are given in the left column.* In adjacent columns, the values of the constants appearing in these burden equations are listed for the various communication system optimization programs. Table B shows components that strongly mission dependent burden constants, principally the launch vehicle and prime power supply. Launch vehicle costs are based on the Saturn V Centaur combination which results in a lower cost per pound of payload than smaller launch systems when the full payload capabilities of that system can be utilized.

*The nomenclature for these equations is defined in Appendix A of this volume.

SYSTEM BURDEN PARAMETERS

Table A. Present Component Burden Relations Not Directly Mission Dependent

Component	Constant	Units	Program HOPS $\lambda = 10.6\mu$	TOPS $\lambda = 10.6\mu$	SOPS $\lambda = 0.5\mu$	ROPS $\lambda = 13$cm
Transmitter Antenna	K_{θ_T}	$/cm^2	14	14	14	4.0
$W_{d_T} = W_{KT} + K_{d_T} d_T^{n_T}$	K_{d_T}	lb/cm^2	0.012	0.012	0.012	4.32×10^{-4}
$C_{d_T} = C_{KT} + K_{\theta_T} d_T^{m_T}$	C_{KT}	$	20×10^3	20×10^3	20×10^3	5.0×10^3
	W_{KT}	lb	5	5	5	0
	m_T	-	2	2	2	2
	n_T	-	2.2	2.2	2.2	2
Receiver Antenna	K_{θ_R}	$/cm^2	8.75	8.75	8.75	6.4×10^{-4}
$C_{d_R} = C_{KR} + K_{\theta_R} d_R^{m_R}$	C_{KR}	$	25×10^3	25×10^3	25×10^3	10^5
	M_R	-	2	2	2	2.7
Transmitter Acquisition and	K_{AT}	$/(radian)^{q_T}	0.71×10^5	0.71×10^5	0.71×10^5	0.71×10^5
Pointing System	$K_{W_{AT}}$	lb/lb	0.13	0.13	0.13	0.15
$W_{QT} = W_{BT} + W_{AT} W_{d_T}$	KP_{QT}	watts/lb	0.48	0.48	0.48	1.0
$C_{QT} = C_{AT} + K_{AT}(\lambda/d_T)^{-q_T}$	C_{AT}	$	0.4×10^6	0.4×10^6	0.4×10^6	0.14×10^6
$P_{QT} = KP_{QT} W_{QT}$	W_{BT}	lb	40	40	40	15
	q_T	-	0.3	0.3	0.3	0.3
Receiver Acquisition and Pointing System	K_{AR}	$/(radian)^{q_R}	0.71×10^5	0.71×10^5	0.71×10^5	Combined with receiver antenna burdens.
$C_{QR} = C_{AR} + K_{AR}(\theta_R)^{-q_R}$	C_{AR}	$	0.2×10^6	0.2×10^6	0.2×10^6	
$P_{QR} = KP_{QR} W_{QR}$	q_R	-	0.3	0.3	0.3	
Modulation Burden	K_{FM}	$/BIT	0.5×10^{-3}	0.5×10^{-3}	7.5×10^{-5}	
$W_M = W_{KM} + K_M R_B$	K_M	lb/BIT	0.3×10^{-6}	0.3×10^{-6}	5.0×10^{-8}	
$C_M = C_{KM} + K_{FM} R_B$	K_{PM}	watt/lb	5	5	5	Assumed negligible.
$P_M = K_{PM} W_M$	C_{KM}	$	15×10^3	15×10^3	7.5×10^3	
	W_{KM}	lb	10	10	5	
Demodulation Burden	K_{FD}	$/BIT	0.1×10^{-3}	5.5×10^{-5}	5.5×10^{-5}	
$W_D = W_{KD} + K_D R_B$	K_D	lb/BIT	0.2×10^{-6}	1.1×10^{-7}	1.1×10^{-7}	
$C_D = C_{KD} + K_{FD} R_B$	K_{PD}	watt/lb	3.33	3.33	3.33	
$P_D = K_{PD} W_D$	C_{KD}	$	27.5×10^3	15×10^3	15×10^3	Combined with receiver antenna burdens
	W_{KD}	lb	55	30	30	
Receiver Power Conditioning	K_{SR}	$/watt	25.0	25.0	25.0	
$C_{SR} = C_{KF} + K_{SR} P_R$	C_{KF}	$	5×10^3	5×10^3	5×10^3	
Spacecraft Transmitter	K_{PT}	$/watt	1.43	1.43	150	120
$WP_T = W_{KP} + K_{WT} P_T^{h_T}$	K_{WT}	lb/watt	2	2	51	0.1
$CP_T = C_{KP} + KP_T P_T^{g_T}$	C_{KP}	$	10×10^3	10×10^3	10×10^3	10×10^3
	W_{KP}	lb	25	25	40	0.7
$P_{ST} = P_T/k_e$	g_T	1	1	1	1	1
	h_T	1	1	1	1	1
Spacecraft Heat Rejection	k_e	%	10	10	0.1	25
$W_H = W_{KH} + K_X \left[(1-k_e)/k_e\right] P_T$	K_H	$/watt	1.97	1.97	0.58	0.58
	K_X	lb/watt	2.5×10^{-2}	2.5×10^{-2}	0.7×10^{-2}	0.7×10^{-2}
$C_H = C_{KH} + K_H \left[(1-k_e)/k_e\right] P_T$	C_{KH}	$	13.8×10^3	13.8×10^3	13.8×10^3	$13.8 \times 10^{+3}$
	W_{KH}	lb	0	0	0	0

Table B. Mission Dependent Burden Relations (Applicable to All Computer Programs – HOPS, TOPS, SOPS, and ROPS)

1. Transmitter Power Supply

$W_{ST} = W_{KE} + Kw_{ST}P_T$

$C_{ST} = C_{KE} + K_{ST}P_T$

Constant	K_{ST}, dollars per watt	Kw_{ST}, pounds per watt	C_{KE}, dollars	W_{KE}, pounds
Mission Category				
Mercury flyby (oriented solar panel)	43	0.04	0	0
Venus flyby (oriented solar panel)	38	0.04	0	0
Near Earth missions (oriented solar panel-uneclipsed)	53	0.05	0	0
Mars flyby (oriented solar panel)	112	0.11	0	0
Jupiter flyby and deep space missions beyond Jupiter:				
Powers exceeding 1 kilowatt (reactor-thermoelectric system)*	5.0×10^2	0.625	1.2×10^6	400
Powers less than 1 kilowatt (radioisotope thermoelectric system)	3.0×10^3	0.7	0	0

2. System Weight Cost:** $C_{W_S} = K_S W_S$

Mission Category		Mission Parameters		Maximum Payload (pounds)		Specific Weight Cost K_S (dollars per pound)	
		Distance from Sun (or Earth†)	Transit Time	Standard Saturn V Centuar	Uprated Saturn V Centuar	Standard Saturn V Centaur	Operated Saturn V Centaur
Mars flyby		1.5 AU	150 days	86,000	97,000	1.78×10^3	1.58×10^3
Liberation point exploration		208,000 nm†	100 hours	85,000	95,500	1.80×10^3	1.61×10^3
Jupiter flyby		5.2 AU	750 days	36,000	44,000	4.25×10^3	3.48×10^3
Solar probe		0.2 AU	80 days	14,000	15,000	10.9×10^3	10.2×10^3
		0.12 AU	76 days	5,500	6,000	28×10^3	25.5×10^3
Out of ecliptic plane	α*** = 25 degrees	1.0 AU	200 days	12,000	12,500	12.75×10^3	12.25×10^3
	α = 35 degrees	1.0 AU	200 days	1,250	3,500	122.5×10^3	43.8×10^3
Out of solar system	α = 0 degrees	40 AU	4000 days	13,000	14,000	11.8×10^3	10.9×10^3
	α = 10 degrees	40 AU	4000 days	8,500	9,000	18×10^3	17×10^3

*Glyte, J.D., and Wimmer, R.E., "Reactor Thermoelectric Power Systems for Unmanned Satellite Applications," Proceedings of the Intersociety Energy Conversion Conference, Los Angeles, California, September 26-28, 1966.

**Based on payload data from Saturn V Mission Planner's Guide, Douglas Aircraft Co., and a total vehicle and launch cost of $153 million.

***Inclination between vehicle trajectory and ecliptic plane.

†Distance from Earth.

BASIS FOR PRESENT BURDEN RELATIONS AND CONSTANTS

Weights and costs are based upon the best estimates for space qualified hardware developed from the most advanced existing technology.

The general assumptions on which the burdens of the previous topic are predicated are as follows:

1. Weights and costs are based on best estimates for space qualified hardware developed from the most advanced existing technology; i. e., that which might, with sufficient emphasis, find a space application within several years.

2. Costs cited are based on production costs for limited production (10 units or less) but do not include basic research or development costs.

Additionally, it is appropriate to mention some of the specific assumptions underlying the burdens for each of the component areas, since in most instances each burden is based on a specific type or configuration of component either dictated by the constraints of the application or indicated by considerations of availability, reliability, weight, or cost. Specific comments follow relative to burden relationships.

Spacecraft Transmitter Antennas and Primary Optics. Spacecraft microwave antenna weight and cost burdens are best estimates for space erectable rigidized inflatable dishes and are felt to be reasonably accurate up to diameters of 35 feet.

Spacecraft primary optical aperture weight and cost burdens are based on available information for beryllium sandwich mirrors. It is more appropriately a first order approximation for apertures up to 120 inch diameter. A more sophisticated weight analysis will take into account the weight dependence on operating wavelength for specified surface accuracy.

Receiver Antennas and Apertures. Microwave receiver antenna costs are considered collectively with receiver pointing and tracking system and receiver power supply costs based on published costs of the 85-foot and 210-foot DSIF site of $1 million and $12 million, respectively.

Optical receiver aperture cost is based on available information on fused silica, cored center, sandwich type mirrors constructed according to the technique developed by Corning Glass Works.

Spacecraft Transmitter Acquisition and Pointing. Microwave transmitter acquisition and pointing cost is based on a three gimbal system similar to that proposed by Hughes for the Apollo LEM with greater angular acceleration (0.01 rad/sec^2) and angular rate 1°/sec capability than required for a deep space vehicle.

Optical transmitter acquisition and pointing system weight is based on the two gimbal telescope system studied by Perkin-Elmer with internal fine pointing to 0.1 μr by a transfer lens and using Risley prisms for point ahead.

Receiver Pointing. For the microwave system receiver pointing and tracking costs are consolidated with the receiver antenna and power supply costs.

Optical system receiver pointing and tracking costs were assumed to have the same variable cost dependence as the spaceborne system.

Modulation. For the microwave system, modulation weight and cost associated was assumed negligible, since it occurs at very low power levels.

Optical modulators were assumed to be driven by solid state circuitry to a level at least half their ultimate modulating capacity with phase or frequency modulation for the heterodyne system and intensity or polarization modulation for photodetection systems.

Demodulation. Negligible weight and cost burdens associated with microwave demodulation are combined with the receiver antenna burdens.

Demodulation for the optical heterodyne system is by a mixer cooled to 100°K. The other optical systems use photodetector receivers.

Spacecraft Thermal Control. Radiator costs and weights are best estimates by a leading environmental control company for oriented active fin and tube aluminum radiators. They depend on the radiator temperature, hence on the transmitting source used. At present rf power levels radiation from the spacecraft structure with conductive coupling to the transmitter source suffices. Weights as listed for the various systems are based on a radiator temperature equal to the operating temperature of the associated transmitting source.

Spacecraft Transmitter Sources. Present microwave weight and cost burdens are based on capabilities of systems using the popular scheme of paralleling traveling wave tube amplifiers to achieve required output powers (as well as enhanced reliability and dispersion of heat sources). In this situation, transmitter system weight and cost are approximately linearly proportional to transmitter power since both are proportional to the number of paralleled tubes. Transmitter source cost and weight burdens include those associated with the required power conditioning electronics and its efficiency includes conversion losses.

Optical transmitting source burdens are known with far less confidence due to the non-existence of space qualified lasers. Present burdens for $\lambda = 0.5\mu$ argon laser sources were extrapolated from a 2-watt airborne unit developed by Hughes Research Laboratories. Included are the weight (10 lb/kw) and cost of required power conditioning equipment based on a laser efficiency of 0.1 percent and a power conditioning efficiency of 80 percent. Due to their low efficiency, liquid cooling is required for all argon lasers (typically coolant is flowed between the concentric solenoid and discharge tube). The portion of the cooling loop integral with the laser is included to arrive at the weight burden. It is significant to the evaluation of the associated radiator burdens that a maximum safe operating temperature of 300°F (limited by safe operation of the solenoid) is assumed.

BASIS FOR PRESENT BURDEN RELATIONS AND CONSTANTS

Present burdens for λ = 10.6μ CO_2 laser sources were inferred from the best estimates of projected weights and costs of space qualified devices in the 10 to 100 watt output power range. Power conditioning system weight (10 lb/kw or 4.55 kg/watt) and cost are included in the burdens based on a laser efficiency of 10 percent and power conversion efficiency of 80 percent. Since CO_2 laser efficiency (hence output power) drops sharply with increased temperature, liquid cooling might be required at power levels of interest for space transmitting sources. The usual technique is to enclose the discharge tube within a concentric cooling jacket and flow coolant through the annular passage between them. This configuration has been assumed in including the integral cooling jacket weight in the CO_2 source weight burden.

Although the CO_2 lasers on which the 10.6μ burdens are based are not themselves capable of the single frequency-single wavelength operation required for heterodyne systems, such devices will have comparable characteristics since the CO_2 laser is nearly as efficient at a single wavelength as when operating in a multiwave length mode. Single frequency-single wavelength CO_2 lasers have achieved 10 to 15 watts in laboratory operation and 100-watt single frequency devices are held attainable with present techniques.

Spacecraft Prime Power Sources. In general, the choice of prime power source type is influenced by output power level, solar illumination intensity, possible spacecraft constraints on tolerable nuclear and thermal radiation levels, and the ubiquitous considerations of cost and weight and weight. Since the prime power source represents a major part of the total system cost and weight, accurate evaluation of its cost and weight burdens is particularly desirable. Solar photovoltaic arrays are the most plausible choice on the basis of proven reliability and competitive cost and weight. They are applicable to deep space missions from within the orbit of Mercury to beyond that of Mars. Photovoltaic arrays also have an accurate and functionally simple burden relation: Photovoltaic array cost and weights vary directly with output power over a range from watts to kilowatts.* If diminished solar intensity or some other consideration precludes using solar arrays, the choice of long life power sources present or imminently available is limited to radioisotope or reactor thermoelectric systems. Radioisotope systems are most applicable to power levels of a kilowatt or less due to economic and technical considerations. For power levels from 1 to 25 kw the most plausible alternative to the solar array is the reactor thermoelectric power system. The reactor thermoelectric power system is complex and not amenable to a simple relation between output power and weight or cost. However, detailed design studies have been performed by Atomics International for a number of power levels in the range of interest. These design studies are the basis of the given power relations for thermoelectric systems. Solar array power burdens are based on estimates of specific weights and costs anticipated within the next few years by NASA and a leading solar cell manufacturer. These solar

*At constant temperature and solar intensity.

array burdens are used for cases at Mars range, corrected for Mars panel temperature and solar intensity. The reactor thermoelectric system burdens are used for cases at Jupiter range.

Payload Weight Cost. The payload weight costs used here depend simply on the total cost of the launch vehicle used and its maximum payload for a given mission. Mission is used in the sense of a specified transit time as well as destination; i. e., the spacecraft trajectory is not necessarily a minimum energy one. The total cost of vehicle and launching for the Saturn V/Centaur combination is approximately $153 million (and presumably similar for the uprated vehicle).

The Saturn V/Centaur combination is very attractive for deep space exploration because of its high performance and corresponding low-cost per pound of payload and is considered for a variety of missions. However, the cost per pound of payload is considerably higher for boosters of lesser capability (Figure A).

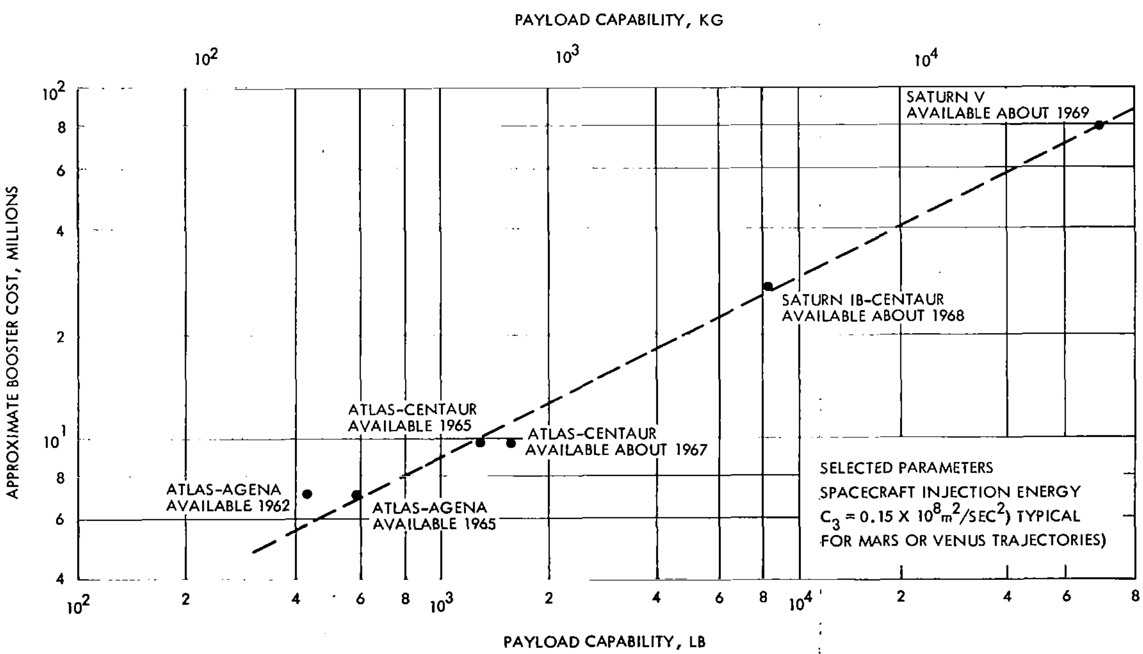


Figure A. NASA Launch-Vehicle Capability for Typical Mars and Venus Missions

UNCERTAINTIES IN PRESENT BURDEN RELATIONS

The greatest burden uncertainties are, in order, the following: Optical pointing system, Microwave pointing system, optical transmitting sources and microwave transmitting sources.

As previously stated, uncertainties exist in present burden relations because of the lack of information about applicable components (due to their nonexistence) and the difficulties in expressing the desired burdens as a function of only one of the communication system variables being optimized. As a result of combination of these factors the major areas of uncertainty are pointing systems and transmitting sources, both at microwave and at optical frequencies.

Pointing Systems

The optimum configuration of pointing systems depends on many indirectly related factors such as required accuracy, initial field of view, influence of disturbing torques, inertial moment of the gimballed mass, and others. Herein lies the difficulty in characterizing pointing system burdens in a form compatible with the existing optimization technique. The complexity of such systems renders it virtually impossible to express their associated weight and cost as functions of only one system variable. The problem is compounded at optical wavelengths, since space qualified laser pointing systems of the accuracy required to fully realize the potential inherent in optical communications do not yet exist. Numerous proven pointing systems of adequate performance for microwave beamwidths provide adequate burden information applicable to a variety of configurations. In addition, microwave pointing systems are less complex because of the less stringent accuracy requirements and applicable burden relations are more easily discerned.

With respect to cost burdens, in particular, the disparity in the development status of optical and radio frequency pointing systems leads to difffulties. Cost comparisons of communication systems are based on costs of small scale component production. In the case of optical pointing systems of accuracy compatible with laser beamwidths; further, more detailed analyses and cost estimation must be performed before the adequacy of this model can be assessed accurately.

Microwave Transmitting Sources

The traveling wave tube commonly used as a power amplifier at S-band frequencies is well established as a reliable (40, 000 hours) and efficient (30 percent) device with accurately known burden (weight, volume, or cost) characteristics. However, space qualified TWT's are presently limited to about 40 watts output and practical upper limit for single tube output is felt to be in the range of 100 watts to 1 kw because of compounded heat dissipation problems and the progressively higher operating voltages required (8 to 9 kv for a 100 watt TWT). A common practice in achieving higher output powers has been to parallel multiple TWT's so that their individual power outputs add. This approach also increases reliability and reduces the spacecraft thermal control problem by dispersing the heat sources. Up to 16 tubes have been paralleled in this manner. This type system yields a straight-forward burden relation since cost and weight are both linearly proportional to the number of tubes, hence to output power.

However, it appears that the traveling wave tube will be used less extensively in the future for S-band sources. Since it is likely to face strong competition by solid state devices - transistors and ultimately Gunn-effect oscillators.

Transistors paralleled in large numbers to achieve required power outputs are comparably efficient, far more compact, and require no high voltage power conditioning, operating directly from a 28V spacecraft bus. Presently, Hughes is operating 20 paralleled 2-watt transistors to achieve a 40-watt S-band output at 30 percent efficiency; a 100 watt 30 percent efficient transistorized S-band transmitter consisting of 20 paralleled 5-watt units is anticipated within 18 months. It is expected to be economically competitive with a comparable TWT unit and weigh perhaps 20 percent less.

Gunn effect solid state oscillators of 20 to 50 watt output per unit are expected to be available by 1970. Their compactness and higher power will make it feasible to mount the paralleled sources directly on the antenna, especially if a transmit only configuration is required.

In conclusion, it is felt that S-band transmitter source technology is in a fluid state with significant advances probable in the near future. Accordingly, a realistic projection of 2.3 GHz system capabilities should not be based solely on the present technique of paralleled TWT's but should consider the probable implications in reduced system weight and/or cost possible with solid state sources.

Laser Transmitting Sources

Relatively little attention has thus far been given to developing lightweight and compact laser sources or to adapting them to function with high reliability in the space environment. As a result of the primitive and fluid state of laser technology for space, accurate definition of laser source weight and particularly cost burdens is presently difficult. A related problem is the determination of power limitations of various laser sources and their characteristics (such as efficiency and reliability) as a function of power level. Requirement of a single wavelength-single frequency output in the case of heterodyne system is a further restriction on the applicability of existing laser sources. Shock and vibration encountered during boost may require that space qualified laser units incorporate subsequent automatic alignment of resonator mirrors (with attendant cost and weight penalties) to obtain peak power output. All these uncertain factors limit the accuracy of present burden relations and necessitate further investigation.

The principal areas of uncertainty in the present component burden relationships in their approximate order of importance are

1. Optical system pointing
2. Microwave system pointing
3. Optical transmitting sources at 10.6μ, 0.5μ and 0.8μ wavelengths with emphasis on factors influencing reliability.
4. Microwave transmitting sources, particularly the implications of the emerging solid state source technology.

MISSION ANALYSIS AND METHODOLOGY

Methodology Examples and Conclusions

IMPLEMENTATION OF DESIGN CRITERIA IN A USEABLE FORM

The Communications Design Criteria has been implemented in a computer program with an easy to use buffer language called COPTRAN. This language enables a user, without a knowledge of computer programming, to obtain optimized solutions to space communications problems.

The optimized communication methodology or design criteria mentioned in the previous topic contains a great amount of detail and requires a large amount of calculation to produce optimized values. Therefore the problem has been implemented into a computer program using FORTRAN IV language. Solutions using this program provides optimum values of the four major system parameters* and values for all the other related communications hardware. This is a versatile computer program which provides optimized values for the communications system. However one further step has been taken. The program, written in FORTRAN IV language, requires a user familiar with this language to obtain optimized results. Therefore a buffer language called COPTRAN (Communication OPtimization program TRANslator) has been developed.

To operate the Design Criteria optimization program using the COPTRAN language involves answering a few simple questions which are written in the language of the user. For instance one question is: "What is the transmission range?" Following this question is a choice of four six letter mnemonics and their meanings. One of these, RANMAR, may be chosen to tell the COPS methodology through the COPTRAN buffer language that the range (RAN) is a Mars (MAR) distance, nominally 10^8 km.

Similar simple questions, again using a multiple choice listing of mnemonics, are answered for such topics as the modulation type, the type of optimization desired, the type of output desired, etc.

The user may also use standard sets of data for the inter-relationship of transmitter cost to power, etc. (burden relationships). Or if the user desired, he may change one or all the nominal constants, thus superseding the stored values.

The mnemonic answers and data values that are selected by the user to describe the problem to be solved are written down by the user on a simple COPTRAN form. This form is then used to punch computer cards, one card per mnemonic or data value. The cards become part of the COPTRAN program and are batch processed by a computer.

The computer results are returned to the user either as a line printout or as Cal Comp plots.

The figure summarizes the steps in obtaining optimized communications parameters using the COPS computer program with COPTRAN language. A detailed description of COPTRAN is given in Appendix B of this volume.

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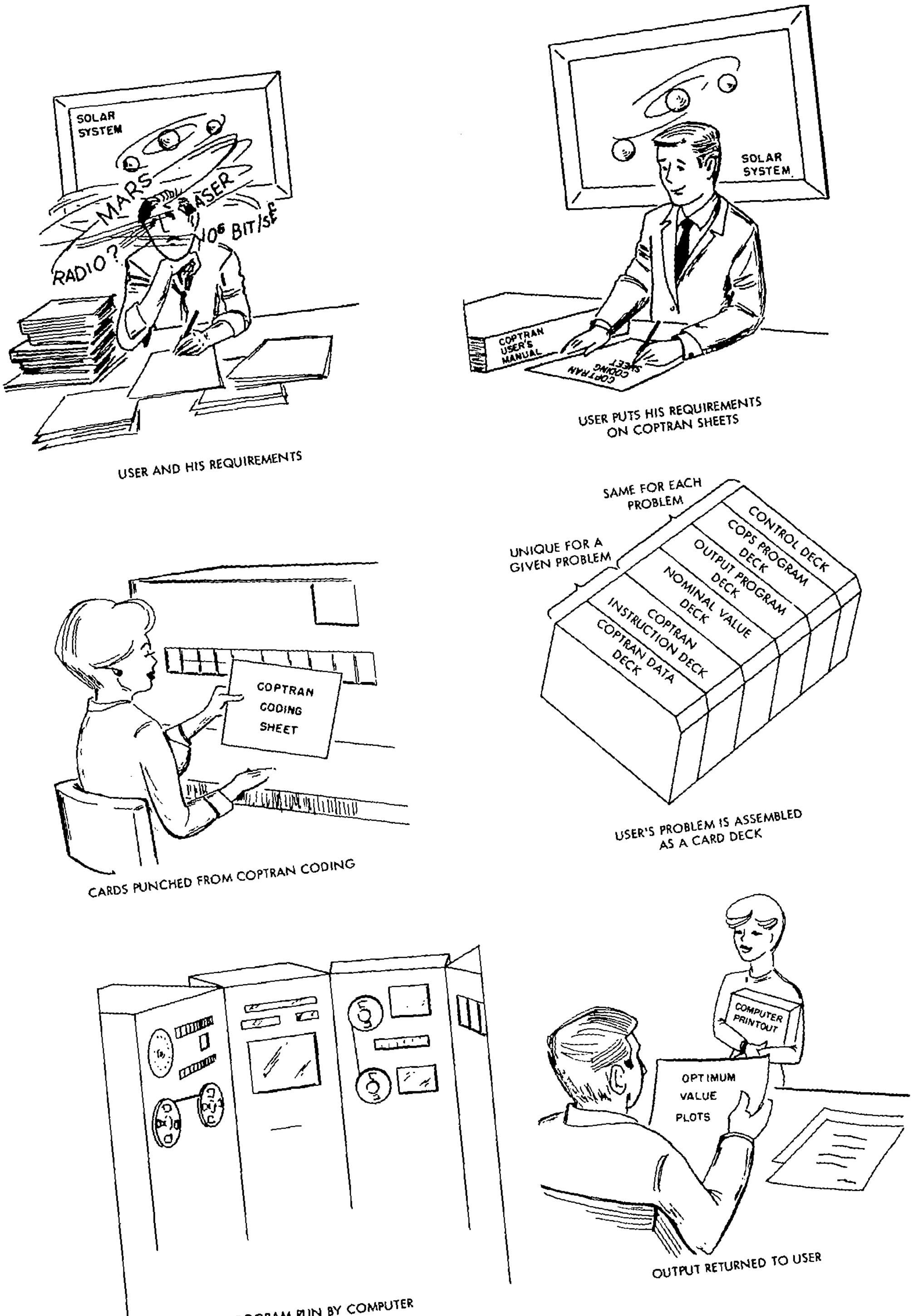
*Transmitter power and antenna gain, receiver antenna gain, and receiver field of view.



COPTRAN Programming

FEASIBILITY OF LASERS FOR SPACE COMMUNICATIONS

Laser communication is feasible for space use when high data rates are required at planetary distances and when the link need not be relied upon 100 percent of the time.

Contract NAS 5-9637 has as one of its purposes to determine the feasibility of lasers for space communications.

This purpose is given in the statement of work as:

> "The contractor shall furnish the personnel, materials, and facilities to conduct a study to determine the feasibility of using continuous wave laser (solid, liquid, gaseous) for future planetary communications and tracking systems."

Large portions of this final report are directed at documenting an answer to this task. What follows is a brief summary of that material.

Lasers hold promise for greatly enlarge communication capability. Two basic characteristics of lasers combine to provide this capability. The first characteristic is the fact that laser oscillations occur at frequencies which provide very large bandwidth for a fractional percentage of the basic oscillator frequency and thus can accommodate high data rates. Secondly, the coherent character of the laser light allows laser radiation to be directed in very narrow beams. The promise of increase performance using laser communications does not necessarily establish feasibility, this is examined below by considering several practical characteristics of laser communications.

Communications Capability

The potential communication capacity for lasers has been documented in this final report and elsewhere. In fact, this calculated potential has given the impetus to the study and analysis of laser communications. The conclusion is that laser communication is feasible from the point of view of communication theory.

Hardware Implementation

Hardware for laser communication is specialized, realtive to radio communication, in the following areas: the transmitting source, the transmitting and receiving optics, the detector, and the pointing and tracking mechanism. Optics technology has been developed over many years and is directly applicable to laser system. The other hardware areas have been under active development during the period of this contract, using both private and governmental funds. This combined effort has produced a space qualified laser; direct detectors which operate in the visible and infrared spectrum and heterodyne detectors which operate in the infrared; and preliminary optical tracking hardware capable of arc second accuracy.

The hardware developments have shown that laser hardware is feasible for space missions although considerable engineering development must yet be done.

Ground Stations

Ground stations for optical space communications may take one of two basic forms. The first is an optical receiving site which receives the laser beam directly from the space borne transmitter. With such a receiving implementation it is virtually impossible to obtain 100 percent contact with the spacecraft due to attenuation of the laser signal by clouds. While 100 percent coverage is very difficult, a number close to 100 percent can be achieved by careful placement of the surface stations and by having more than one station receiving simultaneously for back up.

A second basic form for an optical receiving system is that of a satellite, preferably in synchronous orbit, which receives the laser signal, detects it, and retransmits the data to a surface station using a radio link. Such an implementation, while more complex, can provide 100 percent coverage.

Summary

From the points of view of communication capability, hardware implementation, and ground station configuration it is possible to construct a laser communication link. Such a link is more attractive when very high data rates at long distances are required. Feasibility is enhanced if the data link is not required to be operational continuously allowing the use of a minimum number of surface terminals.

CAPABILITY OF COMMUNICATION SYSTEM (LASER OR MICROWAVE) TO MISSION

Missions suited for laser, microwave and laser/microwave hybrid communication links are noted.

Introduction

It is specifically required by contract NAS 5-9637 that missions be identified which make best use of microwave and laser systems. Specifically the work item reads as follows:

> "The contractor shall perform overall systems trade-off studies in sufficient detail to identify those missions which will make the best use of laser/optical microwave, or a combination of microwave and laser/optical communications and tracking systems."

The analysis required by this portion of the statement of work has been done. It is documented extensively in this final report. The conclusions are documented, although there are some uncertainties.

The applicability of laser or microwave communication systems depend upon three basic factors. These are: 1) the relative capabilities and expense of the two systems, 2) the mission to be performed and 3) the required data rate. Generally the laser system will show a weight or cost advantage over a microwave system when high data rates are required at planetary ranges.

The missions to be performed include those distinguished by being manned or not and those distinguished by their destination (space or heavenly body). Finally, the required data rates are heavily dependent upon the sensors used on the spacecraft, relatively low data rates are required of most sensors with the exception of imagery sensors.

Salient System Features

Before pairing mission and communications systems, some salient features of the two communication systems should be noted. For instance, microwave systems are, to a large degree, implemented e.g., the DSIF. This system is capable of low data rates, 10 to 16,200 bits per second, at planetary ranges, and these data rates can be achieved with relatively simple pointing of the spacecraft antennas.

In the case of laser communications, there is no implementation of a ground station network, and only a limited amount of experimentation is proceeding which could lead to such a network. However, it is possible, within the present state of the art, that laser communication could provide high data rates, 10^5 to 10^8 bits per second, at planetary distances. However to achieve such performance requires sophisticated transmitter antenna pointing in the spacecraft.

Mission and Type of Communication System

When the general capabilities of laser and microwave systems are compared with the data rate estimates, given in the table, certain conclusions may be reached, these are noted below.

Data Rate Estimate

	Manned	Unmanned
Space Probe		
Mars range		low
Jupiter range		low
Flyby		
Mercury		Medium-high
Venus		Medium-high
Mars	Medium-high	Medium-high
Jupiter		Medium-high
Astroids		Medium-high
Orbiter		
Mercury		high
Venus		high
Mars	high	high
Jupiter		high
Lander/Explorer		
Mars	high	high

Low data rate is taken to be less than 100 bits per second; high data rate is taken to be greater than 10^6 bits per second and medium data rate is taken between these two approximate bounds.

CAPABILITY OF COMMUNICATION SYSTEM (LASER OR MICROWAVE) TO MISSION

- A radio communication system should be used for space probes operating at planetary distances. This is largely due to the low data rate which may easily be accommodated by existing radio systems.

- An optical communication system should be used for a planetary orbiting mission. This is due to the very large amount of data which may be gathered using imagery sensors at these long ranges and which will be gathered at high rates for extended periods of time. Thus, not offering an opportunity to store the data and transmitting it at a slower rate.

- An optical communication link is also appropriate for manned lander mission. Here the high data rate obtained from imagery sensors leads to the selection of optical communication.

- In flyby missions the data rate can be high for a short period of time. This allows the use of a storage and playback mode and a radio link. The radio link would also be necessary since, with a flyby mission, continuous communication coverage is usually required during the critical flyby time. This could not be obtained with an optical system unless the additional complexity of an earth orbiting optical receiving station is used to prevent blockage by clouds.

- For a manned orbiting mission a radio system is likely best even though high, long term data rates may be expected. The reason for this is the additional difficulty in decoupling "man caused" mechanical disturbances which are difficult and expensive in terms of control system fuel (weight) to decouple from the optical pointing system.

An optical communication system can provide high data rates at planetary distances. Due to the specialized care required in pointing and tracking this high data rate transmission becomes the principle feature of laser communications. However this is not the only type of communication required by a spacecraft. In fact, there is generally a requirement for continual telemetry data which allows the earth stations to monitor the spacecraft performance and to determine the spacecraft's position. In addition to the transmission of telemetry data, the spacecraft must receive commands and beacon signals from earth. The two functions, commands and telemetry, are accomplished best, be far, by using a radio system. Thus it is seen that any optical system is really a combination of laser/optical and microwave, with the microwave being a relatively low performance communication system (and thus much less costly and lighter than a link that transmits the high data rates) and the optical system being designed to transmit the high data rates.

One other laser/microwave hybrid should be noted, although it has been mentioned briefly above. Since it is extremely difficult to guarantee an optically clear path between a space probe and a receiving station on earth, because of clouds, an intermediate receiving site such as a synchronous satellite, may be used to receive and detect the optical signal and then remodulate it on a radio signal for transmission to earth. This type of hybrid system is a very expensive addition to an optical receiving site and therefore would be difficult to justify. However it should be observed that such a relay satellite could be a multiple purpose satellite, being used for other missions such as astronomy investigations.

MICROWAVE AND LASER SYSTEMS COMPARED USING DESIGN CRITERIA

Microwave systems are superior to laser communication systems up to a bit rate of about 1 megabit/second. At data rates higher than this laser systems are both lighter and less expensive for a given bit rate than microwave systems.

The design criteria* developed during this contract can be used to compare laser and microwave systems where each system configured in an optimum way. The comparison is made on the basis of weight and cost where the optimization procedure selects communication parameters which produce the lightest or least expensive communications hardware. Two systems (e. g. a laser and a microwave) can be designed by this means and the results compared. This has been done for 4 different systems and the results are given in Figures A, B, C and D.

The four systems are 1) a radio system with a carrier frequency of 2. 3 GHz, 2) a radio system with a carrier of 10 GHz, 3) an optical system with a carrier wavelength of 10. 6 microns, and 4) an optical system with a wavelength of 0. 53 microns. These frequencies have been used and have been considered widely for space communications.

The design criteria, embodied in a computer program called COPS, is capable of providing a great variety of outputs. Some of this flexibility is shown and all is described in Appendix B of volume IV. The desired output for the comparison given in this topic was the overall weight and cost of the spaceborne communications hardware. Thus the figures are, in a sense, a summary of many designs (5 were made for each decade of bit rate) where the design is summarized in terms of cost or weight.

The four figures illustrate the combinations of the cost and the weight optimization procedure with two sets of burdens, estimated 1970 burdens and estimated 1980 burdens. **

The figures plot weight and cost against the product of receiver signal to noise rate, S/N, times bit rate, R_B. The curves were actually calculated for a signal to noise ratio of 10. The general form of (S/N) (R_B) is quite valid for all cases except the 0. 53 micron laser case. Here the curve has been calculated using a bit error rate of 0. 001 with S/N = 10 and really is valid only for such a value. The range used is 10^8 km.

Several earth station parameters were fixed (see the table) for the various frequencies and some were specific requests from the Program Director, Dr. Kalil.

As may be expected, a cost optimized system does not provide the lightest system nor does a weight optimized system provide the least expensive system. For this reason weights and costs respectively have been indicated on the cost optimized and weight optimized curves of the comparison.

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*This criteria is described extensively in Appendix A of Volume II of this report.

**Burdens relate the communication parameters to cost and weight.

As may be seen from all the figures, optical systems are both lighter and less expensive than radio systems at very high bit rates while radio systems are superior by both criteria at lower bit rates.

Table of Communication Parameters Used in the Link Comparisons

	Wavelength			
	13 cm	3 cm	10.6 microns	0.53 microns
Receiver Diameter	64 meters	64 meters	4 meters	1 meter
Receiver Noise Temperature	27°K	60°K	--	--
Receiver Aperture Eff.	55%	35%	90%	80%
Transmitter Aperture Eff.	70%	60%	90%	90%
Sky Background*	--	--	2×10^{16}	2×10^{16}
Detector Quantum Eff.	--	--	0.5	0.2
Optical Filter Bandwidth	--	--	--	10^{-3} microns
Transmitter Losses	1.25 db	1.25 db	1 db	1 db
Receiver Losses	4.5 db	4.5 db	2.2 db	1.5 db
Atmospheric Losses	0.2 db	0.2 db	1.0 db	1.0 db
Noise Bandwidth	Bit rate	Bit rate	2 (Bit rate)	Bit rate

*Photons/(sec-cm^2-micron-steradian)

MICROWAVE AND LASER SYSTEMS COMPARED USING DESIGN CRITERIA

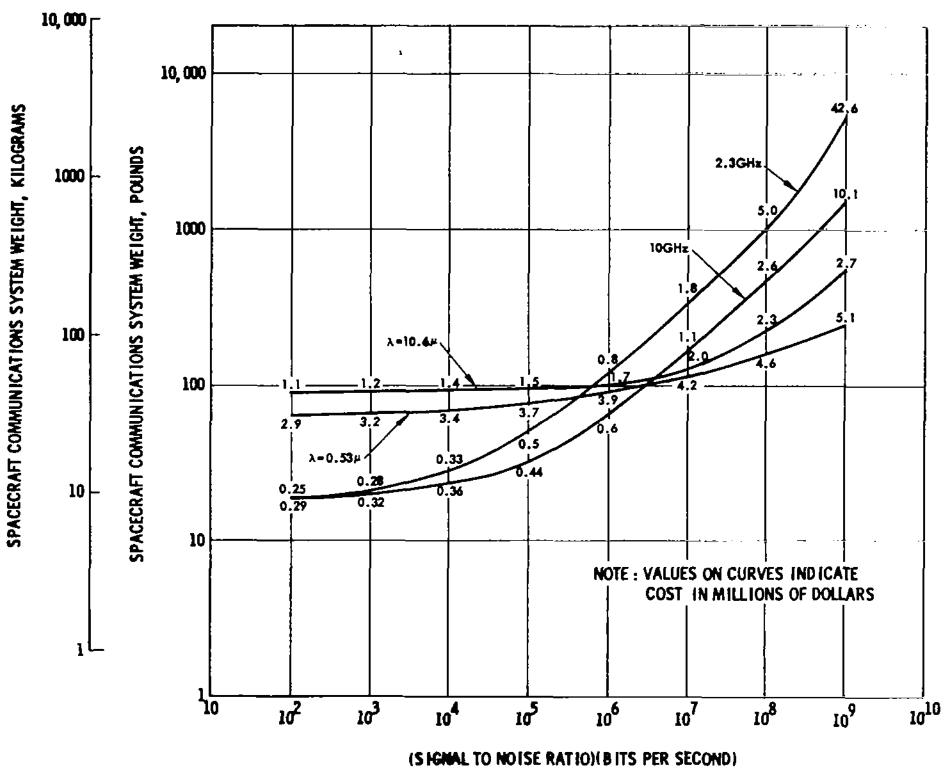


Figure A. Spaceborne Communications Systems Weight as a Function of Performance for Weight Optimized Systems Using 1970 State of the Art and 10^8 Km Range

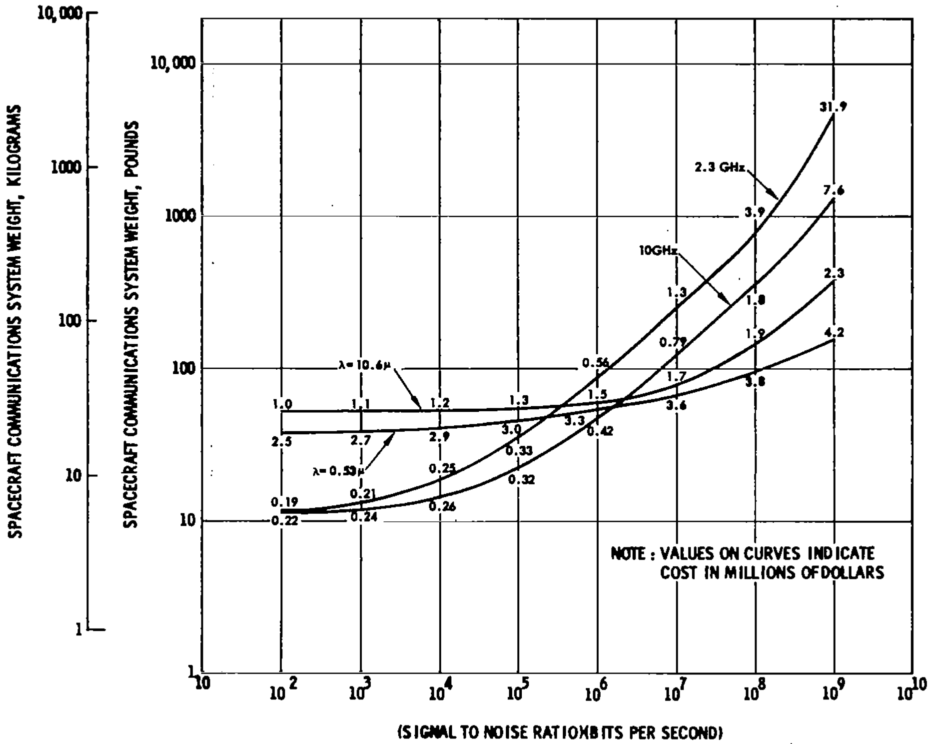


Figure B. Spaceborn Communications Systems Weight as a Function of Performance for Weight Optimized Systems Using 1980 State of the Art and 10^8 Km Range

MICROWAVE AND LASER SYSTEMS COMPARED USING DESIGN CRITERIA

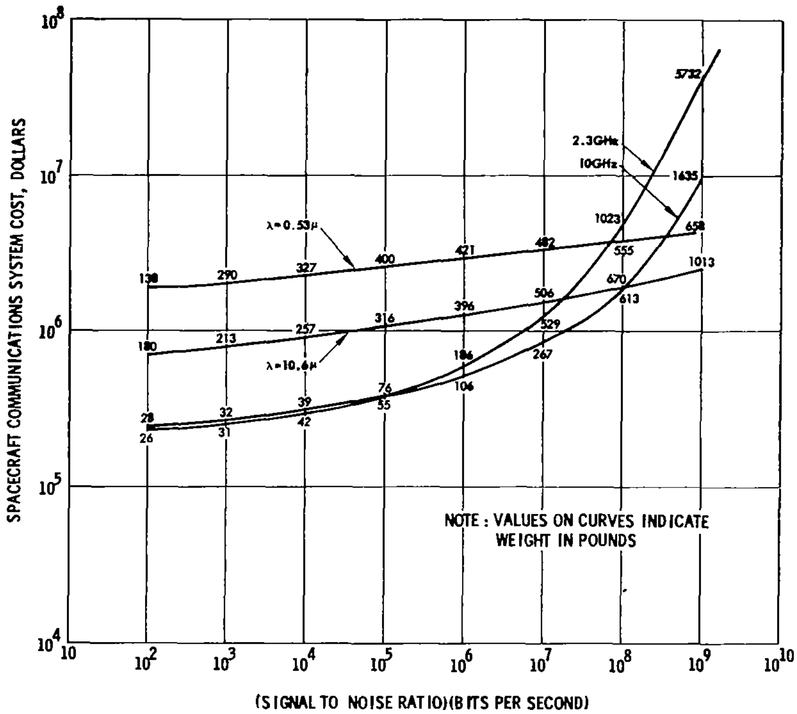


Figure C. Spaceborn Communications System Cost as a Function of Performance for Cost Optimized Systems using 1970 State of the Art and 10^8 Km Range

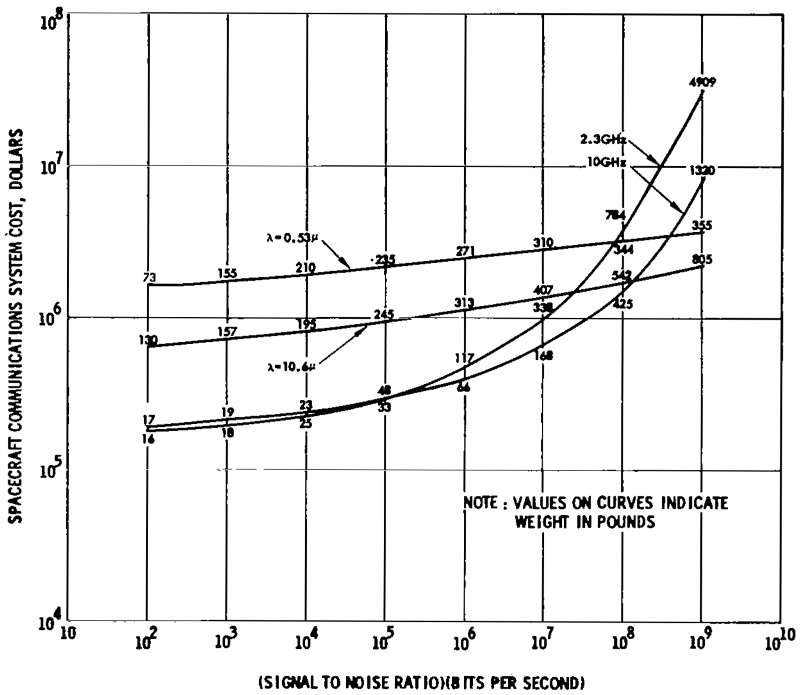


Figure D. Spaceborn Communications System Cost as a Function of Performance for Cost Optimized Systems using 1980 State of the Art and 10^8 Km Range

PART 2 SYSTEM THEORY

Section

INTRODUCTION

Systems theory includes noise analysis, modulation and demodulation techniques.

Systems theory is concerned with information transmission for space communications. Theory is given for both radio and optical communications. Optical communications is emphasized since it is relatively new and not as well documented in texts as is radio communications.

Systems theory is divided into five sections which are briefly introduced below.

Detection Noise Analysis

In any sensing device there are certain random-interfering signals which must be considered. These noise signals include thermal effects, atmospheric effects, signal effects and background effects. These several topics are documented to show the relative importance of these interfering signals.

Optical Detection

Three types of optical detection are examined, direct detection, heterodyne detection and homodyne detection. Equations describing the performance of each are given.

Modulation Methods

Various modulation methods are described which are suitable for radio and optical systems. Relative performance and implementation complexity are indicated.

Telemetry Communications

Multi channel analog telemetry equations are derived and degradation caused by filtering is considered.

Communications Coding

The benefits which are possible using data compression is given. Also included is the cost in data transmission time due to synchronizing signals.

SUMMARY

Systems theory provides the necessary equations to describe communications performance for a variety of hardware implementations.

The System theory documents the basic equations which describe modulation and demodulation implementations. The performance of these implementations is considered in the presence of various types of noise contributions.

In practice many optical and radio communications systems have been constructed and the theoretical performance compared to experimental measurements. The correlation has been good with small degradation allowed for hardware imperfections. It is not practical therefore to describe one type of implementation as "better than" another without listing the all conditions which are required to describe the theoretical performance. Instead the reader may select his own parameter values and compare performance as predicted by the equations in the text.

SYSTEM THEORY

Optical Detection Noise Analysis

OPTICAL DETECTION METHODS

Signal to noise ratio expressions are given for several detection methods as an aid in analyzing these methods. Emphasis is on optical detection. RF detection is discussed in the Telemetry Communications section, page 174.

Various methods of detection are listed in Table A. These detection methods are classified as coherent or noncoherent from a communications standpoint: that is, whether or not knowledge of the phase of the carrier is used in detection.

With heterodyne and homodyne detection systems, it is necessary to mix a reference wave with the incoming signal for detection. The reference for a heterodyne system may be a local oscillator which is frequency locked to the signal but not necessarily in phase lock. Homodyne systems, however, require phase coherence between the reference and information signal. The mixing reference may be obtained from a separately transmitted reference differentially derived from the information signal itself. The possible types of mixer references are as follows:

1. Local oscillator
2. Transmitted
3. Differential

The transmitted and differential references are always in phase lock with the information signal, and are therefore, associated only with coherent detection. The local oscillator reference must be placed in frequency or phase lock by a control system driven from the detector output.

In any communication system, the detection method employed effects the system signal-to-noise ratio (S/N). The transmission capability in terms of the probability of detection error is some function of the SNR, the specific function being based on the type of modulation. Thus, it is possible to analyze detection techniques to a certain extent independent of the types of modulation. Table B summarizes the SNR expressions for various types of receivers.

where:

$\frac{S}{N}$	receiver output power signal-to-noise ratio
$\left[\frac{S}{N}\right]_{IF}$	intermediate frequency output power signal-to-noise ratio
$\mu_{D,\tau}$	average number of dark current photoelectrons emitted per time period τ
$\mu_{B,S}$	average number of background radiation photoelectrons emitted per second
$\mu_{S,S}$	average number of laser radiation photoelectrons emitted per second
$\mu_{O,S}$	average number of local oscillator radiation photoelectrons emitted per second

Table A. Optical Detection Techniques

Noncoherent	Coherent
Direct detection Heterodyne	Homodyne

Table B. Optical Detection Signal-to-Noise Ratio Expressions

Detection Method	Conditions	Expression
Direct detection (analog transmission)		$\frac{S}{N} = \frac{\mu_{S,S}^2}{\frac{kTB_o}{q^2G^2R_L} + 2B_o(\mu_{S,S} + \mu_{B,S} + \mu_{D,S})}$
Direct detection (digital transmission)		$\frac{S}{N} = \frac{\mu_{S,B}^2}{\frac{kTB_o}{q^2G^2R_LR_B^2} + \frac{2B_o}{R_B}(\mu_{S,B} + \mu_{B,B} + \mu_{D,B})}$
Heterodyne detection (analog transmission)		$\left[\frac{S}{N}\right]_{IF} = \frac{\mu_{S,S}\mu_{O,S}}{B_{IF}(\mu_{S,S} + \mu_{O,S} + \mu_{B,S} + \mu_{D,S})}$
	$\mu_{O,S}$ large	$\left[\frac{S}{N}\right]_{IF} = \frac{\mu_{S,S}}{B_{IF}}$
Heterodyne detection (digital transmission)		$\left[\frac{S}{N}\right]_{IF} = \frac{\mu_{S,B}\mu_{O,B}}{\frac{B_{IF}}{R_B}(\mu_{S,B} + \mu_{O,B} + \mu_{B,B} + \mu_{D,B})}$
	$\mu_{O,B}$ large	$\left[\frac{S}{N}\right]_{IF} = \frac{\mu_{S,B}}{\frac{B_{IF}}{R_B}}$
Homodyne detection (analog transmission)		$\frac{S}{N} = \frac{2\mu_{O,S}\mu_{S,S}}{(\mu_{S,S} + \mu_{O,S} + \mu_{B,S} + \mu_{D,S})\,B_o}$
	$\mu_{O,S}$ large	$\frac{S}{N} = \frac{2\mu_{S,S}}{B_o}$
Homodyne detection (digital transmission)		$\frac{S}{N} = \frac{2\mu_{O,B}\mu_{S,B}}{(\mu_{S,B} + \mu_{O,B} + \mu_{B,B}\ \mu_{D,B})\frac{B_o}{R_B}}$
	$\mu_{O,B}$ large	$\frac{S}{N} = \frac{2\mu_{S,B}}{\frac{B_o}{R_B}}$

OPTICAL DETECTION METHODS

$\mu_{S,B}$	average number of signal photoelectrons emitted per bit
$\mu_{D,S}$	average number of dark current photoelectrons emitted per second
$\mu_{B,B}$	average number of background photoelectrons emitted per bit
$\mu_{D,B}$	average number of dark current photoelectrons emitted per bit
$\mu_{O,B}$	average number of local oscillator photoelectrons emitted per bit
R_B	information rate (bits per second)
B_o	receiver output bandwidth
B_{IF}	intermediate frequency output bandwidth
q	electronic charge, 1.6×10^{-19} coulomb
G	photodetector gain
k	Boltzmann's constant (1.38×10^{-23} Joule/degree Kelvin)
T	Absolute Temperature
R_L	receiver load resistance

THERMAL NOISE

The relationship for thermal noise is defined and thermal noise is related to a simple RC circuit.

Thermal or Johnson noise is caused by thermal fluctuations of electrons in a resistor. Consider a "noisy" resistor, R, connected in parallel with a capacitance, C. In a practical detector, R may be the internal resistance of the detector or the load resistor, and C the detector shunt capacitance. The average energy stored in the capacitor in equilibrium may be equated to the thermodynamic energy of the system. Thus,

$$1/2\, C\, \overline{v^2} = 1/2\, kT \qquad (1)$$

where

$\overline{v^2}$ = mean square voltage across resistor

k = Boltzmann's constant, 1.38047×10^{-23} watts/sec - ^{o}K

T = resistor temperature

The thermal noise power is then

$$N_T = \frac{\overline{v^2}}{R} = \frac{kT}{RC} = kTB \qquad (2)$$

where the detector bandwidth is defined to be the reciprocal of the resistor-capacitor time constant.

The corresponding thermal noise power spectral density (two-sided) is

$$G_T = 2\, kTR_L \qquad (3)$$

This is the power spectral density of a noisy resistor connected to any detector filter network. If the detector network were an ideal (but physically unrealizable) bandpass network over a band between $-f_2$ to $-f_1$ and f_1 to f_2, then the thermal noise power would be $N_T = 4kT\Delta f$ where $\Delta f \equiv f_2 - f_1$. This leads to the treatment of thermal noise as being characterized by an open circuit rms voltage of

$$\left[\overline{v_T^2\ (\Delta f)}\right]^{1/2} = (4k\ TR\ \Delta f)^{1/2} \qquad (4)$$

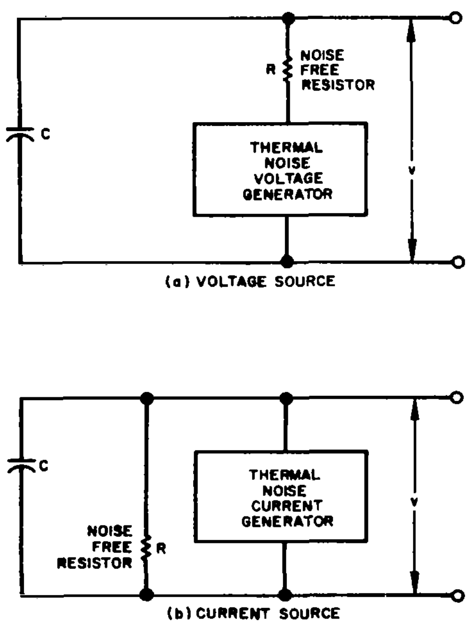
and its rms current equivalent

$$\left[\overline{i_T^{\,2}\;(\Delta f)}\right]^{1/2} = \left(\frac{4kT\;\Delta f}{R}\right)^{1/2} \tag{5}$$

in series or parallel, respectively, with a non-noisy resistor R. Care must be taken in the application of these equations since Δf is, in general, not the bandwidth of the detector, but simply a frequency interval over which the thermal noise spectrum is flat. As an example of the application of these equations consider the thermal noise current source shunted by a capacitor as shown in the Figure. The total thermal noise power is the integral over all positive frequencies of the product of the mean square thermal noise current and the real part of the impedance of the RC parallel combination. Thus,

$$N_T = \int_0^{\infty} \left[\frac{4kT}{R}\right]\left[\frac{R}{1 + (2\pi\, RCf)^2}\right] df = \frac{kT}{RC} = kTB \tag{6}$$

where the detector bandwidth is defined as in Equation (2).



Photodetector with Capacitor Filter
Thermal Noise Model

FLICKER NOISE, CURRENT NOISE, AND DARK-CURRENT SHOT NOISE

Power spectrum relationships are presented for flicker noise, current noise, and shot noise.

Flicker Noise

Fluctuations in the emission from a given point on a photoemissive surface creates flicker noise. The spectrum of this noise is inversely proportional to frequency to less than 1 Hz and to the square of the average photocurrent. Thus,

$$G_F(f) \approx \frac{I^2}{f}$$

Current Noise

Semiconductor devices carrying a steady current exhibit a current or 1/f noise which has a one-sided spectrum proportional to inverse frequency to below 1 Hz and to the square of the average detector current. Thus,

$$G_C(f) \approx \frac{I^2}{f}$$

Trapping of charge carriers near the surface of the semiconductor material is believed responsible for the noise.

Dark Current Shot Noise

A small current will flow in the absence of any external photoexcitation in a photoemissive or photovoltaic detector due to thermal emission, field emission, and current leakage within the detector. Experimental evidence indicates that dark current electron emissions from a cathode are time independent and obey Poisson statistics. The probability that the number of electrons emitted in a time period τ is exactly an integer k is

$$P(V_D = k) = \frac{(\mu_{D,\tau})^k \exp\{-\mu_{D,\tau}\}}{k!}$$

where

$$\mu_{D,\tau} \equiv \frac{I_D \tau}{q} = \text{average number of dark current}$$

electrons released by detector in τ; and I_D = average detector dark current. These k electrons emitted at random times in τ each carry a unit electronic charge q and produce a total current

$$i_D(t) = \sum_{n=1}^{k} Gq\delta(t - t_n) \quad \text{for} \; -\frac{\tau}{2} \le t \le \frac{\tau}{2}$$

where $\delta(t - t_n)$ is the unit impulse occurring at time t_n and G is the post detector current gain.

In order to determine the power spectral density of the dark current fluctuations the autocorrelation function of $i_D(t)$ must be found. The Fourier transform of the autocorrelation yields the noise power spectral density

$$G_{I_D}(f) = G_q^2 I_D + G^2 I_D^2 \; \delta(f)$$

The noise power spectral density due to dark current emissions is thus composed of a flat spectrum ($G_{H_D}(f) = qI_D$) and a dc component. The total noise power, N_{H_D}, due to fluctuations about the mean over a bandwidth B_o at a resistive load R_L is

$$N_{H_D} = 2 G_q^2 I_D B_o R_L$$

This expression is called the Schottky shot noise formula. As the dark current electrons move from the cathode to the anode, the noise spectrum will be modified due to electron transit time effects. The resulting power spectrum is

$$\left[G_q^2 I_D\right] \frac{1}{1 + (2\pi f \tau_a)^2}$$

where τ_a is the electron transit time. In most detectors τ_a is small with respect to the reciprocal detector filter bandwidth, and the electron transit time effect is negligible.

PHOTON FLUCTUATION, SHOT, AND GENERATION – RECOMBINATION NOISE

Shot noise is described and the spectral density from shot noise for photoemissive, photoconductive and photovoltaic detectors due to shot noise are given.

In all types of photodetectors, fluctuations in the arrival time of photons cause noise fluctuations in the detector current. The random arrival of k photons from a general radiative source may be described by

$$M_{R,\tau}(t) = \sum_{n=1}^{k} \delta(t - t_n)$$

Taking the autocorrelation of $M_{R,\tau}(t)$ and the Fourier transform of $M_{R,\tau}(t)$ yields a spectral density of the photon fluctuations.

$$G_{M_{R,\tau}}(f) = \frac{E(W_R)}{\tau} + \left[\frac{E(W_R^2) - E(W_R)}{\tau^2}\right]\delta(f)$$

where $E(W_R)$ and $E(W_R^2)$ are the first and second moments of the distribution $P(W_R = k)$ of the number of photon arrivals in τ.

The number of photon arrivals due to background radiation (reflected sunlight, stars, etc.) obeys Bose-Einstein statistics.

$$P(W_B = k) = \frac{\left[M_{B,\tau}\right]^k}{\left[1 + M_{B,\tau}\right]^{k+1}}$$

where $M_{B,\tau}$ = average number of background photon arrivals in time period τ. The variance in the number of photon arrivals is[1]

$$\sigma^2(WB) = M_{B,\tau} + M_{B,\tau}^2 \frac{A_h}{A_D} \frac{B_o}{B_B}$$

[1] Hodara, H., "Statistics of Thermal and Laser Radiation," Proceedings of the IEEE, 53, No. 7, pp. 696-704, 1965.

where A_h/A_D is the ratio of the radiation coherence area to the detector area and B_o/B_B is the ratio of the detector bandwidth to the coherence bandwidth. (Note: $B_B \equiv 1/2\tau_C$ where τ_C is the coherence time of the radiation.) For background radiation, $A_h/A_D < 10^{-3}$ and $B_B \approx 10^{12}$ Hz. Thus, the second term of the variance expression is negligible. Since the mean of the Bose-Einstein distribution is $M_{B,\tau}$ the spectral density of the background photon fluctuations may be written as the average number of background photon arrivals per second $[M_{B,S} = M_{B,\tau}/\tau]$ as

$$G_{M_{B,S}}(f) = M_{B,S} + M_{B,S}^2\,\delta(f)$$

The statistics of the number of photon arrivals from a laser for various operating conditions is not presently well known. However, if the laser is assumed to be a purely monochromatic, single mode source, the laser photon fluctuations may be described by a Poisson distribution. Thus,

$$P(W_S = k) = \frac{(M_{S,\tau})^k \exp\{-M_{S,\tau}\}}{k!}$$

where $M_{S,\tau}$ = average number of laser photon arrivals in time period τ.

The spectral density of the laser photon fluctuations in terms of the average number of laser photon arrivals per second $[M_{S,S} = M_{S,\tau}/\tau]$ is

$$G_{M_{S,S}}(f) = M_{S,S} + M_{S,S}^2\,\delta(f)$$

In a photoemissive detector each arriving photon liberates an average of $\mu_{B,S} = \eta M_{B,S}$ and $\mu_{S,S} = \eta M_{S,S}$ electrons due to background and laser radiation where η is the detector quantum efficiency. While in photovoltaic and photoconductive detectors* the arriving photons create $\mu_{B,S}$ and $\mu_{S,S}$ hole-electron pairs which create an electron current flow. Thus, photon fluctuations at the input of a detector will produce photoelectron fluctuations at the output. The spectral densities of the electron emissions are then

$$G_{\mu_{S,S}}(f) = \mu_{S,S} + \mu_{S,S}^2\,\delta(f)$$

*The following statements to be made for photoconductive detectors apply also for photoelectromagnetic detectors since their physical mechanisms are similar.

PHOTON FLUCTUATION, SHOT, AND GENERATION – RECOMBINATION NOISE

and

$$G_{\mu_{B,S}}(f) = \mu_{B,S} + \mu_{B,S}^2 \ \delta(f)$$

Since each photoelectron carries a unit charge, the power spectral densities of the detector currents about the average signal and background currents are

$$G_{H_S} = G^2 \ q \ I_S$$

and (photoemissive detector)

$$G_{H_B} = G^2 \ q \ I_B$$

The noise power spectral densities are of the same form as the shot noise power spectral densities due to dark current, and are also referred to as shot noise.

In a photoconductive detector the simultaneous generation and recombination processes result in electron fluctuations twice as large as the photon fluctuations. The resulting noise power spectral densities about the mean detector currents are

$$G_{G_S}(f) = 2 \ G^2 \ q \ I_S$$

and (photoconductive detector)

$$G_{G_B}(f) = 2 \ G^2 \ q \ I_B$$

This noise spectrum is called generation-recombination noise by many authors, and simply shot noise by others. Lattice vibrations in the photoconductive material will cause a modification of the basic generation-recombination noise spectrum. The modification can be found by multiplying the G-R noise spectral density by the square of the absolute value of the impulse response of the lattice variations.

This transfer function is dependent upon the fractional ionization of the material and whether the material is intrinsic or extrinsic. Jamieson, et al.,[2] gives the G-R noise power spectral densities for these cases. In most situations the lattice time constants are short with respect to the reciprocal detector filter bandwidth, and the additional complexity is not warranted.

The recombination lifetimes in a photovoltaic detector are so short that the recombination process does not produce significant fluctuations. The expressions for the photon fluctuation noise power spectral densities for a photovoltaic detector are then the same as the expressions for a photoemissive detector.

$$G_{G_S}(f) = G^2 \; q \; I_S$$

(photovoltaic detector)

$$G_{G_B}(f) = G^2 \; q \; I_B$$

[2] Jamieson, J. A., et al., Infrared Physics and Engineering, McGraw-Hill, 1963.

BACKGROUND RADIATION NOISE, RADIATION FLUCTUATION NOISE, AND PHASE NOISE

The relative importance of background radiation noise, intensity noise, and phase noise is given.

Background Radiation Noise

An optical direct detection receiver produces a detector current proportional to the instantaneous radiation intensity at the input to the receiver regardless of the frequency of the radiation passing through the optical input filter. Thus, if the direct detection receiver is subject to a constant intensity background radiation, the only effect will be to raise the dc level of the detector output which does not affect the detection process.

In an optical heterodyne or homodyne receiver the constant intensity background radiation may mix with the receiver local oscillator to produce noise in the IF bandpass filter or output filter. The degree of mixing is proportional to the coherence of the background radiation. In general very little mixing occurs, and background radiation noise is negligible.

A radio frequency receiver responds to the electric field of the background radiation. Mixing of the background radiation with itself and with a local oscillator will occur in nonlinear radio detectors producing appreciable background radiation noise.

Radiation Intensity Fluctuation Noise

Random variations in the intensity of radiation causes noise fluctuations in the detector current. Variations in the background intensity are due to natural pulsations of the solar source or stars. Lasers suitable for communications generally are intensity stabilized, and therefore are not a serious source of radiation intensity fluctuations in themselves. However, all radiation passing through the atmosphere is subject to intensity variations due to the statistically changing atmospheric transmissivity.

A first order analysis of intensity fluctuations describes the fluctuations by some average percentage of intensity modulation of the source over a given frequency range. As an example, narrow-band background radiation intensity fluctuations may be described by an intensity fluctuation noise power of

$$N_{F_B} = M_F^2 \, G^2 \, I_B^2 \, R_L$$

where

R_L = Load resistor

G = Photodetector gain

I_B = Current due to background photoelectrons

M_F = intensity fluctuation modulation index ($M_F \leq 1$)

For typical background radiation levels M_F must be less than 10 percent if the intensity fluctuation noise power is to be less than shot noise due to the background radiation.

Phase Noise

In a heterodyne or homodyne optical receiver in which optical mixing occurs, the line or spectral shape of the transmitting and local oscillator lasers becomes significant because the laser lines are essentially shifted intact to a lower radio frequency called an intermediate frequency (IF). With a direct detection receiver consisting of a photodetector followed by a filter, laser line shape is not a consideration since the photodetector cannot differentiate between narrow-band optical frequencies. The spectral width at the IF becomes a problem if frequency or phase detection is employed since the line width represents a phase uncertainty. With any type of optical mixing some form of phase or frequency detection is necessary in order to frequency or phase lock the laser carrier to the local oscillator, hence the phase uncertainty or phase noise is a problem even for an intensity modulation laser communication system.

The analysis of the effect of phase noise on a laser communication system is complicated by spectral variations of the laser radiation due to the atmosphere. The general approach is to determine the spectral shape of the IF signal and its statistical variations. The standard techniques of analysis developed for phase lock loops are then applicable.

OPTICAL DETECTION NOISE

The spectrum relationships of various types of noise found in communications systems are given.

Detection Noise

Noise in the detection process of a communication system arises from radiation entering the communications receiver and internally generated noise. The major types of detection noise are listed below:

Internal Noise

Thermal noise

Flicker noise

Current noise

Dark current shot noise

External Noise

Photon fluctuation shot and generation-recombination noise

Background radiation noise

Radiation intensity fluctuation noise

Phase noise

The Section on Detectors in Volume III contains details on these noise sources and their relationship to the physical parameters of the detectors. The following present an analysis of spectra of the noise sources.

Summary of Detection Noise Source

The Table lists the noise power spectral densities of the major detection noise sources. Flicker noise and current noise are low frequency phenomena, and their effects can be avoided by restricting the information signal bandwidth to above a low frequency cutoff of from 10 to 100 Hz or by placing the information on a radio frequency subcarrier. The same techniques often negate the effects of intensity fluctuations of incident radiation on the detector.

The shot and generation-recombination (G-R) noise spectra due to dark current, background radiation, and laser radiation add to the detector output to produce a total shot or G-R noise power spectrum of

$$G_H(f) = G^2 \, qI \text{ (photoemissive detector)}$$

$$G_G(f) = G^2 \, qI \text{ (photovoltaic detector)}$$

$$G_G(f) = 2G^2 \, qI \text{ (photoconductive detector)}$$

where

I = total average detector current

$G_H(f)$ = shot noise power spectral density

$G_G(f)$ = generation-recombination noise power spectral density

q = electronic charge

Thermal noise is a universal type of noise found in all detection systems, and is usually the limiting noise source for semiconductors and photoemissive detectors without secondary gain mechanisms. Secondary electron multiplication in a photomultiplier tube usually makes the detector shot noise limited. The dominance condition is that the shot noise be greater than the thermal noise power, or

$$2G^2 \, qI \, B_O \, R_L > k \, T \, B_O$$

The current gain required for shot noise limited operation is thus

$$G > \sqrt{\frac{kT}{2qIR_L}}$$

where

G = photodetector gain

B_O = receiver output bandwidth

R_L = receiver load resistance

k = Boltzmann's constant

T = Temperature

where

R = Resistance

α_F = proportionality constant

α_C = proportionality constant

I_D = average detector dark current

f = frequency

Power Spectral Densities of Major Sources of Optical Detection Noise

Type	Expression
Thermal noise	$2kTR$
Flicker noise (photoemissive detector)	$\alpha_F G^2 \frac{I^2}{f}$
Current noise (photovoltaic and photoconductive detectors)	$\alpha_c G^2 \frac{I^2}{f}$
Dark current shot noise (photoemissive and photovoltaic detectors)	$G^2 qI_D$
Photon fluctuation shot noise (photoemissive detector)	$G^2 qI$
Photon fluctuation generation-recombination noise (photovoltaic detector)	$G^2 qI$
Photon fluctuation generation-recombination noise (photoconductive detector)	$2G^2 qI$

OPTICAL DETECTION STATISTICS

By assuming the optical statistics to be Poisson, relationships are derived which relate required threshold to signal, dark current noise, and background noise.

The statistical distributions of laser and background radiation photons at the input of a photodetector are complex functions, not necessarily time stationary. Mandel[1] has shown, however, for low intensities the laser and background statistics may be assumed Poisson. Thus, let the probability distributions of laser and background photon counts be

$$P(W_S = k) = \frac{(M_{S,\tau})^k \exp\{-M_{S,\tau}\}}{k!}$$

$$P(W_B = k) = \frac{(M_{B,\tau})^k \exp\{-M_{B,\tau}\}}{k!}$$

where

W_B is the number of background radiation photons at detector in time period τ

W_S is the number of laser radiation photons at detector in time period τ

$M_{B,\tau}$ is the average number of background radiation photon arrivals per time period τ

$M_{S,\tau}$ is the average number of laser radiation photon arrivals per time period τ

k is an integer

Since the photon counts are related to the photoelectrons counts by the quantum efficiency, η, the output distributions of photoelectrons is also Poisson. The probability distributions of photoelectron counts due to laser and background radiation are

$$P(V_S = k) = \frac{(\mu_{S,\tau})^k \exp\{-(\mu_{S,\tau})\}}{k!}$$

$$P(V_B = k) = \frac{(\mu_{B,\tau})^k \exp\{-(\mu_{B,\tau})\}}{k!}$$

---

[1]Mandel, L., "Fluctuations of Light Beams," in Progress in Optics, John Wiley and Sons, 1963.

where

$\mu_{S,\tau} \equiv \eta M_{S,\tau}$ and $\mu_{B,\tau} \equiv \eta M_{B,\tau}$

V_B is the number of background radiation photoelectrons emitted in time period τ

V_S is the number of laser radiation photoelectrons emitted in time period τ

In addition to the laser and background emissions, the detector will also release electrons due to the detector dark current. The probability distributions of the dark current emission is also Poisson.

$$P(V_D = k) = \frac{(\mu_{D,\tau})^k \exp\{-\mu_{D,\tau}\}}{k!}$$

where

$\mu_{D,\tau} = \frac{I_D \tau}{q}$, and I_D = average detector dark current.

V_D = number of dark current photoelectrons emitted in time period τ

The three emission processes are independent, and hence, the probability distributions of photoelectrons due to the simultaneous presence of laser and background radiation and dark current are Poisson distributions whose means are the sums of the means of the constituent distributions. The photoelectron count distribution for no laser signal present is

$$P(V_N = k) = \frac{(\mu_{N,\tau})^k \exp\{-\mu_{N,\tau}\}}{k!}$$

where

$\mu_{N,\tau} = \mu_{B,\tau} + \mu_{D,\tau}$

V_N = Number of noise radiation photoelectrons emitted in time period τ.

The corresponding distribution when the laser signal is present is

$$P(V_{SN} = k) = \frac{(\mu_{S,\tau} + \mu_{N,\tau})^k \exp\{-(\mu_{S,\tau} + \mu_{N,\tau})\}}{k!}$$

OPTICAL DETECTION STATISTICS

where

V_{SN} = Number of signal and noise radiation photoelectrons emitted in time period τ.

In many communication systems the absence or presence of a laser signal is determined by comparing the received photoelectron count with a predetermined threshold level. The threshold level is determined from the likelihood ratio test of decision theory.[2] The likelihood ratio test states that a signal is present if

$$\Lambda(k) \equiv \frac{P\,(V_{SN} = k)}{P\,(V_N = k)} \geq \frac{P\,(S \neq 0)}{1 - P\,(S \neq 0)}$$

where

$\Lambda(k)$ = likelihood ratio

$P\,(S \neq 0)$ = a priori probability that signal is not present

At the threshold value k_t of k,

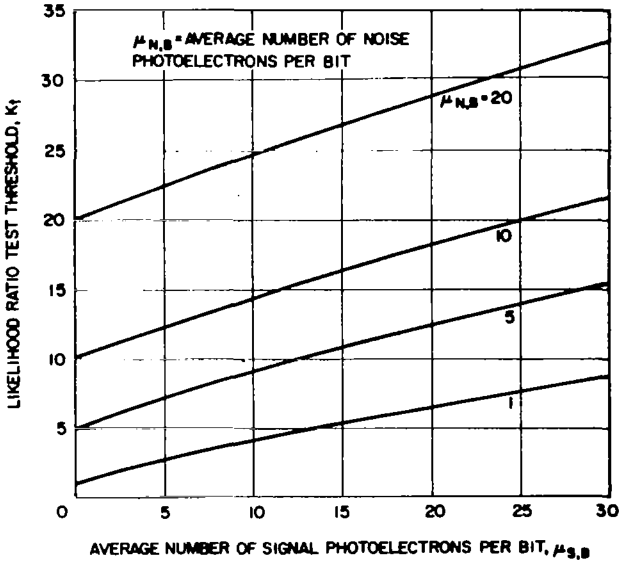
$$\Lambda(k_t) = \left[1 + \frac{\mu_{S,\tau}}{\mu_{N,\tau}}\right]^{k_t} \exp\,\{-\mu_{S,\tau}\}$$

Since the likelihood ratio is a monotonic function of the threshold value, the expression may be inverted to yield

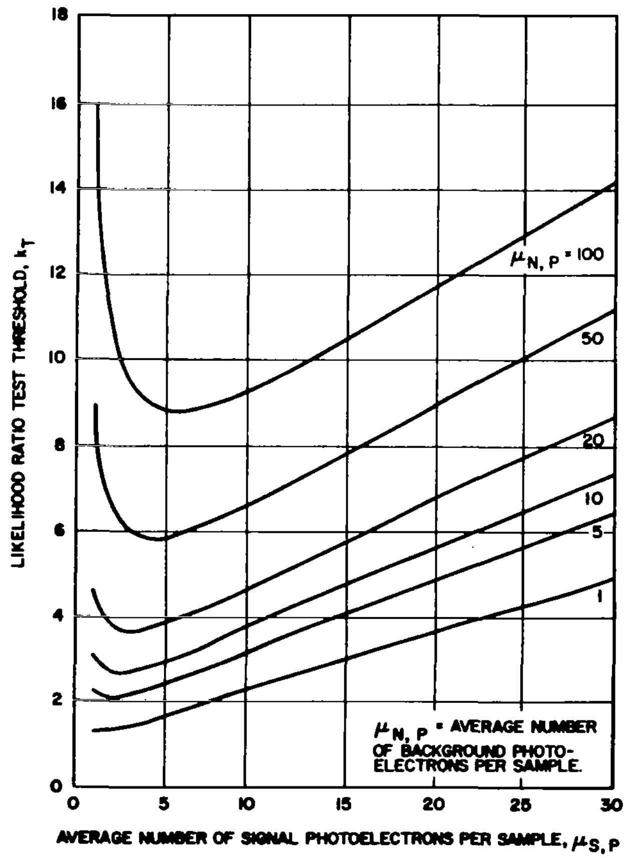
$$k_t = \frac{\mu_{S,\tau} + \ln\left[\frac{P\,(S \neq 0)}{1 - P\,(S \neq 0)}\right]}{\ln\left[1 + \frac{\mu_{S,\tau}}{\mu_{N,\tau}}\right]}$$

The output of a photodetector is an integer number of photoelectrons, and hence, the actual threshold N_t chosen should be the greatest integer value of k_t. The Figures show the likelihood ratio test threshold as a function of the signal and noise photoelectron counts for PCM and PPM threshold detection.

[2] Reiffen, B. and Sherman, H., "An Optimum Demodulator for Poisson Processes: Photon Source Detectors," Proceedings of the IEEE, 53, No. 10, p. 1660, October 1965.



Likelihood Ratio Test Threshold for PCM/IM Laser Communication System



PPM/IM Likelihood Ratio Test Threshold

SYSTEM THEORY

Optical Detection

OPTICAL DIRECT DETECTION

The signal to noise ratio is developed for the general case and then modified for a variety of special cases of optical direct detection.

The operation of an optical direct detection receiver is illustrated by Figure A. The current produced by the background noise and the signal itself combine with the dark current to produce shot noise in the detector. The composite signal and shot noise current is multiplied, filtered, and combined with thermal noise in the load. The detector multiplication factor may be unity to encompass devices without photomultiplication.

A photodetector is essentially an intensity to current converter in the wave sense or a photon to electron converter in the quantum sense. Let

$M_{S,S}$ = average number of signal photons impinging on photodetector per second

$\mu_{S,S}$ = average number of signal photoelectrons released by photodetector per second

η = detector quantum efficiency ($\eta < 1$)

h = Planck's constant (6.624×10^{-34} joules-sec)

f_c = carrier frequency

P_C = carrier power at detector surface

Then the average signal photon count per second is equal to the ratio of the average signal power to the energy of a single photon at the carrier frequency.

$$M_{S,S} = \frac{P_C}{hf_c}$$

Note: In this and the following two topics only the principal noise sources – shot and thermal noise – are considered. For a photoconductive or photoelectromagnetic detector the shot noise power should be doubled.

A group of $M_{S,S}$ photons striking the detector releases an average of $\eta M_{S,S}$ photoelectrons. Thus,

$$\mu_{S,S} = \eta M_{S,S} \text{ (photon to electron converter)}$$

Each photoelectron carries a charge of 1.6×10^{-19} coulombs to produce an average detector signal current of

$$I_S = q\mu_{S,S}$$

Thus,

$$I_S = \eta q M_{S,S} = \frac{\eta q P_C}{hf_c} \text{ (intensity to current converter)}$$

The signal power at the detector output consisting of a load resistance R_L is

$$S = (GI_S)^2 R_L = \left(\frac{G\eta q}{hf_c} PC\right)^2 R_L$$

where

G is the photomultiplication gain

R_L is the load resistance

The average current at the output of the photodetector due to background radiation is

$$I_B = \frac{P_B}{hf_c} \eta q$$

where

P_B is the power of the background radiation at the detector surface

The shot noise power as given by the Schottky formula is

$$N_H = 2\, qG^2\, I\, B_o R_L$$

where

B_o is the receiver output bandwidth, I is the average detector current

$$I = I_S + I_B + I_D$$

OPTICAL DIRECT DETECTION

and

I_D = dark current

Then

$$N_H = 2q\,B_o G^2\left(\frac{\eta q}{hf_c} P_C + \frac{\eta q}{hf_c} P_B + I_D\right) R_L$$

The thermal noise power is

$$N_T = k\,TB_o$$

The signal-to-noise ratio is then

$$\boxed{\frac{S}{N} = \frac{\left(\frac{G\eta q}{hf_c} P_C\right)^2 R_L}{k\,TB_o + 2q\,B_o G^2\left(\frac{\eta q}{hf_c} P_C + \frac{\eta q}{hf_c} P_B + I_D\right) R_L}}$$

For a detector with large postdetector gain the shot noise and background noise are much larger than the thermal noise. Thus,

$$\frac{S}{N} = \frac{\left(\frac{\eta q}{hf_c} P_S\right)^2}{2q\,B_o\left(\frac{\eta q}{hf_c} P_C + \frac{\eta q}{hf_c} P_B + I_D\right)} \quad \text{(no thermal noise)}$$

The dark current of a detector can be made negligible by cooling the detector. Then

$$\frac{S}{N} = \frac{\eta P_C^{\,2}}{2\,B_o hf_c\,(P_C + P_B)} \quad \text{(no dark current)}$$

If the background noise input power is larger than the carrier noise input power

$$\frac{S}{N} = \frac{\eta P_C^2}{2 B_o h f_c P_B} \quad \text{(background shot noise limited operation)}$$

If the carrier input power is larger than the background noise input power

$$\frac{S}{N} = \frac{\eta P_C}{2 B_o h f_c} \quad \text{(carrier shot noise limited operation)}$$

The complete optical communication system into which the direct detection fits is shown in Figure B.

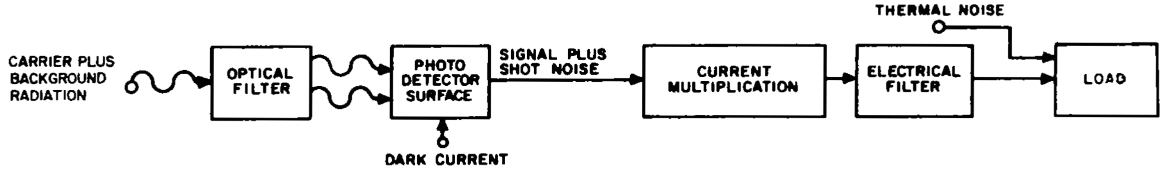


Figure A. Direct Detection Model

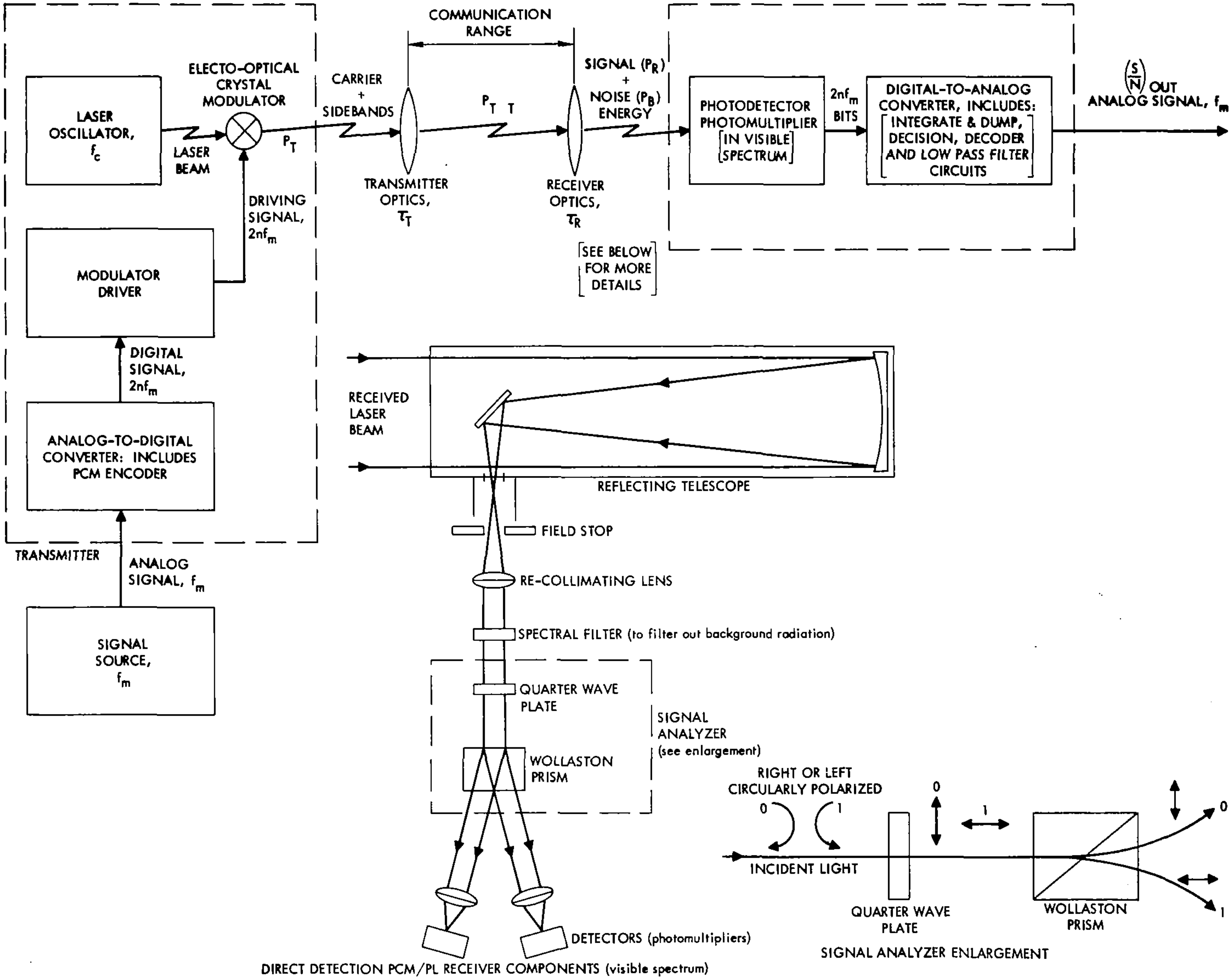


Figure B. Optical Digital Communication System Using Direct Detection

OPTICAL HETERODYNE DETECTION

The signal-to-noise ratio for an optical detection receiver is derived and compared with optical direct detection.

In a heterodyne detector, as shown in Figure A, the incoming carrier is mixed with a reference wave on a photodetector surface producing sum and difference frequencies. The difference frequency is then passed through an electrical filter to the load.

The principal advantages of heterodyne operation are the relative ease of amplification at an intermediate frequency, and the fact that the local oscillator power may be set to swamp out the thermal noise and shot noise caused by all other sources than the local oscillator itself.

Figure B illustrates the spatial combination of the carrier and local oscillator on the detector surface when the beams are misaligned by an angle ψ. Let

$A_c \cos(\omega_c t + \phi_c)$ = received carrier with average power $P_S = 1/2\, A_c^2$

$A_o \cos(\omega_o t + \phi_o - \beta x)$ = local oscillator with average power $P_O = 1/2\, A_o^2$

where $\beta \equiv \omega_o/v_x$ and v_x is the local oscillator wave velocity along the detector surface. The carrier and local oscillator instantaneous amplitudes combine at the photodetector surface to yield an input normalized power to the detector of

$$\left[A_c \cos(\omega_c t + \phi_c) + A_o \cos(\omega_o t + \phi_o - \beta x)\right]^2$$

The resultant instantaneous carrier and local oscillator current at the photodetector output is the spatial integral of the light intensity over the detector surface.

$$i_P = D \int_{-d/2}^{+d/2} \Big\{ 1/2\, A_c^2 + 1/2\, A_o^2 + A_c A_o \cos\left[(\omega_o - \omega_c)t + (\phi_o - \phi_c) - \beta x\right]$$

$$+ A_c A_o \cos\left[(\omega_o + \omega_c)t + (\phi_o + \phi_c) - \beta x\right]$$

$$+ 1/2\, A_c^2 \cos 2\omega_c t + 1/2\, A_o^2 \cos 2(\omega_o t - \beta x) \Big\}\, dx$$

where

$$D = \frac{\eta q}{hf_c}$$

η = quantum efficiency

g = electronic charge

h = Planck's constant

f_c = carrier frequency

d = surface dimension

The average photodetector current due to the carrier and local oscillator is

$$I_P = \frac{D}{2}\left(A_c^2 + A_o^2\right) = D\,(P_C + P_O)$$

The intrinsic bandwidth limitations of the photodetectors provides a filter for the double frequency terms. Only the difference frequency will be passed by the IF filter to give an instantaneous IF frequency current.

$$i_F = D \int_{-d/2}^{+d/2} \left\{A_c A_o \cos\left[(\omega_o - \omega_c)\,t + (\phi_o - \phi_s) - \beta x\right]\right\} dx$$

Performing the integration yields

$$i_F = D\,A_c A_o \cos\left[(\omega_o - \omega_c)\,t + (\phi_o - \phi_s)\right] \frac{\sin\left(\frac{\beta d}{2}\right)}{\left(\frac{\beta}{2}\right)}$$

From Figure B

$$\sin \psi = \frac{c}{v_x}$$

where

c = velocity of light

OPTICAL HETERODYNE DETECTION

and therefore,

$$\beta = \frac{\omega_o \sin \psi}{c} \approx \frac{2\pi \psi}{\lambda_o}$$

where

λ_o = local oscillator wavelength

In order that signal phase cancellation due to misalignment be kept to 10 percent or less ($\beta d/2$) must be 0.8 radian or less. Thus,

$$\psi < 1.6 \frac{\lambda_o}{d}$$

At a wavelength of 10^{-4} cm and for a detector surface of 1 cm, ψ must be held to 10^{-4} radian or less. The spatial alignment requirement can be minimized somewhat by focusing the signal beam to its diffraction limited spot size on the detector surface which may be on the order of 0.01 cm yielding an allowable misalignment angle of 10^{-2} radian. If such a procedure is followed the local oscillator beam must be focused or field stopped to the signal spot size to prevent additional shot noise due to the local oscillator.

Assuming perfect spatial alignment, the average carrier power at the IF filter referenced to a unit resistance is

$$[S]_{IF} = \overline{[Gi_F]^2} = 2G^2 D^2 P_O P_C$$

where G is the net amplification.

The shot noise power at the output of the IF filter referred to a unit resistance is

$$[N_H]_{IF} = 2G^2 qIB_{IF}$$

where

$I = I_P + I_B + I_D$

Then

$$[N_H]_{IF} = 2G^2 q B_{IF}(DP_C + DP_O + DP_B + I_D)$$

The SNR at the output of the IF filter is

$$\left[\frac{S}{N}\right]_{IF} = \frac{2\left[G\frac{\eta q}{hf_c}\right]^2 P_O P_C}{2G^2 q\, B_{IF}\left\{\left(\frac{\eta q}{hf_c}\right)\left[P_C + P_O + P_B\right] + I_D\right\} + kTB_{IF}}$$

If the local oscillator power is large, all signal, background and dark current shot noise effects plus the thermal noise will be swamped out by the local oscillator shot noise. The S/N is then

$$\left[\frac{S}{N}\right]_{IF} = \frac{\eta P_C}{h f_c B_{IF}}$$

Since the IF bandwidth B_{IF} is at least twice as large as the baseband B_O, the SNR of a heterodyne receiver can at most equal the SNR of a direct detection receiver for signal shot noise limited operation. Second detection must now be performed to obtain the information signal from the IF carrier. First consider that the electrical detector is a square law device in which the IF output is squared. The output of the electrical square law detector is

$$i_Q \equiv i_F^{\,2} = D^2\left\{\frac{A_c^{\,2} A_o^{\,2}}{2} - \frac{A_c^{\,2} A_o^{\,2}}{2}\cos\left[2(\omega_o - \omega_c)t + 2(\phi_o - \phi_c)\right]\right\}$$

At the output of the subsequent low pass filter the signal current is

$$i_S = \frac{G^2 D^2 A_c^{\,2} A_o^{\,2}}{2} = 2G^2 D^2 P_O P_C$$

which yields an output current directly proportional to the input power.

The output power is

$$S = \overline{i_S^{\,2}}\, R_L = 4G^4 D^4 P_O^{\,2} P_C^{\,2} R_L$$

OPTICAL HETERODYNE DETECTION

The IF filter noise output when fed to the square law detector along with the signal will result in signal and noise cross product terms. It may be assumed that the shot noise in the IF filter bandwidth, which has a flat spectrum, is generated by a narrow band Gaussian process. Then the analysis[1] for a modulated sine wave plus Gaussian noise input to a square law detector will apply.

In this case the receiver output noise is related to the IF output noise by

$$N = [N_H]_{IF}^2 R_L + 2[S]_{IF} [N_H]_{IF} R_L$$

The output signal-to-noise ratio is then

$$\left(\frac{S}{N}\right)_{OUT} = \frac{\left[\frac{S}{N}\right]_{IF}^2}{1 + 2\left[\frac{S}{N}\right]_{IF}}$$

(square law second detection of heterodyne receiver)

In the limit when the IF SNR is large

$$\left(\frac{S}{N}\right)_{OUT} = \frac{1}{2}\left[\frac{S}{N}\right]_{IF}$$

and when the IF SNR is small

$$\left(\frac{S}{N}\right)_{OUT} = \left[\frac{S}{N}\right]_{IF}^2$$

Thus, square law second detection results in at least a 3 db reduction in SNR, and significantly degrades the receiver output if the IF SNR is low.

For a low IF signal-to-noise ratio, synchronous second detection produces better results. In a synchronous second detector the IF output is multiplied by a sine wave at the IF center frequency.

The output of the electrical synchronous detector is

$$i_R \equiv i_F \cos \omega_d t = \frac{GDA_c A_o}{2} \cos(\phi_o - \phi_c) - \frac{GDA_c A_o}{2} \sin 2\omega_d t \sin(\phi_o - \phi_c)$$

---

[1] Davenport, W. B., Jr. and Root, W. L., An Introduction to the Theory of Random Signals and Noise, McGraw-Hill, 1958.

where

$$\omega_d \equiv \omega_o - \omega_c$$

At the output of the low pass the filter signal current is

$$i_S = \frac{GD\, A_c A_o}{2} \cos(\phi_o - \phi_c)$$

to yield a signal power of

$$S = \overline{i_S^2}\, R_L = \overline{\frac{G^2 D^2 A_c^2 A_o^2}{4} \cos^2(\phi_o - \phi_c)\, R_L}$$

$$= G^2 D^2 P_S P_O \overline{\cos^2(\phi_o - \phi_c)}\, R_L$$

Assuming a uniform distribution of the phase angle $\phi_o - \phi_c$, the signal power is

$$S = \frac{G^2 D^2}{2} P_C P_O R_L$$

The shot noise power in the output filter bandwidth is reduced by the ratio of the receiver output bandwidth to the IF bandwidth

$$N_H = [N_H]_{IF} \frac{B_o}{B_{IF}}$$

Since B_{IF} is ideally $2B_o$, the receiver output noise power is one half the IF output noise power.

Then the signal-to-noise ratio is

$$\frac{S}{N} = \left[\frac{S}{N}\right]_{IF} \frac{B_{IF}}{4B_o}$$

OPTICAL HETERODYNE DETECTION

or

$$\frac{S}{N} = \frac{\eta P_O P_C}{4hf_c B_o (P_C + P_O + P_B)}$$

For P_O large

$$\frac{S}{N} = \frac{P_C}{4hf_c B_o}$$

Synchronous second detection thus results in a SNR of one-half that obtained for a signal shot noise limited direct detection receiver.

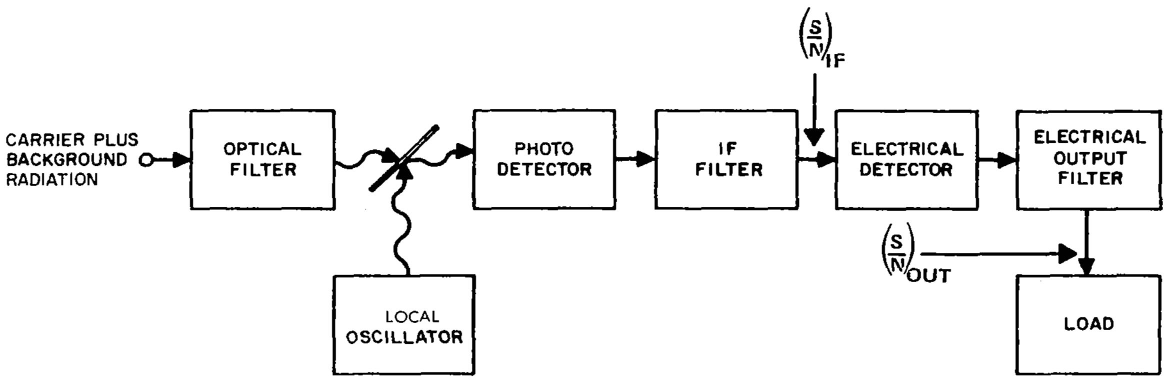


Figure A. Local Oscillator Reference Heterodyne Detection Model

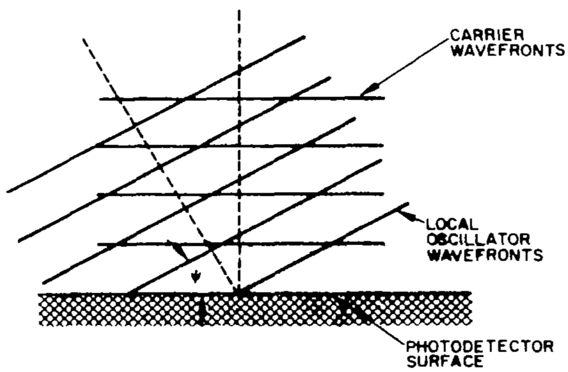


Figure B. Spatial Combination of
Carrier and Local Oscillator

OPTICAL HOMODYNE DETECTION

The signal-to-noise ratio for an optical homodyne detector is derived and shown to be 6 db higher than the signal-to-noise obtained using a direct detector.

In the homodyne detector shown in the Figure, the reference wave is set at the same frequency and phase as the carrier prior to mixing. The incoming carrier is split and combined with the local oscillator output in one channel and the oscillator output shifted in phase 90 degrees in the other channel. The resultant photodetector outputs represent the in-phase and quadrature signal components in an information bandwidth about the baseband. Quadrature detection then yields the demodulated information.

Let

$$A_c \cos(\omega_c t + \phi_c) = \text{received carrier}$$

$$A_o \cos(\omega_c t + \phi_o) = \text{local oscillator}$$

The carrier and local oscillator instantaneous amplitudes combine at the photoconductor surface to yield a normalized input power to the detector of

$$[A_c \cos(\omega_c t + \varphi_c) + A_o \cos(\omega_c t + \varphi_o)]^2$$

The resultant instantaneous current at the photodetector assuming perfect spatial alignment is

$$i_P = D\left\{\frac{1}{2}A_c^2 + \frac{1}{2}A_o^2 + A_c A_o \cos(\varphi_o - \varphi_c)\right.$$

$$\left. - A_c A_o \cos[2\omega_c t + (\varphi_o + \varphi_c)] - \frac{1}{2}A_c^2 \cos 2\omega_c t - \frac{1}{2}A_o^2 \cos 2\omega_c t\right\}$$

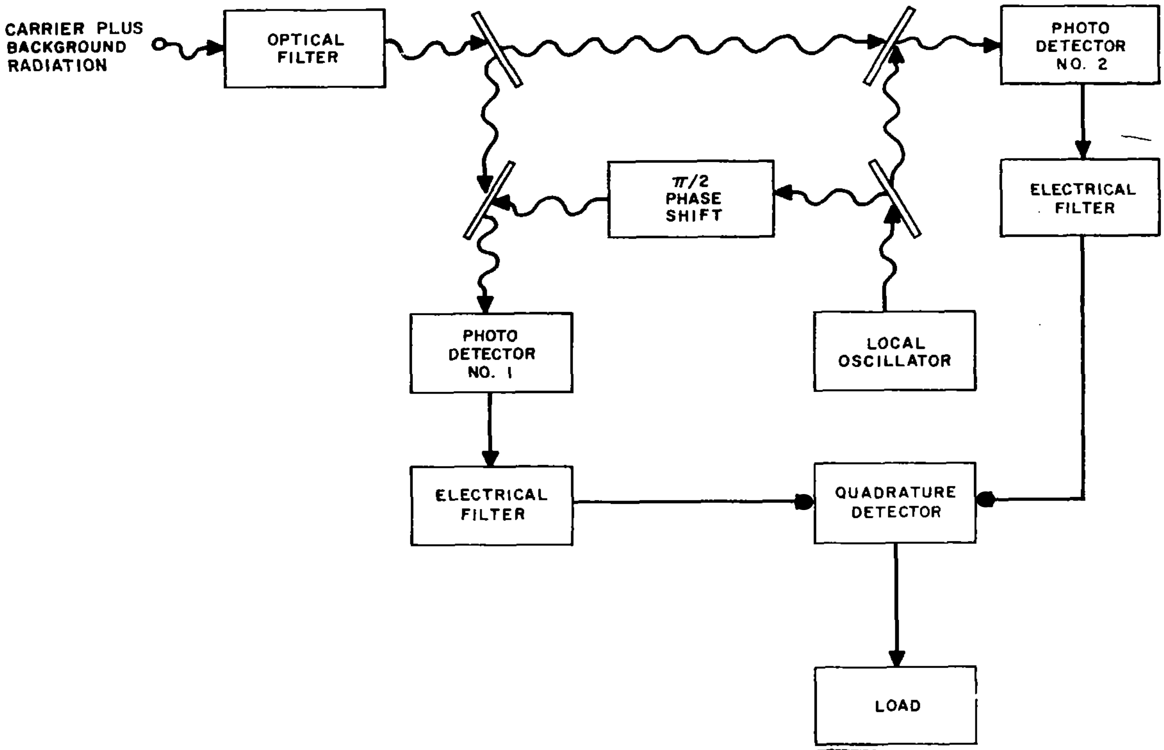
where

η = quantum efficiency

q = electronic charge

h = Plank's constant

f_c = carrier frequency



Local Oscillator Reference Homodyne Detection Model

OPTICAL HOMODYNE DETECTION

i_P = instantaneous detector current due to carrier and local oscillator

i_H = instantaneous homodyne receiver output current

i_S = instantaneous receiver output current

The intrinsic bandwidth limitation of the photodetector provides a filter for the double frequency terms to yield,

$$i_H = D\left\{\frac{1}{2}A_c^{\ 2} + \frac{1}{2}A_o^{\ 2} + A_c\, A_o \cos\,(\varphi_o - \varphi_c)\right\}$$

In a homodyne receiver the carrier and local oscillator are phase locked so that $\phi_o = \phi_c$. The signal portion of the output is then

$$i_S = D\, A_c\, A_o$$

and the signal power is

$$S = \overline{(G\, i_S)^2}\, R_L = 4G^2\, D^2\, P_O\, P_C\, R_L$$

where

G is the net receiver gain

R_L is the load resistance

The shot noise power neglecting dark current is

$$N_H = 2q\, G^2\, B_o\, [D\,(P_C + P_O + P_B)]$$

Thus the signal-to-noise is

$$\boxed{\frac{S}{N} = \frac{2\eta\, P_O\, P_C}{hf_c\,(P_C + P_O + P_B)\, B_o}}$$

If the local oscillator power is large

$$\frac{S}{N} = \frac{2\eta\, P_C}{hf_c\, B_o} \qquad \text{(strong local oscillator)}$$

The signal-to-noise ratio for a homodyne receiver is therefore 6 db greater than the SNR for signal shot noise limited direct detection receiver.

SYSTEM THEORY

Modulation Methods

INTRODUCTION

Modulation methods are defined by the extent the data signal is modified before it is impressed upon the carrier.

Methods of modulation can be classified into three essential techniques. The first transforms a source signal waveform into a continuously variable modulation parameter. The second involves time sampling with continuous modulation parameters. The third is characterized by sampling time and allowing the source signal to take on only a discrete set of possible values. These three techniques are summarized in the Table.

Where:

AM	amplitude modulation
FM	frequency modulation
IM	intensity modulation
PAM	pulse amplitude modulation
PIM	pulse intensity modulation
PPM	pulse position modulation
PDM	pulse duration modulation
PCM	pulse code modulation
PCM/AM	PCM amplitude modulation
PCM/IM	PCM intensity modulation
PCM/FM	PCM frequency modulation
PCM/PL	PCM polarization modulation
PCM/PM	PCM phase modulation

Laser Modulation Techniques

	Type I	Type II	Type III
Time	Continuous	Sampled	Sampled
Modulation parameter (amplitude, frequency phase, polarity, etc.)	Continuous	Continuous or quantized	Quantized and coded
Examples	FM, AM, IM	PAM, PIM, PPM, PDM	PCM/AM PCM/PL PCM/IM PCM/FM PCM/PM

TYPE I MODULATION SYSTEMS

Several Type I communication modulation methods are related to general expressions for the transmitted field vectors.

Communication systems utilizing Type I modulation techniques employ modulation which varies the parameters of the sinusoidal carrier waveform. In considering the modulation methods, the condition that the carrier waveform is spectrally isolated from the modulation waveform must be satisfied. The Type I modulation systems can be described by the orthogonal electric field vectors

$$E_x(t) = F_x(t) \cos \left[\omega_c t + \varphi_x(t)\right]$$

$$E_y(t) = F_y(t) \cos \left[\omega_c t + \varphi_y(t)\right]$$

where $F_x(t)$, $F_y(t)$, $\phi_x(t)$, and $\phi_y(t)$ are amplitude and phase functions of the modulating signal x(t) and the type of modulation. The conditions of this equation for various types of modulation are listed.

Amplitude Modulation

$$\phi_x(t) = \phi_y(t) = \phi_c$$

$$x(t) \approx \sqrt{F_x^2(t) + F_y^2(t)}$$

Intensity Modulation

$$\phi_x(t) = \phi_y(t) = \phi_c$$

$$x(t) \approx F_x^2(t) + F_y^2(t)$$

Frequency Modulation

$$F_x(t) = F_1, \quad F_y(t) = F_2$$

$$\phi_x(t) = \phi_y(t) = \phi_c(t)$$

$$x(t) \approx \frac{d\phi_c(t)}{dt}$$

Phase Modulation

$$F_x(t) = F_1, \quad F_y(t) = F_2$$

$$\phi_x(t) = \phi_y(t) = \phi_c(t)$$

$$x(t) \approx \phi_c(t)$$

Polarization Modulation

$$\phi_x(t) = \phi_y(t) = \phi_c$$

$$x(t) \approx \tan^{-1}\left(\frac{F_y(t)}{F_x(t)}\right)$$

A radio frequency carrier can be amplitude, frequency, or phase modulated. At optical frequencies polarization modulation is possible as well as intensity, frequency, or phase modulation.

TYPE II MODULATION SYSTEMS

In Type II modulation systems, the modulation is imposed upon a pulsed carrier energy.

In time-sampled systems a sample from a signal source is used to modulate a carrier waveform so that at the receiving end of the communication link a sampled representation of the signal source may be reconstructed. For a band-limited information signal of bandwidth B, a signal sampled at a rate of 2B samples per second can be faithfully reconstructed at the receiver. In practice, sampling rates higher than the theoretical minimum are often required because most signals are not truly band-limited.

Waveform parameters are available for Type II systems which cannot be applied to Type I systems. These parameters include the shaping of a transmission pulse in some manner or the variation of the time occurrence of a pulse. The commonly used systems of pulse modulation are listed below.

PAM – pulse amplitude modulation

PIM – pulse intensity modulation

PDM – pulse duration modulation

PPM – pulse position modulation

In radio or optical frequency Type II communication systems a burst of the carrier is transmitted. The envelope of the carrier forms a pulse, and it is the amplitude, duration, or position of this pulse envelope that carries the transmitted information.

In pulse intensity modulation, PIM, the signal keys the carrier on and off.

TYPE III MODULATION SYSTEMS

Probability of error relationships are given for various PCM radio and optical communication systems.

In Type III modulation systems the signal parameter is quantized, and the signal is time sampled. A finite number of waveforms is used to represent each signal sample; the smallest number of waveforms is, of course, two. Modulation systems employing only two transmitter waveforms are called pulse code modulation (PCM) systems. Systems employing a large number of waveforms have found little application in communications to date but hold promise of improved performance over two level systems.

In theory the two transmitter waveforms of PCM could take any form. For optimum detection the waveforms should be the negative of each other or orthogonal. The usual forms of the transmitted waveforms are rectangular pulses. PCM data can be conveyed by several means: a burst of the carrier of the absence of it –, intensity modulation, PCM/IM; amplitude modulation, PCM/AM; a carrier of two possible frequencies –, frequency shift keying, PCM/FM; a carrier with a 0- or 180-degree phase relationship – phase shift keying, PCM/PM; or a carrier of right- or left-hand polarization – polarization shift keying, PCM/PL.

Probability of detection error expressions are summarized in the Table.

P_{SN}^{B}	probability that signal plus noise photoelectron count equals or exceeds decision threshold during a bit period
P_{SN}^{P}	probability that signal plus noise photoelectron count equals or exceeds decision threshold during a sample period
P_{N}^{B}	probability that noise photoelectron count equals or exceeds decision threshold during a bit period
P_{N}^{P}	probability that noise photoelectron count equals or exceeds decision threshold during a sample period
P_e	probability of bit detection error
P'_e	probability of sample detection error
$\mu_{N,B}$	average number of noise photoelectrons emitted in a bit period
$\mu_{S,B}$	average number of signal photoelectrons emitted in a bit period
$\mu_{N,P}$	average number of noise photoelectrons emitted in a sample period
$\mu_{S,P}$	average number of signal photoelectrons emitted in a sample period

Probability of Error Expressions

System	Detection Statistics	Expression
Optical PCM/IM (threshold detection)	Poisson	$P_e = \frac{1}{2}\left(1 + P_N^B - P_{SN}^B\right)$ where $P_N^B = \sum_{k=N_t^B}^{\infty} \frac{\left(\frac{\mu_{N,B}}{L}\right)^k \exp\left\{-\left(\frac{\mu_{N,B}}{L}\right)\right\}}{k!}$ $P_{SN}^B = \sum_{k=N_t^B}^{\infty} \frac{\left(\mu_{S,B} + \mu_{N,B}\right)^k \exp\left\{-\left(\mu_{S,B} + \mu_{N,B}\right)\right\}}{k!}$ where N_t = greatest interger value of k_t^B $k_t^B = \frac{\mu_{S,B}}{\ln\left[1 + \frac{\mu_{S,B}}{\mu_{N,B}}\right]}$
Radio PCM/AM (noncoherent detection)	Gaussian	$P_e = \frac{1}{2}\exp\left\{-\frac{K^2}{2N_o}\right\}\left[1 + \exp\left\{-\frac{2E}{N_o}\right\}\right]\sum_{m=1}^{\infty}\left\|\frac{K}{2\sqrt{E}}\right\|^m I_m\left(\frac{2K\sqrt{E}}{N_o}\right)$ where K is defined by $\frac{2E}{N_o} = \ln I_o\left(\frac{2\sqrt{E}K}{N_o}\right)$
Radio PCM/AM (coherent detection)	Gaussian	$P_e = \frac{1}{2}\left[1 - \text{erf}\sqrt{\frac{E}{2N_o}}\right]$
Optical PCM/PL	Poisson	$P_e = 1 - \exp\left\{\left(\mu_{S,B} + \mu_{N,B}\right)\right\}\sum_{j=1}^{\infty}\left[\frac{2\mu_{S,B} + \frac{\mu_{N,B}}{2}}{\mu_{N,B}}\right]^{j/2} I_j\left[\sqrt{2\left(\mu_{S,B} + \frac{\mu_{N,B}}{2}\right)\mu_{N,B}}\right]$ $+ \frac{1}{2} I_o\left[\sqrt{2\left(\mu_{S,B} + \frac{\mu_{N,B}}{2}\right)\mu_{N,B}}\right]$
Optical PCM/FM (heterodyne detection)	Gaussian	$P_e = \frac{1}{2}\exp\left\{-\frac{1}{2}\left[\frac{S}{N}\right]_{IF}\right\}$
Radio PCM/FM (noncoherent detection)	Gaussian	$P_e = \frac{1}{2}\exp\left\{-\frac{E}{2N_o}\right\}$

TYPE III MODULATION SYSTEMS

System	Detection Statistics	Expression
Radio PCM/FM (coherent detection)	Gaussian	$P_e = \frac{1}{2}\left[1 - \text{erf}\sqrt{\frac{E}{2N_o}}\right]$
Radio PCM/AM (coherent detection)	Gaussian	$P_e = \frac{1}{2}\left[1 - \text{erf}\sqrt{\frac{E}{N_o}}\right]$
Radio PCM/AM (differentially coherent detection)	Gaussian	$P_e = \frac{1}{2}\exp\left\{-\frac{E}{N_o}\right\}$
Optical PPM (threshold detection)	Poisson	$P_e' = \left[1 - \frac{P_{SN}^P}{LP_N^P}\right] + \left[\frac{\left(1 - P_N^P\right)^{L-1}}{LP_N^P}\right]\left[P_{SN}^P - P_N^P\right]$ where $P_N^P = \sum_{k=N_t}^{\infty} \frac{\left(\frac{\mu_{N,P}}{L}\right)^k \exp\left\{-\left(\frac{\mu_{N,P}}{L}\right)\right\}}{k!}$ $P_{SN}^P = \sum_{k=N_t^P}^{\infty} \frac{\left(\mu_{S,P} + \frac{\mu_{N,P}}{L}\right)^k \exp\left\{-\left(\mu_{S,P} + \frac{\mu_{N,P}}{L}\right)\right\}}{k!}$ N_t^P = greatest integer value of k_T^P $k_t^P = \frac{\mu_{S,P} + \ln(L-1)}{\ln\left[1 + \frac{L\mu_{S,P}}{\mu_{N,P}}\right]}$

L number of time positions

E Signal energy per bit

N_O noise spectral density

$\left[\frac{S}{N}\right]_{IF}$ intermediate frequency output power signal-to-noise ratio

OPTICAL PULSE CODE INTENSITY MODULATION

Probability of bit-error for an intensity modulated optical carrier is derived and plotted as a function of signal and background photoelectrons.

In the optical PCM/IM system, signal photons are transmitted for a "one" bit and no signal photons are transmitted for a "zero" bit. Let

P_{SN}^B = probability that the signal plus noise photoelectron count equals or exceeds decision threshold N_T during a bit period.

P_N^B = probability that the noise photoelectron count equals or exceeds decision threshold N_T during a bit period.

Then, based upon Poisson detection statistics, the signal plus noise and noise detection probabilities are

$$P_{SN}^B = \sum_{i=N_t^B}^{\infty} \frac{\left(\mu_{S,B} + \mu_{N,B}\right)^i \exp\left\{-\left(\mu_{S,B} + \mu_{N,B}\right)\right\}}{i\,!}$$

$$P_N^B = \sum_{i=N_t^B}^{\infty} \frac{\left(\mu_{N,B}\right)^i \exp\left\{-\left(\mu_{N,B}\right)\right\}}{i\,!}$$

where

$\mu_{S,B}$ = average number of signal photoelectrons emitted by photodetector per bit period

$\mu_{N,B}$ = average number of noise photoelectrons emitted by photodetector per bit period.

The optimum threshold, N_t^B, is the greatest integer value of the likelihood ratio threshold, k_T^B, where

$$k_t^B = \frac{\mu_{S,B} + \ln\left(\frac{p}{1-p}\right)}{\ln\left[1 + \frac{\mu_{S,B}}{\mu_{N,B}}\right]}$$

where

p = a priori probability of transmitting a "one" bit.

The probability of a bit error is then

$$P_e = \left[\text{probability that a "one" is transmitted}\right] \cdot \left[\begin{array}{l}\text{probability that signal plus noise does not} \\ \text{exceed threshold}\end{array}\right] + \left[\text{probability that a "zero" is transmitted}\right] \cdot \left[\text{probability that noise equals or exceeds threshold}\right]$$

Thus,

$$P_e = (p)\left(1 - P_{SN}^{B}\right) + (1 - p)\left(P_N^{B}\right)$$

For

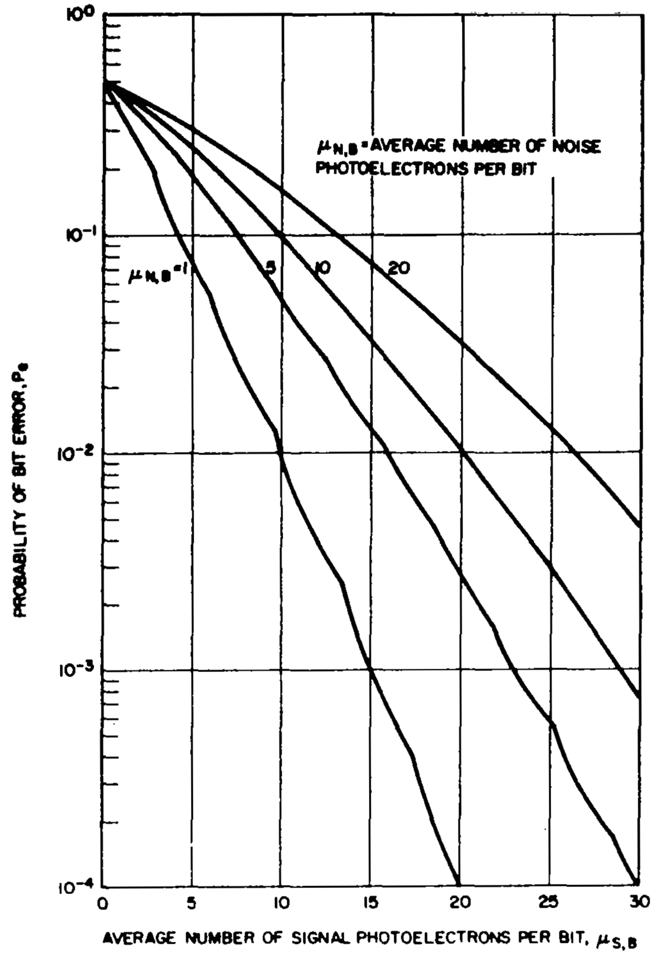
$$p = \frac{1}{2}$$

$$P_e = \frac{1}{2}\left[1 - P_{SN}^{B} + P_N^{B}\right]$$

In terms of the detection probabilities

$$P_e = \frac{1}{2}\left\{1 - \exp\left\{-(\mu_{N,B})\right\} \sum_{i=N_T}^{\infty}\left[\frac{\left(\mu_{S,B} + \mu_{N,B}\right)^i \exp\left\{-\left(\mu_{S,B}\right)\right\} - \left(\mu_{N,B}\right)^i}{i\,!}\right]\right\}$$

The Figure shows the probability of detection error as a function of the signal and noise photoelectron counts per bit period.



Probability of Error for PCM/IM
Laser Communication System

OPTICAL PCM POLARIZATION MODULATION

Probability of bit error for a polarization modulated optical carrier is derived and plotted as a function of signal and background photoelectrons.

In the optical PCM/PL system, the carrier is transmitted in right circular polarization to represent a "one" bit, and in left circular polarization to represent a "zero" bit. The probability of detection error may now be derived for the difference detection model illustrated in Figure A. Let

X = right detector output

Y = left detector

Z = X - Y

Assuming that the laser carrier is right circularly polarized, a detection error will occur when Y > X with probability 1, or when Z = 0 with probability of 1/2. By symmetry of the channels the probability of error is

$$P_e = 1 + \frac{1}{2} P(Z = 0) - \sum_{j=0}^{\infty} P(Z = j)$$

The term P (Z = j) may be determined by summing over the joint distribution of the output channel yielding a difference, Z = j.

$$P(Z = j) = \sum_{m=0}^{\infty} P(X = j + m)\, P(Y = m) \qquad \text{for } j \geq 0$$

where based upon Poisson detection statistics, the detection probabilities of the X and Y channels are

$$P(X = i) = \frac{\left(\mu_{S,B} + \mu_{N,B,R}\right)^{i} \exp\left\{-\left(\mu_{S,B} + \mu_{N,B,R}\right)\right\}}{k\,!}$$

$$P(Y = i) = \frac{\left(\mu_{N,B,L}\right)^{i} \exp\left\{-\left(\mu_{N,B,L}\right)\right\}}{i\,!}$$

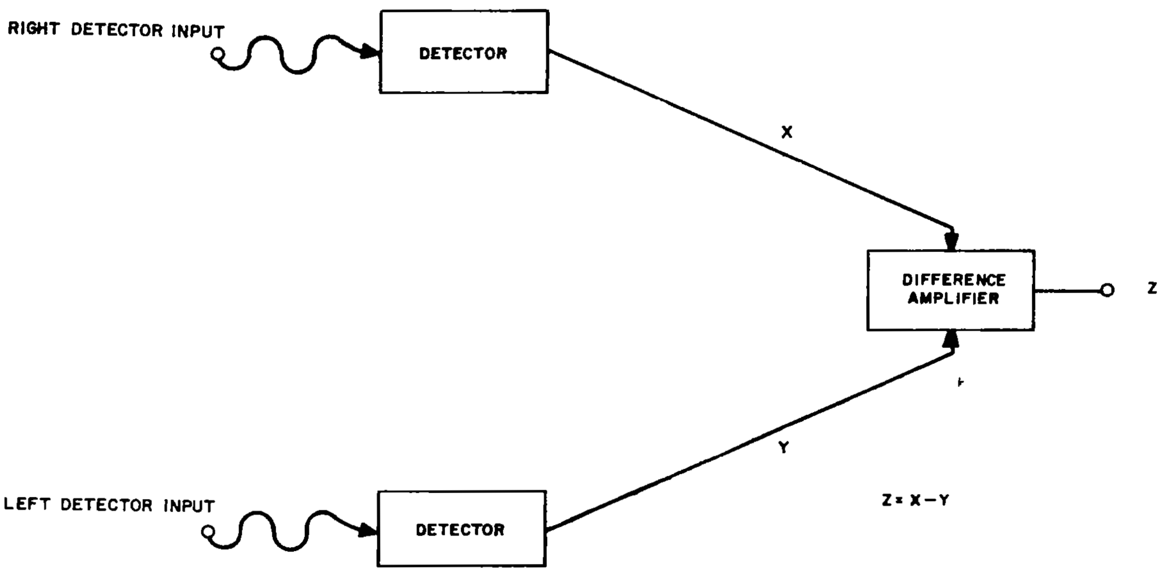


Figure A. Difference Channel Detection Method

OPTICAL PCM POLARIZATION MODULATION

where

$\mu_{S,B}$ = average number of signal photoelectrons released by right detector per bit interval

$\mu_{N,B,R}$ = average number of right channel noise photoelectrons released by right detector per bit interval

$\mu_{N,B,L}$ = average number of left channel noise photoelectrons released by left detector per bit interval

In terms of the detection statistics the probability of detection error is

$$P_e = \left[1 - \exp\left\{ - \left(\mu_{S,B} + \mu_{N,B,R} + \mu_{N,B,L}\right)\right\} \sum_{j=0}^{\infty} \sum_{m=0}^{\infty} \frac{\left(\mu_{S,B} + \mu_{N,B,R}\right)^j \left[\left(\mu_{S,B} + \mu_{N,B,R}\right)\left(\mu_{N,B,L}\right)\right]^m}{m!\,(j+m)!} \right]$$

$$+ \frac{1}{2} \exp\left\{ - \left(\mu_{S,B} + \mu_{N,B,R} + \mu_{N,B,L}\right)\right\} \sum_{m=0}^{\infty} \frac{\left[\left(\mu_{S,B} + \mu_{N,B,R}\right)\left(\mu_{N,B,L}\right)\right]^m}{m!\,m!}$$

If the average value of the shot noise is the same in both detectors let

$$\mu_{N,B,R} = \mu_{N.B,L} \equiv \frac{\mu_{N,B}}{2}$$

then the probability of detection error can be written in terms of modified bessel functions.

$$P_e = 1 - \exp\left[- \left(\mu_{S,B} + \mu_{N,B}\right)\right] \sum_{j=1}^{\infty} \left[\frac{2\left(\mu_{S,B} + \frac{\mu_{N,B}}{2}\right)}{\mu_{N,B}} \right]^{\frac{j}{2}} I_j \left[\sqrt{2\left(\mu_{S,B} + \frac{\mu_{N,B}}{2}\right) \mu_{N,B}} \right]$$

$$+ \frac{1}{2} I_o \left[\sqrt{2\left(\mu_{S,B} + \frac{\mu_{N,B}}{2}\right) \mu_{N,B}} \right]$$

Figure B shows the probability of detection error for the PCM/PL system as a function of the signal and noise photoelectron counts.

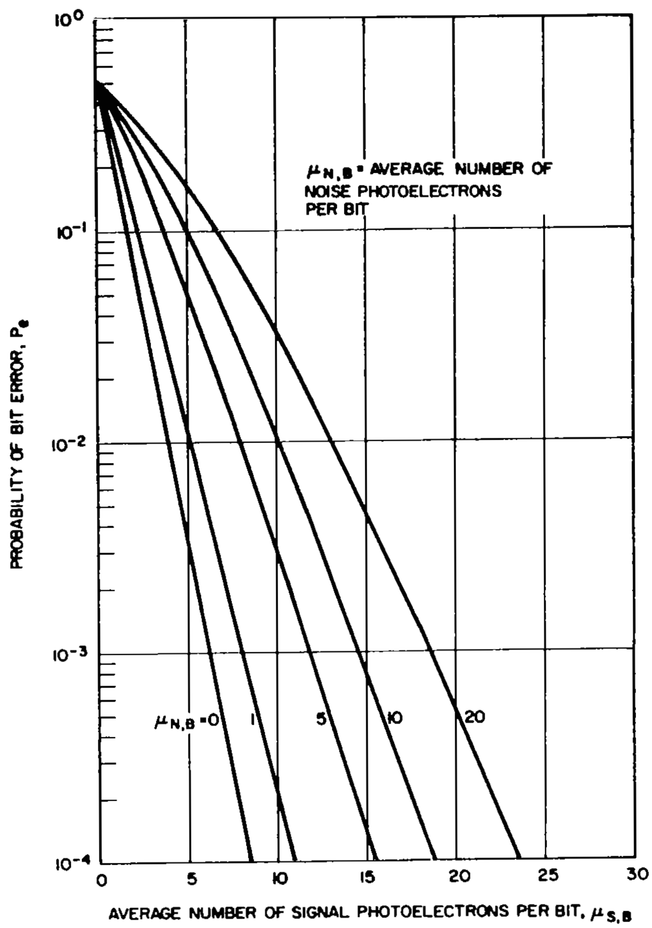


Figure B. Probability of Detection Error for PCM/PL Laser Communication System

OPTICAL PCM FREQUENCY MODULATION

By assuming Gaussian statistics, an expression for probability of error is derived and plotted for optical frequency modulation.

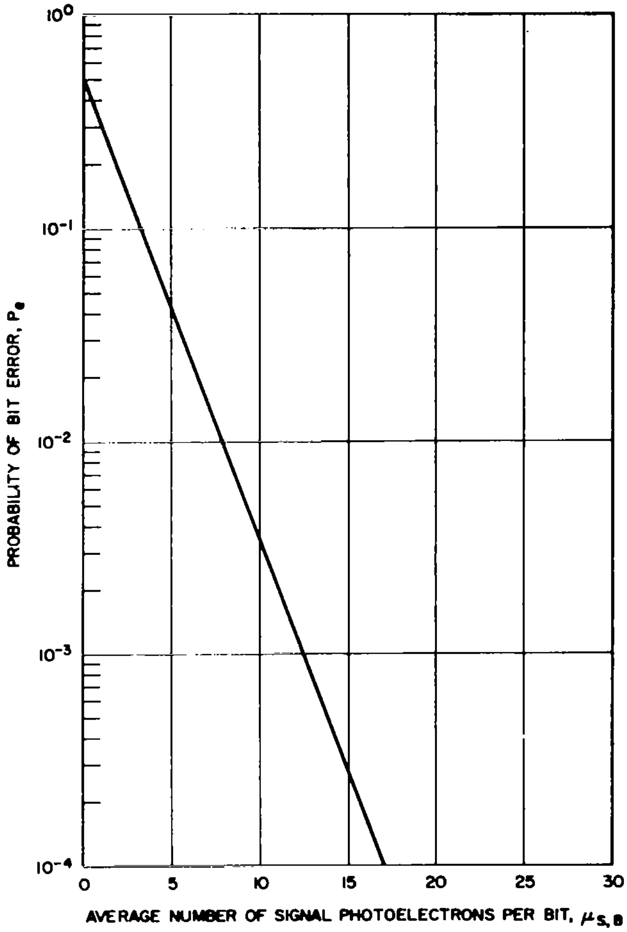
In the optical PCM frequency modulation system information is conveyed by transmission of the carrier at one of two different frequencies to represent "one" and "zero" bits. Demodulation could conceivably be performed by placing two optical filters, centered at the two possible carrier frequencies, before a pair of photodetectors. The detection model would then be the same as that for polarization modulation. However, optical filters at present are extremely wide band and do not exhibit sharp frequency cutoff properties. Therefore, spectral isolation of the transmitted frequencies is not simple. Frequency demodulation may be performed by heterodyning the laser carrier to an IF frequency where a standard radio frequency FM receiver can provide frequency detection.

Unfortunately, little is presently known of the detection statistics of a heterodyne receiver. It is possible, however, to determine an expression for the probability of error of a heterodyne PCM/FM system by assuming that the IF output noise is Gaussian. Then, from the theory of radio frequency detection,[1] the probability of error at the FM receiver output is

$$P_e = \frac{1}{2} \exp \left\{ - \frac{1}{2} \left[\frac{S}{N}\right]_{IF} \right\}$$

where $[S/N]_{IF}$ is the signal-to-noise ratio at the IF output of the heterodyne receiver. The Figure gives the probability of detection error as a function of the signal photoelectron counts.

[1] Pratt, W.K., "Binary Detection in an Optical Polarization Modulation Communication Channel," IEEE Transactions on Communication Technology, October 1966.



Probability of Detection Error for PCM/FM Laser Communication System

OPTICAL PPM INTENSITY MODULATION

Probability of bit error for a PPM intensity modulated optical carrier is derived and plotted as a function of signal and background photoelectrons.

In the optical PPM system, signal photons are transmitted in one of L time slots. Let

P_{SN}^{P} = probability that the signal plus noise photoelectron count equals or exceeds the decision threshold N_T during a sample period.

P_{N}^{P} = probability that the noise photoelectron count equals or exceeds the decision threshold N_T during a sample period.

Then, based upon Poisson detection statistics, the signal plus noise and noise detection probabilities are

$$P_{SN}^{P} = \sum_{i=N_t^P}^{\infty} \frac{\left(\mu_{S,P} + \frac{\mu_{N,P}}{L}\right)^i \exp\left\{-\left(\mu_{S,P} + \frac{\mu_{N,P}}{L}\right)\right\}}{i\,!}$$

$$P_{N}^{P} = \sum_{i=N_t^P}^{\infty} \frac{\left(\frac{\mu_{N,P}}{L}\right)^i \exp\left\{-\left(\frac{\mu_{N,P}}{L}\right)\right\}}{i\,!}$$

where

$\mu_{S,P}$ = average number of signal photoelectrons emitted by photodetector per sample period

$\mu_{N,P}$ = average number of noise photoelectrons emitted by photodetector per sample period

The optimum threshold N_t^P is the greatest integer value of the likelihood ratio threshold k_t^P where

$$k_t^P = \frac{\mu_{S,P} + \ln\left[\sum_{i=1}^{\infty} p_i (1 - p_i)\right]}{\ln\left[1 + \frac{L\mu_{S,P}}{\mu_{N,P}}\right]}$$

where

p_i = *a priori* probability of transmitting a signal in the i^{th} slot.

The probability of a sample error is then

$$P_e' = \begin{bmatrix}\text{probability that noise equals or exceeds threshold before} \\ \text{signal slot}\end{bmatrix}$$

$$+ \begin{bmatrix}\text{probability that noise equals or exceeds threshold} \\ \text{after signal slot, given signal plus noise does not} \\ \text{equal or exceed threshold}\end{bmatrix}$$

$$+ \begin{bmatrix}\text{probability that neither noise} \\ \text{nor signal plus noise equals} \\ \text{or exceeds threshold}\end{bmatrix} \begin{bmatrix}\text{probability of} \\ \text{incorrect random} \\ \text{choice}\end{bmatrix}$$

Then,

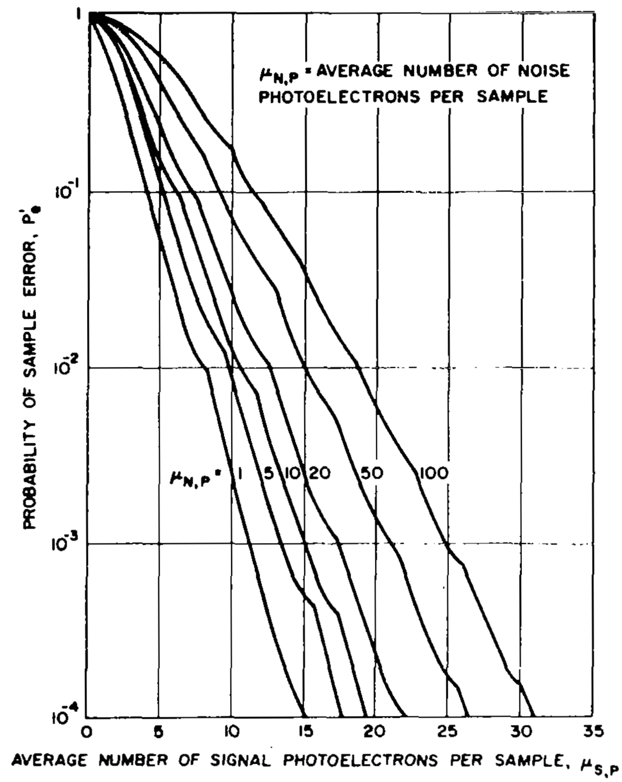
$$P_e' = \sum_{i=1}^{L} p_i \left[1 - \left(1 - P_N^P\right)^{i-1}\right] + \sum_{i=1}^{L} p_i \left(1 - P_N^P\right)^{i-1} \left(1 - P_{SN}^P\right)$$

$$\left[1 - \left(1 - P_N^P\right)^{L-i}\right] + \left(1 - P_N^P\right)^{L-1} \left(1 - P_{SN}^P\right) \sum_{i=1}^{L} p_i (1 - p_i)$$

For a uniform source distribution, $p_i = 1/L$, the probability of error is

$$P_e' = \left(1 - \frac{P_{SN}^P}{LP_N^P}\right) + \frac{\left(1 - P_N^P\right)^{L-1}}{L P_N^P} \left(P_{SN}^P - P_N^P\right)$$

The Figure illustrates the probability of detection error as a function of the signal and noise photoelectron counts per sample period.



Probability of Detection Error for
PPM/IM Threshold Detection
Laser Communication
System

RADIO AMPLITUDE, FREQUENCY, AND PULSE CODE MODULATION

Signal to noise ratio relationships are given for amplitude and frequency modulation and probability of error relationships are given for pulse code modulation.

Figure A illustrates the components to be considered for either an analog or digital radio communication system.

Radio Amplitude Modulation

In the radio amplitude modulation (AM) system the amplitude of the carrier is directly proportional to the amplitude of an information signal.

Radio AM transmission is normally done in one of three ways, conventional AM (carrier present), double sideband AM (no carrier present), and single sideband AM (no carrier present). An important relationship in these three transmission variations is the relationship of the radio frequency or intermediate frequency signal to noise ratio $[S/N]_{IF}$ to the signal-to-noise ratio at the output of a peak detector, $[S/N]_D$, measured in the information bandwidth, B. These relationships are given below. It should be noted that the r-f or i-f bandwidth required for single sideband AM is one half that of double sideband AM and conventional AM.

For conventional AM

$$\left[\frac{S}{N}\right]_D = \left[\frac{m_a^2}{1 + \frac{m_a^2}{2}}\right]\left[\frac{S}{N}\right]_{IF} \quad \text{For } \left[\frac{S}{N}\right]_{IF} > 10$$

where m_a is the modulation index ($0 < ma < 1$).

For double sideband AM

$$\left[\frac{S}{N}\right]_D = 2\left[\frac{S}{N}\right]_{IF}$$

For single sideband AM

$$\left[\frac{S}{N}\right]_D = \left[\frac{S}{N}\right]_{IF}$$

Radio Frequency Modulation

In the radio frequency modulation system the frequency of the carrier is set proportional to the amplitude of an information signal. The instantaneous phase $\phi_c(t)$ of the carrier is

$$\phi_c(t) = m_f \int_{-\infty}^{t} x(t)\, dt$$

where x(t) represents the information signal and m_f is the frequency modulation index (m_f = peak carrier frequency deviation/modulating frequency).

The relationship between the r-f or i-f signal to noise ratio, $[S/N]_{IF}$, measured in a bandwidth B_{IF} and the detected signal-to-noise ratio measured in a bandwidth, B, for a sine wave modulation of frequency f_m, is given by:

$$\left[\frac{S}{N}\right]_D = \left[\frac{3\ B_{IF}\ m_f^2}{2\ f_m}\right]\left[\frac{S}{N}\right]_{IF}$$

Radio PCM Amplitude Modulation

In the radio PCM/AM system, a signal carrier is transmitted for a "one" bit and no signal carrier is transmitted for a "zero" bit. The probability of detection error for detection in the presence of white Gaussian noise is.[1]

Noncoherent Detection

$$P_e = \frac{1}{2} \exp\left\{-\frac{K^2}{2\,N_o}\right\}\left[1 + \exp\left\{-\frac{2\,E}{N_o}\right\}\right] \sum_{m=1}^{\infty} \left[\frac{K}{2\sqrt{E}}\right]^m I_m \left[\frac{2\,K\sqrt{E}}{N_o}\right]$$

Coherent Detection

$$P_e = \frac{1}{2}\left[1 - \operatorname{erf}\sqrt{\frac{E}{2\,N_o}}\right]$$

where K is defined by

$$\frac{2E}{N_o} = \ln I_o \left(\frac{2\sqrt{E}\,K}{N_o}\right)$$

[1] Lawton, J. G., "Comparison of Binary Data Transmission Systems," Proceedings Second National Convention on Military Electronics, 1958.

RADIO AMPLITUDE, FREQUENCY, AND PULSE CODE MODULATION

and where

E = signal energy per bit

N_o = noise power spectral density

Figure B shows the probability of detection error as a function of the ratio E/N_o.

Radio PCM Frequency Modulation

In the radio PCM frequency modulation system information is conveyed by transmission of the carrier at one of two frequencies to represent "one" and "zero" bits. The probability of detection error for detection is the presence of white Gaussian noise is *.

Noncoherent Detection

$$P_e = \frac{1}{2} \exp \left\{ - \frac{E}{2 N_o} \right\}$$

Coherent Detection

$$P_e = \frac{1}{2} \left[1 - \operatorname{erf} \sqrt{\frac{E}{2 N_o}} \right]$$

Figure B shows the probability of detection error as a function of the ratio E/N_o.

Radio PCM Phase Modulation

In the radio PCM/PM system, the carrier is transmitted at one of two phase angles 180 degrees apart to represent "one" and "zero" bits. The probability of detection error for detection in the presence of white Gaussian noise is,

Coherent Detection

$$P_e = \frac{1}{2} \left[1 - \operatorname{erf} \sqrt{\frac{E}{N_o}} \right]$$

Differentially Coherent Detection

$$P_e = \frac{1}{2} \exp \left\{ - \frac{E}{N_o} \right\}$$

The Figure shows the probability of detection error as a function of the ratio E/N_o.

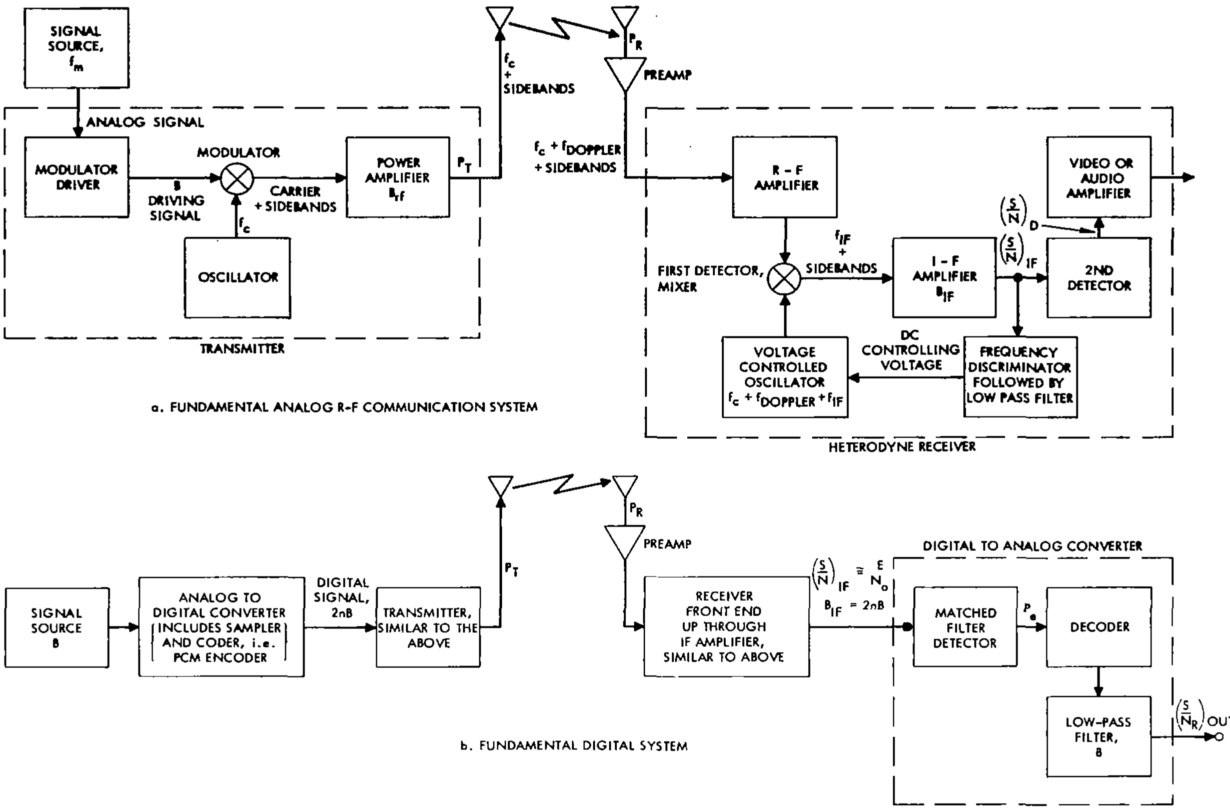
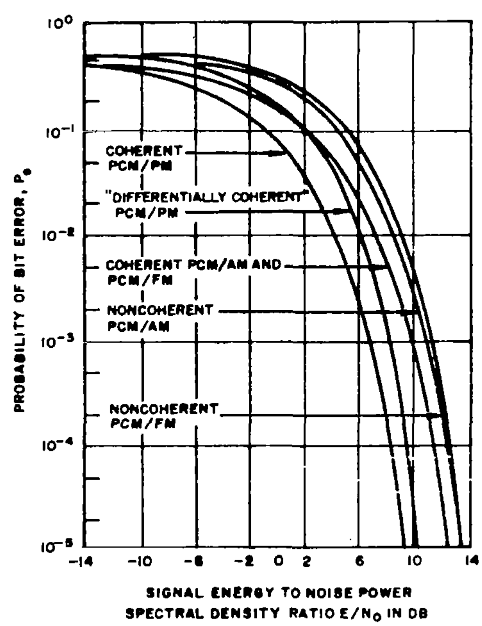


Figure A. Fundamental Analog (RF) and Digital (RF and/or Optical) Communication Systems, Block Diagram

Figure B. Probability of Detection Error for PCM Radio Communication Systems



PSEUDO RANDOM NOISE MODULATION FOR RADIO COMMUNICATIONS SYSTEMS

The basic concept of pseudo random noise modulation is to communicate data values by means of orthogonal code words.

Pseudo random noise (PRN) can be used in such a manner as to encode a word message. If an exact replica of the PRN sequence is available at the receiver, correlation detection can take place; if not, the detection process is non-coherent.

Viterbi[1] of the Jet Propulsion Laboratory has analyzed several forms of block type coding systems. He has included the use of pseudo random noise in these coding methods. The basic model is shown in the Figure. The analysis runs as follows:

In order to communicate n bits of information, 2^n degrees of freedom must be available at the transmitter. These 2^n arbitrary messages or words are to be stored or generated at the transmitter. Depending on the information to be sent, one of the 2^n words is sent over a period of nT seconds; T being the transmission time allotted per bit. The communications channel is assumed to add an arbitrary disturbance to the transmitted signal. The ideal receiver computes the conditional probability that each of the possible 2^n words was transmitted over the interval of nT seconds, given the received word. It has been shown that if the channel disturbance is white gaussian noise, the probability computer consists of 2^n correlators which multiply the incoming signal by each of the 2^n stored or locally generated replicas of the possible transmitted words, integrate over the transmission interval, and are sampled at the end of this time. Thus, the output of the k th correlator, which corresponds to the k th word x_k is

$$\int_0^{nT} x_k(t)\, y(t)\, dt$$

where

$$y(t) = x_m(t) + N(t)$$

$x_m(t)$ is the received signal, and N(t) is the channel noise. If the 2^n words were a priori all equally likely to be transmitted with equal energy, i. e., $P(x_i) = P(x_j)$ and

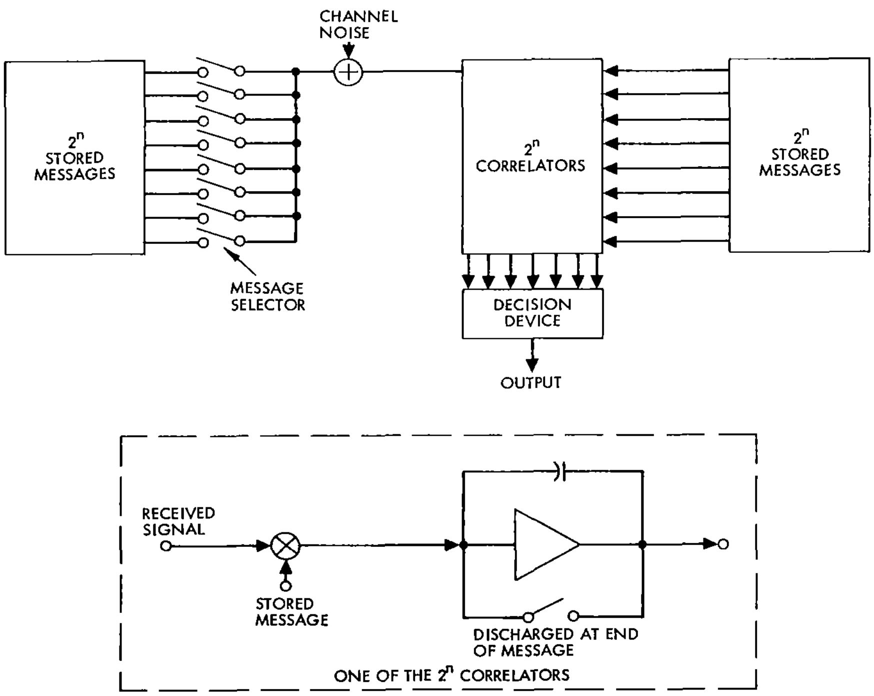
$$\int_0^{nT} x_k(t)\, y(t)\, dt.$$

[1] Viterbi, A. J., "On Coded Phase-Coherent Communications," IRE Trans. on Space Elect. and Comm., Set-7, March 1961.

It follows intuitively that in order to achieve low error probabilities, the waveforms should be as unlike as possible, such that in a noisy channel there will be the least possible chance to make the wrong selection of the word transmitted. More precisely, the cross-correlation coefficients among all pairs of words,

$$P = \frac{\int_{o}^{nT} x_i(t)x_j(t)dt}{\left[\int_{o}^{nT} x_i^{\,2}(t)dt + \int_{o}^{nT} x_j^{\,2}(t)dt\right]^{1/2}}$$

should be as low as possible. Low cross correlation coefficients are obtained by various coding combinations.



The Basic Model

SYSTEM THEORY

Communication Coding

COMMUNICATION CODING

DATA COMPRESSION

Data compression can be applied to engineering data, scientific data, or pictorial data. The reduction in equivalent bit rate is as high as a factor of 10.

A generalized block diagram of the coding elements of a communication system is shown in the Figure. The source coder at the transmitter is the equipment that converts the source data — e. g. , TV, voice, scientific information — into a sequence of code bits of minimum possible length. The receiver source decoder performs the inverse operation of reproducing the source data from the code bits. The operation of source coding and decoding is denoted as data conditioning and reconstruction.

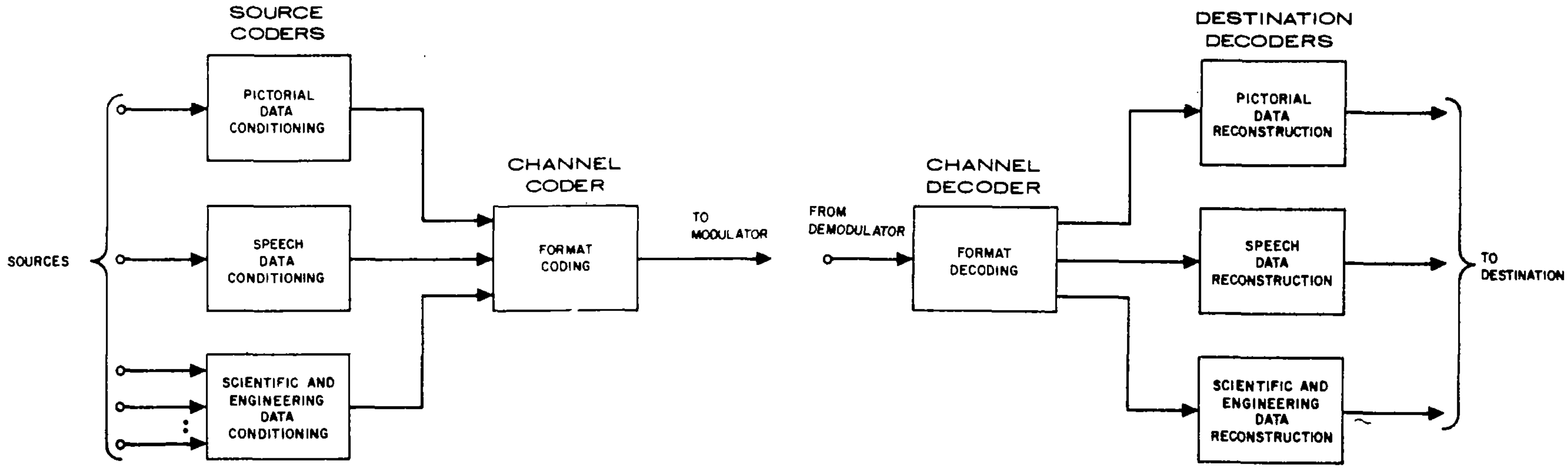
The channel coding equipment at the transmitter puts the source message sequence in a form that will minimize the effects of channel noise. At the receiver the channel decoding equipment reconstructs the source message sequence. The channel coding and decoding operations are performed by the format coding and decoding equipment. In addition, the format coding operation consists of message arrangement and identification for transmission.

Data Compression

Data conditioning offers the possibility of an increase in the information rate of a communication system after optimum coding and modulation techniques have been applied to the system, and when the physical limits of communications equipment have been reached. The information rate increase is realized by transforming the source data, by an elimination of redundancy, into a form in which fewer symbols are required to describe the data. The theoretical possibilities of this type of data compression for voice and picture communication are enormous. Data compression for scientific and engineering data is a function of the type of data but, in general, scientific data is capable of a large amount of reduction. The Table presents estimates of source bit rate reduction possible with various techniques of compression schemes.

It would be desirable to employ a single, simple data compression device for all classes of data in a generalized communication system. However, such a device has not been developed or even approached to date. The most promising path to the realization of a generalized data compressor in the near future seems to be the development of separate compression schemes for the three main classes of data — pictorial, speech, scientific, or engineering. In such a system, the physical characteristics of each class of data can be employed to realize practical data compression most efficiently.

Source Bit Rate Reduction



a. Transmitting System

Communication Coding

Source Bit Rate Reduction

Type of Data	Bandwidth	PCM Equivalent	Delta Coding	Stop Scan Edge Detection	Multiple Interlace Encoding	Predictive Coding	Vocoding
Scientific	0 to 1 KHZ	Up to 18 kilobits/ second				Up to 6 kilobits/ second	
Engineering	0 to 1 KHE	Up to 18 kilobits/ second				Up to 6 kilobits/ second	
Pictorial information (real-time TV)	4 MHZ	48 megabits/ second	24 megabits/ second	12 megabits/ second	12 megabits/ second		
Voice	4 KHZ	40 kilobits/ second	20 kilobits/ second				3 to 6 kilobits/ second

SYNCHRONIZATION

Time synchronization is required for digital transmission, a variety of synchronizing methods are received.

Time division modulation systems, such as PCM and PPM, require synchronization between the transmitting and receiving equipment to ensure accurate decoding. The degree to which synchronization is established directly affects the signal-to-noise performance of a communications system.

Accurate timing references can be generated at the receiving terminal of a PPM communication system by using synchronization information contained in the transmitted waveform without using additional transmitter power for this purpose. Synchronization can best be made where each successive waveform is guaranteed to possess a unique characteristic or where each succeeding waveform is guaranteed to be in some way different from its predecessor. For example, a PPM system may convey frame synchronization by making one of its bursts of information wider than any other in the sequence.

In PCM modulation systems, a receiving station must lock in frequency and phase on the transmitted digital rates to fulfill its requirement to gain synchronization. This lock must be achieved and maintained even when the transmission medium is noisy for the data to be interpreted correctly. The synchronizer must have the ability to detect transmitted sync codes even when they are corrupted with erroneous bits, to verify that the detected codes are transmitted periodically, to compute the detected code frequency of occurrence, and to measure the mean error rate to ascertain whether or not the detected code is compatible with the expected code. Usually several levels of synchronization exist concurrently in a PCM telemeter format – bit, word, frame, and subframe synchronization.

The PCM synchronizer must operate in three different modes: (1) the search mode during which the synchronizer looks throughout the transmitted PCM data for the synchronization pattern; (2) the check mode during which the synchronizer verifies that the pattern found in search does occur periodically, which will increase the probability for that pattern to be transmitted synchronization code; and (3) the lock mode during which the synchronizer will put the emphasis on its fly-wheel characteristics to maintain lock as long as the mean error rate is compatible.

Word synchronization has been accomplished by the separation of words in time by a pulse of a different amplitude, or by a special code consisting of a few bits. Because of its bandwidth requirements, word synchronization has fallen into disuse. Frame synchronization is usually accomplished by transmitting a special code every time the basic commutator recycles. This code must be detected by the frame synchronizer, which in turn resets the decommutator word-per-frame counter. Whenever the telemeter format involves a solid word synchronization, it is possible to forbid the generation of any given code sequence, and therefore the frame sync code pattern is unique, but only if a noise-free transmission link is assumed. In the absence of word sync patterns, uniqueness is impossible to preserve since adjacent portions of sequential words may create a spurious code pattern. A known solution for the problem of quasi-static data, which may construe data bits into a sync code pattern, is the alternative transmission of sync code patterns and their binary complements. This method will completely eliminate the possibility of not acquiring a sync because of the presence of quasi-static data.

Subframe synchronization utilizes two different methods. One — the recycling method — consists of transmitting a code pattern during the basic frame where the subcommutator recycles. This code can be transmitted where the subcommutated primary channel would have a predetermined position within the primary frame independent of the location of the subcommutated channel. The other method — countdown — consists of transmitting the number corresponding to the segment position of the subcommutator every frame. This method requires more bandwidth than the recycling method. The countdown method permits on the average a faster subcommutator sync acquisition but is extremely vulnerable to noise and should be used only where the error rate is expected to be low.

A synchronization process that may be used in a telemetry system is a unique combination of the basic properties of phase-lock groups and quasi-random binary sequences, commonly called pseudo-noise (PN) sequences. A PN sequence, which is odd in length, when phase compared with a duplicate of itself does not look like this duplicate until both sequences are in perfect alignment. Therefore, this process is capable of producing a unique sync pulse rate. The autocorrelation function if a PN sequence is obtained by comparison of adjacent bits in the duplicate sequences. The autocorrelation function — (number of similar bits — number of dissimilar bits)/total number of bits in sequence — will have its numerator equal to 1 whatever the sequences are not in alignment and will equal 0 whenever the sequences are aligned.

SYSTEM THEORY

Telemetry Communications

FM AND FM/FM LINK EQUATIONS[1]

FM improvement formula are given for FM links and FM links using FM subcarriers (FM/FM).

Introduction

The elements of a typical FM or FM/FM transmission link are shown in the Figure. An FM link would begin at the modulator input, and terminate at the carrier demodulator output (after postdetection filtering). The modulating data signals considered will be assumed sinusoids; however, this is not a limitation, since the postdetection SNR derived can be considered to apply to aperiodic signals during their time of occurrence.

The FM/FM link in its most general sense will employ i subcarriers, of different center frequencies and deviations, each frequency modulating the carrier.

TABULATION OF SNR IMPROVEMENT FORMULAE

The glossary of terms is given at the conclusion of this topic. Sinusoidal signal modulation is presumed.

Single FM (same as second detection in FM/FM link)

$$\left(\frac{S}{N}\right)_o = \left[\frac{(1.5)B_{if}(\Delta f_c)^2\ \delta}{(f_m)^3}\right]\left(\frac{S}{N}\right)_{if} \tag{1}$$

(Carson's rule states that the if bandwidth, $b_{if} = 2\,f_m(m+1) = 2\,f_m\left(\frac{\Delta f}{f_m} + 1\right)$)

For ideal link elements, δ, the degradation factor, is set at $\cong 1.0$.

Otherwise, a value of δ can be selected from the appropriate Figures given in the following topic.

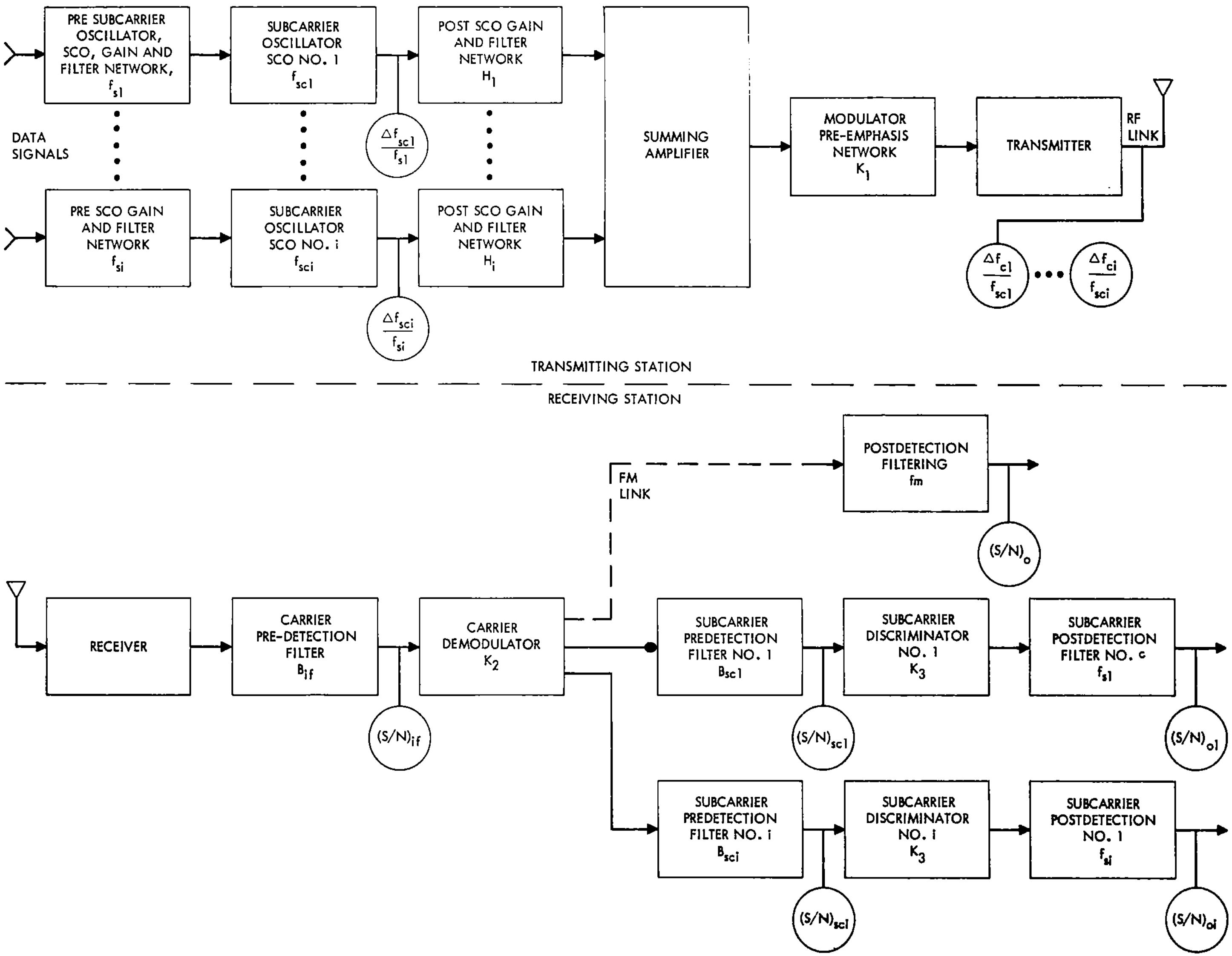
A more general form of Equation (1), which can be used below threshold (defined as the departure from linearity on the SNR transfer characteristic) is given below[2]

$$\left(\frac{S}{N}\right)_o = \left[\frac{1.5\ B_{if}(\Delta f_c)^2\ \delta}{(f_m)^3}\right]\left[\frac{1}{1 + \frac{1}{SNR_{if}} + \frac{2}{(SNR_{if})^2} + \frac{3}{(SNR_{if})^3} + \ldots}\right]\left(\frac{S}{N}\right)_{if} \tag{2}$$

---

[1] Rechter, Robert J., "Summary and Discussion of Signal-to-Noise Ratio Improvement Formulae for FM and FM/FM Links," International Telemetry Conference Proceedings, 2, October 1967, p. 172.

[2] Duncan, John, "FM Demodulator Threshold Reduction," Final Report, No. ERL-8-0009-623, Electronics Research Laboratory.



Typical FM or FM/FM Transmission Link

FM AND FM/FM LINK EQUATIONS

For $SNR_{if} \gg 1$, i.e., the above-threshold case, Equation 2 simplifies to Equation 1.

Subcarrier Predetection SNR Relative to Carrier SNR, in FM/FM Link

$$\left(\frac{S}{N}\right)_{sci} = \left[\frac{3\, B_{if}(\Delta f_{ci})^2}{2(f_{ubei}{}^3 - f_{lbei}{}^3)}\right]\left(\frac{S}{N}\right)_{if} \qquad (3)$$

This is the general form of the equation; for subcarrier peak deviations small in comparison with subcarrier center frequency (i.e., the IRIG channels) Equation 3 can be simplified to

$$\left(\frac{S}{N}\right)_{sci} \cong \left[\frac{B_{if}(\Delta f_{ci})^2}{4\Delta f_{sci}(f_{sci})^2}\right]\left(\frac{S}{N}\right)_{if} \qquad (4)$$

Subcarrier Postdetection SNR, Relative to Carrier Predetection SNR, in a FM/FM Link (Overall SNR)

The general relationship, for sinusoidal modulation, using the approximation of Equation 4.

$$\left(\frac{S}{N}\right)_{oi} \cong \left[\frac{0.375\, B_{if} B_{sci}(\Delta f_{ci})^2\, \Delta f_{sci}}{(f_{sci})^2\,(f_{si})^3}\right]\left(\frac{S}{N}\right)_{if} \qquad (5)$$

B_{if} = Carrier predetection equivalent noise bandwidth, Hz

B_{sci} = Predetection equivalent noise bandwidth of ith subcarrier, Hz

f_c = Carrier center frequency, Hz = $\omega_c/2\pi$

f_{sci} = Center frequency of ith subcarrier, Hz

f_{lbei} = Lower bandedge frequency of ith subcarrier, Hz

f_{ubei} = Upper band edge frequency of ith subcarrier, Hz

f_{si} = Subcarrier postdetection equivalent noise bandwidth, Hz

f_m = Carrier-modulating data baseband, Hz

Δf_c = Peak carrier deviation

Δf_{ci} = Peak carrier deviation due to ith subcarrier, Hz

Δf_{sci} = Peak deviation of ith subcarrier center frequency, Hz

$\Delta f_{ci}/f_{sci}$ = Modulation index of ith subcarrier on the carrier, radians

$\Delta f_{sci}/f_{si}$ = Deviation ratio or ith data signal-subcarrier, radians

$(S/N)_{sci}$ = Signal-to-noise (SNR) ratio in ith subcarrier predetection bandwidth, dB

$(S/N)_{if}$ = Carrier predetection SNR

$(S/N)_{oi}$ = Postdetection SNR of ith subcarrier channel

$(S/N)_{o}$ = Post detection SNR.

DEGRADATION CAUSED BY NONIDEAL POSTDETECTION FILTERING

The degradation caused by postdetection filtering is given for Butterworth, Bessel, and Chebyshev filter functions.

Only in an ideal link is the postdetection degradation factor, δ, unity (see prior topic). Assuming that the degradation of SNR from theoretical rests mainly in the nonideal nature of the FM demodulator postdetection (output) filter, allows the use of Figures A through C(4) to give δ in logarithmic notation for the Butterworth, Bessel, and Chebyshev filter functions. These figures clearly show the very significant degradation due to low order postdetection filtering. For instance, a first order function would result in infinite output noise power, for the mathematically ideal case, since the asymptotic slopes of the noise and filter functions cancel. Even a second order Butterworth results in a $\delta \cong 5.2$ db.

The factor δ is computed as follows

defining

N_o as the spectral density (usually presumed quadratic)

G_j as the postdetection filter amplitude transfer

The total noise power transmitted by a physically realizeable output filter can be computed as follows:

$$P_{or} = \sum_{j=1}^{k} N_{oj} \, G_j^2 \tag{1}$$

The noise power transmitted by a zonal filter, i. e., a filter which has the amplitude transfer characteristic

$$\begin{aligned} G_j &\equiv 1 \text{ over the baseband, } f_s: \\ &\equiv 0 \text{ elsewhere} \end{aligned} \tag{2}$$

is given by

$$P_{oz} = \sum_{j=1}^{k} N_{oj} \tag{3}$$

and the degradation factor, δ, is computed as

$$\delta = 10 \text{ Log} \left[\frac{P_{or}}{P_{oz}}\right] \text{db} \tag{4}$$

Assumptions and Deviations from Ideal Modeling

The degradation δ, from ideal SNR improvement previously defined, presumed quadratic postdetection noise spectral density. In actuality, nonzonal predetection filtering will tend to make the postdetection noise spectrum less than quadratic, thus reducing the magnetude of δ, as can be observed in Figure D, if $B_{if}/2 \gg f_{si}$, is the baseband. In any case, a precise evaluation of δ would require proper shaping of the output noise spectrum, to account for nonzonal predetection filtering.

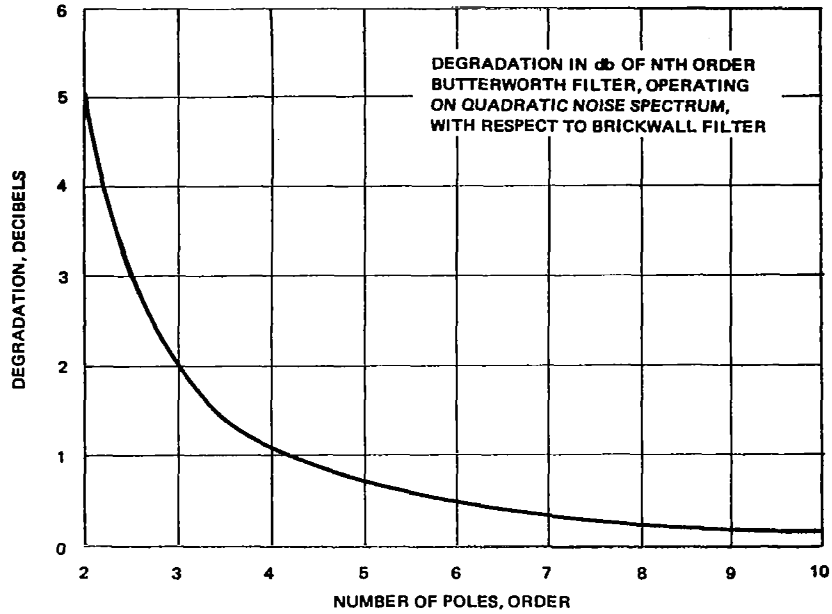


Figure A

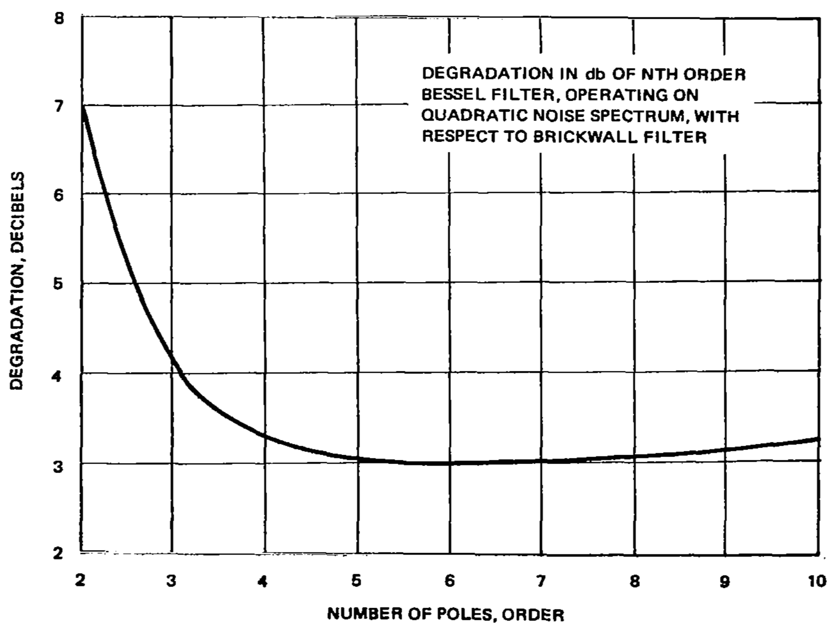


Figure B

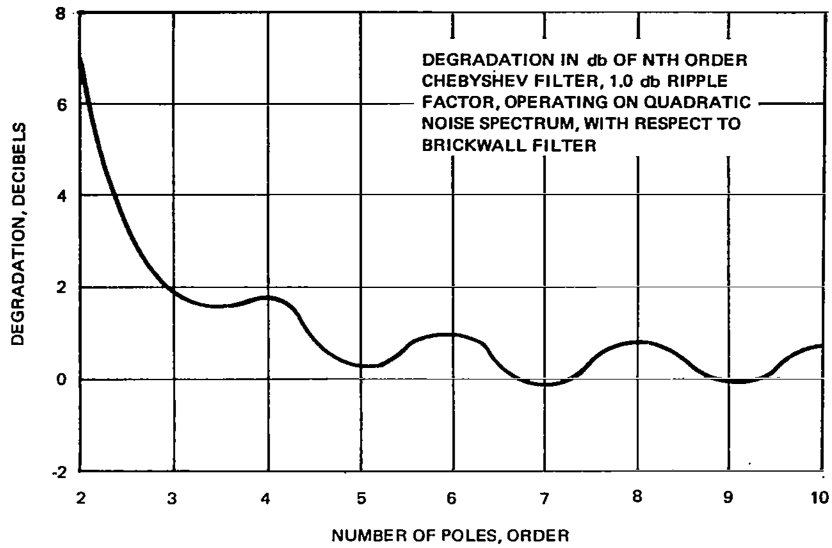


Figure C (a)

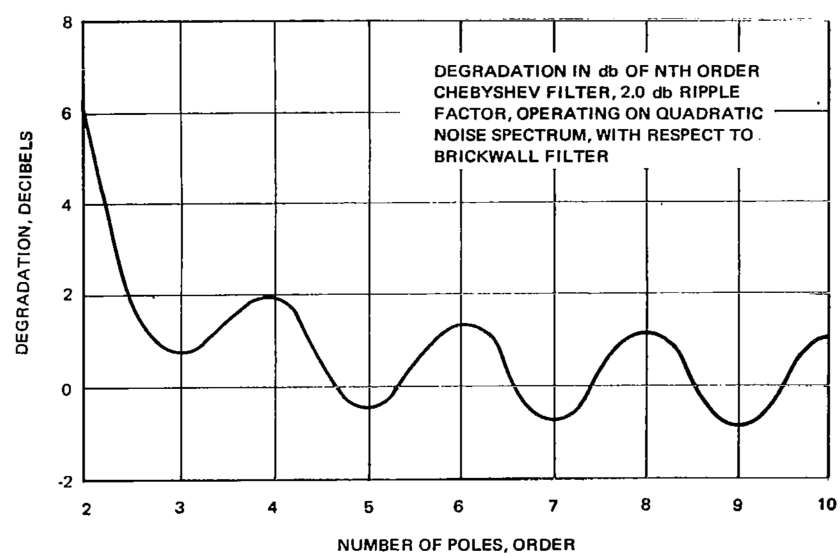


Figure C (c)

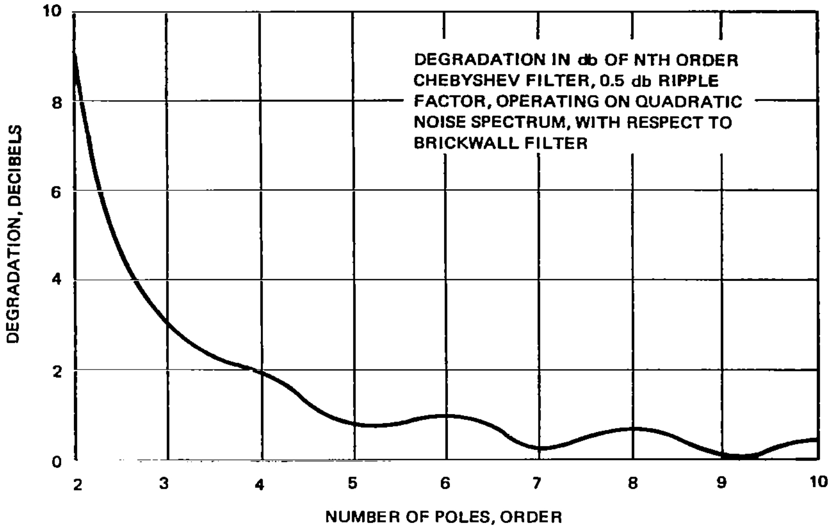


Figure C (b)

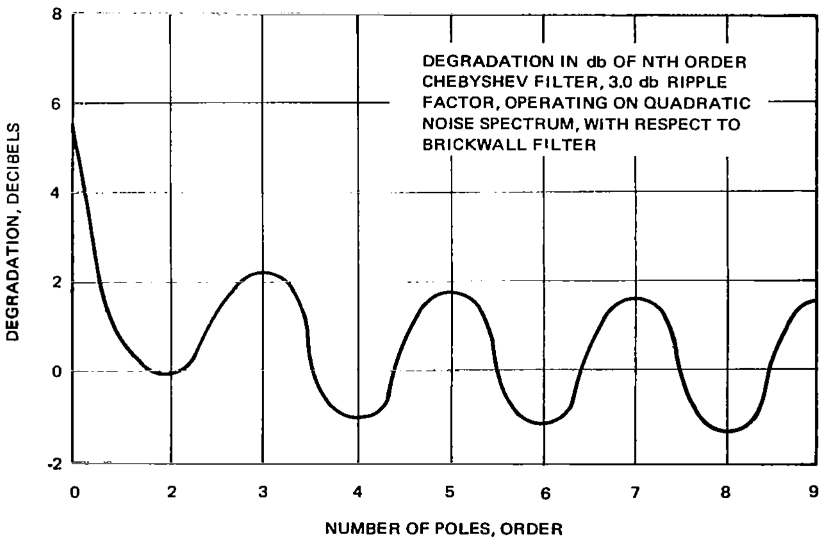


Figure C (d)

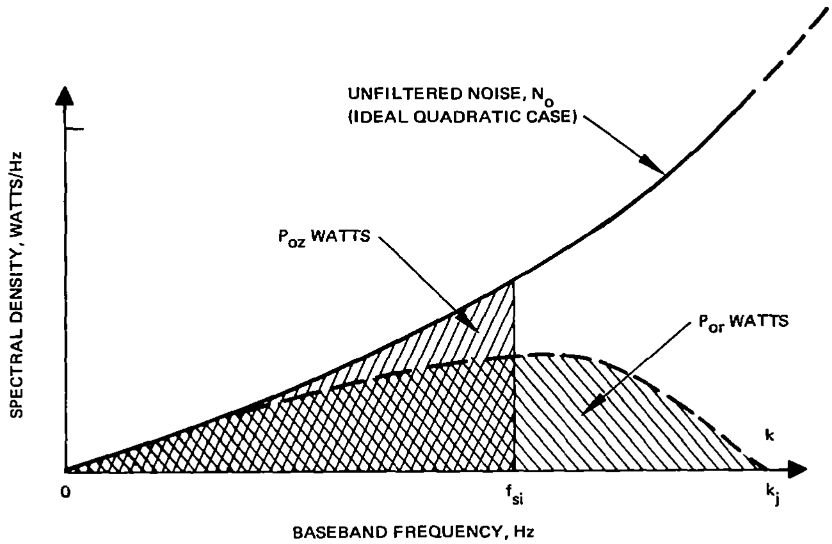

UNFILTERED NOISE, N_o
(IDEAL QUADRATIC CASE)
P_{oz} WATTS
P_{or} WATTS
SPECTRAL DENSITY, WATTS/Hz
k
0
f_{si}
k_j
BASEBAND FREQUENCY, Hz

Figure D

APPENDIX A

COMMUNICATION SYSTEMS OPTIMIZATION METHODOLOGY

APPENDIX A

COMMUNICATION SYSTEMS OPTIMIZATION METHODOLOGY

A. 1 INTRODUCTION

The complexity of evaluating the relative roles of systems for future spacecraft communication and tracking applications, considering the broad spectrum of potential manned and unmanned space missions, demands a unified methodical approach. As shown in Figure A-1, the task is one of examining the study data compiled by communication components analysis, and communication systems analysis studies; and then determining the optimum parameters for communication systems. In brief, the communication components analysis task provides data on the system parameters with relationship to the fabrication cost, weight, size, etc., of the component implementation. The communication systems analysis provides the relationships between the communication parameters, noise effects, and system constraints. While the general goals of the systems optimization task can be stated rather simply, its implementation will require a significant amount of effort due to the large number of parameters that must be considered.

This communication systems optimization methodology section is divided into sub-sections which treat the general optimization procedure for communication systems, followed by examples of the optimization procedure. The section concludes with a design methodology which summarizes the results of the optimization methodology for optical and radio systems, and presents short cut methods of evaluating systems.

A. 2 COMMUNICATION COMPONENTS ANALYSIS

The communication components analysis task is illustrated by the flow chart of Figure A-2. For each component the weight, fabrication cost, power requirement, and power dissipation are derived as a function of the system parameters. A total component cost is developed as the sum of the fabrication cost and cost of placing the component weight aboard a spacecraft, if applicable.

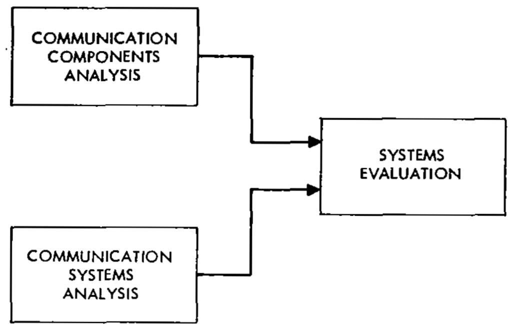


Figure A-1. Systems optimization flow chart.

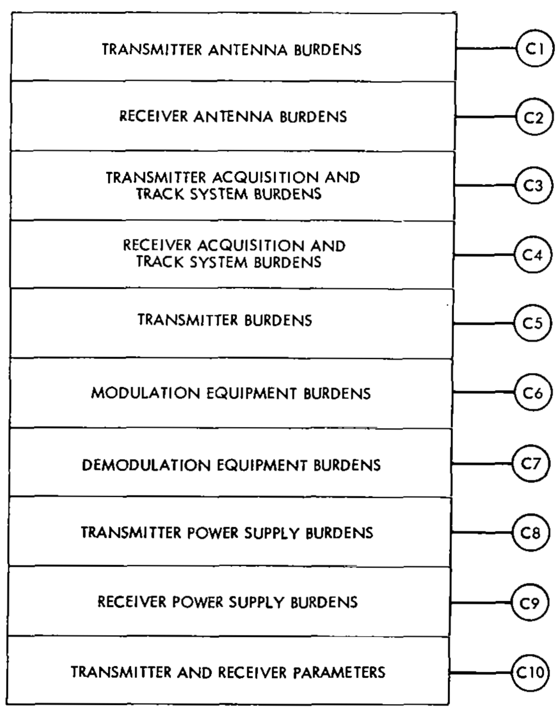


Figure A-2. Communication components analysis flow chart.

(C1) Transmitter Antenna Burdens

The weight and fabrication cost of a transmitter antenna are proportional to the transmitter aperture diameter. The transmitter antenna weight is

$$W_{d_T} = K_{d_T} (d_T)^{n_T} + W_{KT}$$

and the fabrication cost is

$$C_{\theta_T} = K_{\theta_T} (d_T)^{m_T} + C_{KT}$$

where

d_T = transmitter aperture diameter

K_{d_T} = constant relating transmitter antenna weight to transmitter aperture diameter

K_{θ_T} = constant relating transmitter antenna fabrication cost to transmitter aperture diameter

W_{KT} = transmitter antenna weight independent of transmitter aperture diameter

C_{KT} = transmitter antenna fabrication cost independent of transmitter aperture diameter

n_T = constant

m_T = constant

The total cost associated with the transmitter antenna is the fabrication cost and the cost of placing the weight W_{d_T} aboard a spacecraft. Thus,

$$C_{d_T} = K_{\theta_T} (d_T)^{m_T} + K_S K_{d_T} (d_T)^{n_T} + C_{KT} + K_S W_{KT}$$

where

K_S = cost per unit weight for spaceborne equipment

(C2) Receiver Antenna Burdens

The weight and fabrication cost of a receiver antenna are proportional to the receiver aperture diameter. The receiver antenna weight is

$$W_{d_R} = K_{d_R} (d_R)^{n_R} + W_{KR}$$

and the fabrication cost is

$$C_{\theta_R} = K_{\theta_R} (d_R)^{m_R} + C_{KR}$$

where

d_R = receiver aperture diameter

K_{d_R} = constant relating receiver antenna weight to receiver aperture diameter

K_{θ_R} = constant relating receiver antenna fabrication cost to receiver aperture diameter

W_{KR} = receiver antenna weight independent of receiver aperture diameter

C_{KR} = receiver antenna fabrication cost independent of receiver aperture diameter

n_R = constant

m_R = constant

The total cost associated with the receiver antenna is the fabrication cost and the cost of placing the weight W_{d_R} aboard a spacecraft. For optical systems there is an additional fabrication cost due to fabrication of a high quality short focal length aperture when the receiver field of view is much larger than the diffraction limit, but this additional cost is usually negligible with respect to the aperture diameter dependent cost. The total receiver antenna cost is then

$$C_{d_R} = K_{\theta_R} (d_R)^{m_R} + K_S K_{d_R} (d_R)^{n_R} + C_{KR} + K_S W_{KR}$$

(C3) Transmitter Acquisition and Track System Burdens

The transmitter must illuminate the receiver under fixed acquisition time limits and then maintain an angular tracking accuracy. Acquisition and tracking equipment consists of a gimbal system to slew the transmitter antenna to the desired pointing angle, a sensor to detect the line of sight rotational error between the transmitter and receiver by monitoring a communication or beacon signal emitted from the receiving site, and a stable platform reference for the sensor. The acquisition and tracking sensor signal may be obtained from 1) a secondary antenna, 2) the transmitter antenna acting as a receiving antenna on a shared basis, or 3) the antenna of a communications receiver if available at the transmitter. A beacon at the transmitter used by the receiver for its acquisition and tracking function will not affect the system parameters optimization since the beacon burdens are independent of the system parameters. Beacon burdens are considered as part of the fixed burdens associated with the spacecraft transmitter acquisition and track system.

The weight and fabrication cost of the acquisition equipment is relatively independent of the transmitter beamwidth.

The weight of the transmitter acquisition and track system is relatively insensitive to the tracking accuracy and depends primarily upon the weight of the transmitter antenna and the weight of the transmitter sensor, stabilization, and acquisition systems. The weight of the transmitter acquisition and track system is

$$W_{QT} = W_{BT} + K_{W_{AT}} W_{d_T}$$

or

$$\boxed{W_{QT} = W_{BT} + K_{W_{AT}} K_{d_T} (d_T)^{n_T}}$$

where

W_{BT} = transmitter acquisition and track equipment and beacon system weight independent of transmitter beamwidth

$K_{W_{AT}}$ = constant relating transmitter tracking equipment weight to transmitter antenna weight

W_{d_T} = transmitter antenna weight

The tracking accuracy requirement may be stated as some fixed percentage of the transmitter beamwidth. The fabrication cost of the tracking equipment is inversely proportional to the tracking accuracy, and hence, to the inverse of the transmitter beamwidth. Since the transmitter is diffraction limited, ($\theta_T \approx \lambda / d_T$), the fabrication cost of the transmitter tracking equipment is proportional to the transmitter aperture diameter.

The total fabrication cost of the transmitter acquisition and track system is then

$$C_{NT} = C_{AT} + K_{AT} (\theta_T)^{-q_T}$$

or

$$\boxed{C_{NT} = C_{AT} + \frac{K_{AT}}{(\lambda)^{q_T}} (d_T)^{q_T}}$$

where

λ = transmission wavelength

C_{AT} = transmitter acquisition and track equipment and beacon system fabrication cost independent of transmitter beamwidth

K_{AT} = constant relating transmitter tracking equipment fabrication cost to transmitter beamwidth

θ_T = transmitter beamwidth

q_T = constant

The total cost associated with the transmitter acquisition and track system is

$$C_{QT} = C_{AT} + \frac{K_{AT}}{(\lambda)^{q_T}} (d_T)^{q_T} + K_S \left[W_{BT} + K_{W_{AT}} K_{d_T} (d_T)^{n_T} \right]$$

The power requirement of the transmitter acquisition and track equipment is directly proportional to the weight of the acquisition and track system.* Thus,

$$P_{QT} = K_{P_{QT}} \left[W_{BT} + K_{W_{AT}} K_{d_T} (d_T)^{n_T} \right]$$

where

$K_{P_{QT}}$ = constant relating transmitter acquisition and track equipment power requirement to equipment weight

(C4) Receiver Acquisition and Track System Burdens

The receiver must locate the transmitter in its field of view and then maintain an angular tracking accuracy. The implementation of the receiver acquisition and track system is the same as the transmitter acquisition and track system.

The weight and fabrication cost of the acquisition equipment is relatively independent of the receiver field of view. The weight of the receiver tracker is relatively insensitive to the tracking accuracy, and depends primarily on the weight of the receiver antenna and the weight of the receiver sensor, stabilization, and acquisition systems. The weight of the receiver acquisition and tracking systems is

$$W_{QR} = W_{BR} + K_{W_{AR}} W_{d_R}$$

or

$$W_{QR} = W_{BR} + K_{W_{AR}} K_{d_R} (d_R)^{n_R}$$

*This assumption is not strictly applicable to all tracking systems and will be examined in subsequent reports.

where

W_{BR} = receiver acquisition and track equipment and beacon system weight independent of receiver field of view.

$K_{W_{AR}}$ = constant relating receiver tracking equipment weight to receiver antenna weight

W_{d_R} = receiver antenna weight

The tracking accuracy requirement may be stated as some fixed percentage of the receiver field of view. The fabrication cost of the tracking equipment is inversely proportional to the tracking accuracy, and hence to the inverse of receiver field of view. The total fabrication cost of the receiver acquisition and track system is then

$$C_{NR} = C_{AR} + K_{AR}(\theta_R)^{-q_R}$$

where

C_{AR} = receiver acquisition and track equipment and beacon system fabrication cost independent of receiver field of view

K_{AR} = constant relating receiver tracking equipment fabrication cost to receiver field of view

q_R = constant

θ_R = receiver field of view

The total cost associated with the receiver acquisition and track system is

$$C_{QR} = C_{AR} + K_{AR}(\theta_R)^{-q_R} + K_S \left[W_{BR} + K_{W_{AR}} K_{d_R} (d_R)^{n_R} \right]$$

The power requirement of the receiver acquisition and track equipment is directly proportional to the weight of the acquisition and track system.* Thus,

$$P_{QR} = K_{P_{QR}} \left[W_{BR} + K_{W_{AR}} K_{d_R} (d_R)^{n_R} \right]$$

where

$K_{P_{QR}}$ = constant relating receiver acquisition and track equipment power requirement to equipment weight

(C5) Transmitter Burdens

The weight and fabrication cost of radio transmitters are proportional to the transmitter output power. Laser transmitters are available only at discrete wavelengths, and each laser is capable of operation over only a restricted range of output power by increasing the laser pumping power; however, at each wavelength within limits the laser weight and fabrication cost are proportional to the laser output power. Thus, the transmitter weight is

$$W_T = K_{WT} \left(P_T\right)^{h_T} + W_{KP}$$

and the fabrication cost is

$$C_{FL} = K_{PT} \left(P_T\right)^{g_T} + C_{KP}$$

*This assumption is not strictly applicable to all tracking systems and will be examined in subsequent reports.

where

P_T = transmitter power

K_{WT} = constant relating transmitter weight to transmitter power

K_{PT} = constant relating transmitter fabrication cost to transmitter power

W_{KP} = transmitter weight independent of transmitter power

C_{KP} = transmitter fabrication cost independent of transmitter power

h_T = constant

g_T = constant

A heat exchanger may be required for the transmitter. The fabrication cost and weight of the heat exchanger are proportional to the power dissipated by the transmitter. The heat exchanger weight is

$$\boxed{W_H = K_X \left(\frac{1-k_e}{k_e} \right) P_T + W_{KH}}$$

and the heat exchanger fabrication cost is

$$\boxed{C_H = K_H \left(\frac{1-k_e}{k_e} \right) P_T + C_{KH}}$$

where

W_{KH} = transmitter heat exchanger weight independent of transmitter

C_{KH} = transmitter heat exchanger fabrication cost independent of transmitter power dissipation

K_X = constant relating transmitter heat exchanger weight to transmitter power dissipation

K_H = constant relating transmitter heat exchanger fabrication cost to transmitter power dissipation

k_e = transmitter power efficiency, from the prime power source to the output power

The total transmitter cost is then the fabrication costs of the transmitter and associated heat exchanger and the cost of placing these units aboard a spacecraft. Thus,

$$C_{P_T} = K_{P_T}(P_T)^{g_T} + K_S K_{W_T}(P_T)^{h_T} + K_H\left(\frac{1-k_e}{k_e}\right)P_T$$
$$+ K_S K_X\left(\frac{1-k_e}{k_e}\right) P_T + C_{KP} + C_{KH}$$
$$+ K_S W_{KP} + K_S W_{KH}$$

The transmitter power requirement is

$$P_{PT} = \frac{1}{k_e} P_T$$

(C6) Modulation Equipment Burdens

For each type of modulation, the modulation equipment weight and fabrication cost are proportional to the information rate. The modulation equipment weight is

$$W_M = K_M R_B + W_{KM}$$

and the modulation equipment fabrication cost is

$$C_{FM} = K_{FM} R_B + C_{KM}$$

where

R_B = information rate

K_M = constant relating modulation equipment weight to information rate.

K_{FM} = constant relating modulation equipment fabrication cost to information rate

W_{KM} = modulation equipment weight independent of information rate

C_{KM} = modulation equipment fabrication cost independent of information rate

The total cost associated with the modulation equipment is the fabrication cost and the cost of placing the equipment aboard a spacecraft. Thus,

$$C_M = K_{FM}R_B + C_{KM} + K_S K_M R_B + K_S W_{KM}$$

The power requirement of the modulation equipment is proportional to its weight. Thus,

$$P_M = K_{P_M} K_M R_B + K_{P_M} W_{KM}$$

where

K_{P_M} = constant relating modulation equipment power requirement to equipment weight

The modulation equipment burdens include coder burdens.

(C7) Demodulation Equipment Burdens

The demodulation equipment consists of a carrier receiver followed by a subcarrier receiver, if necessary. Also included in the demodulation equipment is any cooling equipment required to lower the receiver temperature to reduce dark current and thermal noise. For each type of demodulation system the equipment weight is proportional to the information rate. The demodulation equipment weight is

$$W_D = K_D R_B + W_{KD}$$

and the demodulation equipment fabrication cost is

$$C_{FD} = K_{FD} R_B + C_{KD}$$

where

K_D = constant relating demodulation equipment weight to information rate

K_{FD} = constant relating demodulation equipment fabrication cost to information rate

W_{KD} = demodulation equipment weight independent of information rate

C_{KD} = demodulation equipment fabrication cost independent of information rate

The total cost associated with the demodulation equipment is the fabrication cost and the cost of placing the equipment aboard a spacecraft. Thus,

$$C_D = K_{FD}R_B + C_{KD} + K_S K_D R_B + K_S W_{KD}$$

The power requirement of the demodulation equipment is proportional to its weight

$$P_D = K_{P_D} K_D R_B + K_{P_D} W_{K_D}$$

where

K_{P_D} = constant relating demodulation equipment power requirement to equipment weight

The demodulation equipment burdens include decoder burdens.

(C8) Transmitter Power Supply Burdens

The input power requirement of the transmitter specifies the power requirement for the transmitter power supply. The power supply is defined here to include the power source plus voltage or current conversion equipment. The power supply weight and fabrication cost are proportional to the power requirement. The transmitter power supply weight is

$$W_{ST} = K_{W_{ST}} P_{ST} + W_{KE}$$

and the fabrication cost is

$$C_{FT} = K_{ST}P_{ST} + C_{KE}$$

where

W_{KE} = transmitter power supply weight independent of transmitter power requirement

C_{KE} = transmitter power supply fabrication cost independent of transmitter power requirement

P_{ST} = transmitter power supply power requirement

$K_{W_{ST}}$ = constant relating transmitter power supply weight to power requirement

K_{ST} = constant relating transmitter power supply fabrication cost to power requirement

The transmitter power supply power requirement is

$$P_{ST} = P_M + P_{PT} + P_{QT}$$

where

$P_M = K_{P_M} K_M R_B + K_{P_M} W_{KM}$ = modulation equipment power

$P_{PT} = \dfrac{P_T}{k_e}$ = transmitter power requirement from the prime power source

$P_{QT} = K_{P_{QT}} \left[W_{ST} + K_{W_{AT}} K_{d_T} (d_T)^{n_T} \right]$ = transmitter acquisition and tracking equipment power requirement

The transmitter power supply weight is then

$$W_{ST} = K_{W_{ST}} \left\{ K_{P_M} K_M R_B + K_{P_M} W_{KM} + \frac{P_T}{k_e} + K_{P_{QT}} \left[W_{BT} + K_{W_{AT}} K_{d_T} (d_T)^{n_T} \right] \right\} + W_{KE}$$

The total cost associated with the transmitter power supply is the transmitter power supply fabrication cost plus the cost of placing the equipment weight aboard a spacecraft. Thus,

$$C_{ST} = \left[K_{ST} + K_S K_{W_{ST}}\right]\left\{K_{P_M} K_M R_B + K_{P_M} W_{KM} + \frac{P_T}{k_e} + K_{P_{QT}}\left[W_{BT} + K_{W_{AT}} K_{d_T} (d_T)^{n_T}\right]\right\} + K_S W_{KE} + C_{KE}$$

(C9) Receiver Power Supply Burdens

The input power requirements of the receiver specify the power requirement for the receiver power supply. The power supply weight and fabrication cost are proportional to the power requirement.

The receiver power supply weight is

$$W_{SR} = K_{W_{SR}} P_{SR} + W_{KF}$$

and the fabrication cost is

$$C_{FR} = K_{SR} P_{SR} + C_{KF}$$

where

W_{KF} = receiver power supply weight independent of receiver power requirement

C_{KF} = receiver power supply fabrication cost independent of receiver power requirement

P_{SR} = receiver power supply power requirement

$K_{W_{SR}}$ = constant relating receiver power supply weight to power requirement

K_{SR} = constant relating receiver power supply fabrication cost to power requirement

The receiver power supply power requirement is

$$P_{SR} = P_D + P_{QR}$$

where

$$P_D = K_{P_D} K_D R_B + K_{P_D} W_{KD}$$ = demodulation equipment power requirement

$$P_{QR} = K_{P_{QR}} \left[W_{BR} + K_{W_{AR}} K_{d_R} (d_R)^{n_R} \right]$$ = receiver acquisition and tracking equipment power requirement

The receiver power supply weight is then

$$W_{SR} = K_{W_{SR}} \left\{ K_{P_D} K_D R_B + K_{P_D} W_{KD} + K_{P_{QR}} \left[W_{BR} + K_{W_{AR}} K_{d_R} (d_R)^{n_R} \right] \right\} + W_{KF}$$

The total cost associated with the receiver power supply is the receiver power supply fabrication cost plus the cost of placing the equipment aboard a spacecraft. Thus,

$$C_{SR} = \left[K_{SR} + K_S K_{W_{SR}} \right] \left\{ K_{P_D} K_D R_B + K_{P_D} W_{KD} + K_{P_{QR}} \left[W_{BR} + K_{W_{AR}} K_{d_R} (d_R)^{n_R} \right] \right\} + C_{KF}$$

(C10) Transmitter and Receiver Parameters

The transmitter and receiver of an optical communication system are characterized by the following parameters:

η = quantum efficiency

I_d = dark current

G = photo detector gain

R_L = receiver load resistance

P_O = local oscillator power

B_i = optical input filter bandwidth

B_o = receiver output filter bandwidth

τ_t = transmitter transmissivity

τ_r = receiver transmissivity

A. 3 COMMUNICATION SYSTEMS ANALYSIS

The communication systems analysis task is illustrated by the flow chart of Figure A-3.

(T1) Signal-to-Noise Ratio at Receiver Output

For each type of receiver the signal-to-noise power ratio at the receiver output may be expressed as a function of the transmitter power, transmitter aperture diameter, receiver aperture diameter, receiver field of view, receiver parameters, background radiation, receiver temperature, receiver bandwidth, transmission path, transmission wavelength, and communication range.

$$\frac{S}{N} = f\left[P_T, d_T, d_R, \theta_R, Q_B, B_o, R, \lambda, \tau_t, \tau_r, \tau_a, G, \eta, R_L, P_o, B_i, T\right]$$

(T2) Background Noise Effects

The background noise will be expressed as a power spectral density in both frequency and space so that the background noise power input to the receiver may be found by integrating the background spectral radiance over the input filter bandwidth and the receiver field of view.

(T3) Atmospheric Transmission Effects

Signals traveling through the atmosphere will experience a transmission loss due to absorption and scattering by particles in the atmosphere. The ratio of the signal intensity leaving the transmitter to the signal intensity entering the receiver is the atmospheric transmissivity, τ_a, whose value is dependent upon the transmission wavelength. The atmospheric index of refraction is time varying because of wind and thermal gradients in the atmosphere. This causes a scintillation effect in which the received signal beam occasionally moves entirely or partially out of the receiver field of view. In addition, changes in the composition of the atmosphere cause perburbations in the phase fronts of the transmitted beam. This destroys the spatial coherence of the signal and reduces the receiver collector area over which heterodyning may be performed. The relationship between atmospheric effects and this coherence area is presently ill defined. For heterodyne and homodyne detection systems in which spatial coherence is critical, the effect of the atmosphere may be described by the signal coherence area over which mixing may be performed. The coherence area limits the usable size of the receiver aperture.

A. 4 SYSTEMS EVALUATION

The systems evaluation task is illustrated by the flow chart of Figure A-4.

(E1) Express Signal-to-Noise Ratio as a Function of System Parameters

For each type of receiver the signal-to-noise ratio can be expressed in terms of the system parameters.

$$\frac{S}{N} = f\left[P_T, d_T, \theta_R, d_R\right]$$

where

P_T = transmitter power

d_T = diameter of the transmitter antenna

θ_R = receiver field of view

d_r = diameter of the receiver antenna

(E2) Express System Costs as a Function of System Parameters

Composite relationships may be developed between the major system parameters which appear in the signal-to-noise ratio

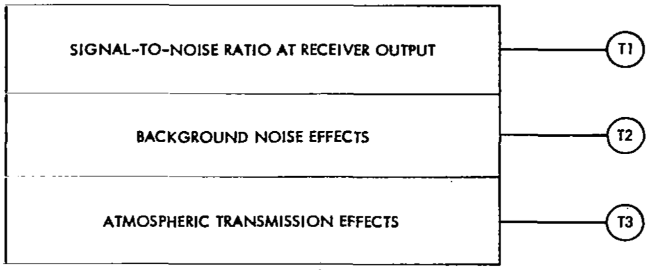


Figure A-3. Communication systems analysis flow chart.

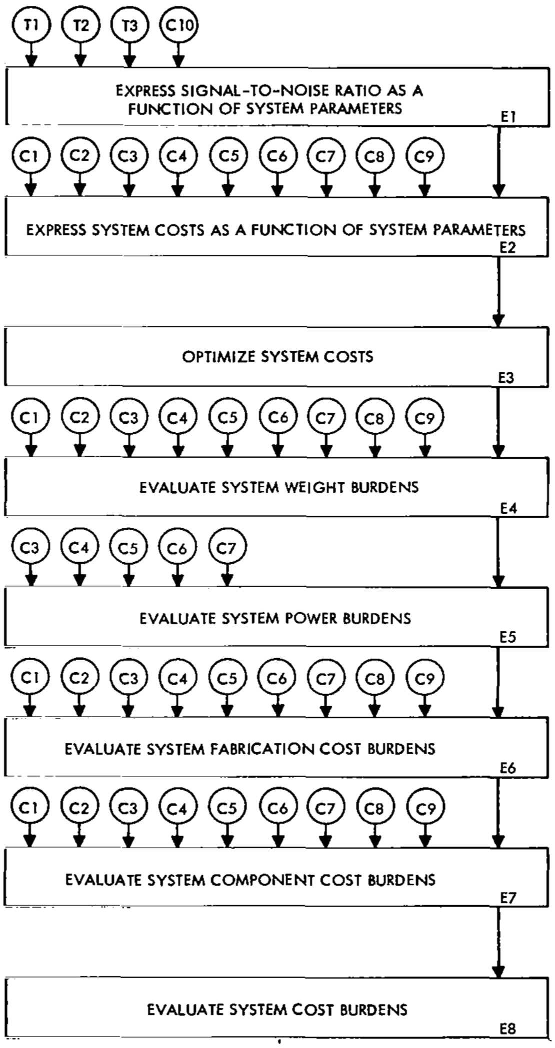


Figure A-4. Systems evaluation flow chart.

expression and the various system burdens by manipulation of the following set of functional relations.

(C1) Transmitter antenna cost

$$C_{d_T} = K_{\theta_T}(d_T)^{m_T} + K_S K_{d_T}(d_T)^{n_T} + C_{KT} + K_S W_{KT}$$

(C2) Receiver antenna cost

$$C_{d_R} = K_{\theta_R}(d_R)^{m_R} + K_S K_{d_R}(d_R)^{n_R} + C_{KR} + K_S W_{KR}$$

(C3) Transmitter acquisition and track system cost

$$C_{QT} = C_{AT} + \frac{K_{AT}}{(\lambda)^{q_T}}(d_T)^{q_T} + K_S\left[W_{BT} + K_{W_{AT}} K_{d_T}(d_T)^{n_T}\right]$$

(C4) Receiver acquisition and track system cost

$$C_{QR} = C_{AR} + K_{AR}(\theta_R)^{-q_R} + K_S\left[W_{BR} + K_{W_{AR}} K_{d_R}(d_R)^{n_R}\right]$$

(C5) Transmitter cost

$$C_{P_T} = K_{P_T}(P_T)^{g_T} + K_S K_{W_T}(P_T)^{h_T} + K_H\left(\frac{1 - k_e}{k_e}\right)P_T + K_S K_X\left(\frac{1 - k_e}{k_e}\right)P_T$$

$$+ C_{KP} + C_{KH} + K_S W_{KP} + K_S W_{KH}$$

(C6) Modulation equipment cost

$$C_M = K_{FM} R_B + K_S K_M R_B + C_{KM} + K_S W_{KM}$$

(C7) Demodulation equipment cost

$$C_D = K_{FD}R_B + C_{KD} + K_S K_D R_B + K_S W_{KD}$$

(C8) Transmitter power supply cost

$$C_{ST} = \left[K_{ST} + K_S K_{W_{ST}}\right]\left\{K_{P_M} K_M R_B + K_{P_M} W_{KM} + \frac{P_T}{k_e} + K_{P_{QT}}\left[W_{BT} + K_{W_{AT}} K_{d_T} (d_T)^{n_T}\right]\right\} + K_S W_{KE} + C_{KE}$$

(C9) Receiver power supply cost

$$C_{SR} = \left[K_{SR} + K_S K_{W_{SR}}\right]\left\{K_{P_D} K_D R_B + K_{P_D} W_{KD} + K_{P_{QR}}\left[W_{BR} + K_{W_{AR}} K_{d_R} (d_R)^{n_R}\right]\right\} + K_S W_{KF} + C_{KF}$$

The expressions for (C1), (C3), and (C8), combine to give a relationship between transmitter aperture diameter and the cost, C_T of the transmitter optics and associated tracking equipment which is dependent upon the transmitter aperture diameter.

$$C_T \equiv \underbrace{\frac{K_{AT}}{(\lambda)^{q_T}}(d_T)^{q_T}}_{\text{fabrication cost of transmitter tracker}} + \underbrace{K_{\theta_T}(d_T)^{m_T}}_{\text{fabrication cost of transmitter antenna}} + \underbrace{K_S K_{d_T}(d_T)^{n_T}}_{\text{weight cost transmitter antenna}} + \underbrace{K_S K_{d_T} K_{W_{AT}}(d_T)^{n_T}}_{\text{weight cost of transmitter tracker}}$$

$$+ \underbrace{K_S K_{W_{ST}} K_{P_{QT}} K_{W_{AT}} K_{d_T} (d_T)^{n_T}}_{\text{weight cost of transmitter tracker power supply}} + \underbrace{K_{ST} K_{P_{QT}} K_{W_{AT}} K_{d_T} (d_T)^{n_T}}_{\text{fabrication cost of transmitter tracker power supply}}$$

In simplified form

$$C_T = K_{q_T} (d_T)^{q_T} + K_{m_T} (d_T)^{m_T} + K_{n_T} (d_T)^{n_T}$$

where

$$K_{q_T} \equiv \frac{K_{AT}}{(\lambda)^{q_T}}$$

$$K_{m_T} \equiv K_{\theta_T}$$

$$K_{n_T} \equiv K_{d_T} \left\{ K_S \left[1 + K_{W_{AT}} \right] + K_{P_{QT}} K_{W_{AT}} \left[K_{ST} + K_S K_{W_{ST}} \right] \right\}$$

The expressions for (C2), (C4), and (C9) combine to give a relationship between receiver aperture diameter and the cost, C_R, of the receiver optics and associated tracking equipment which is dependent upon the receiver aperture diameter.

$$C_R \equiv \underbrace{K_{\theta_R} (d_R)^{m_R}}_{\text{fabrication cost of receiver antenna}} + \underbrace{K_S K_{d_R} (d_R)^{n_R}}_{\text{weight cost of receiver antenna}} + \underbrace{K_S K_{d_R} K_{W_{AR}} (d_R)^{n_R}}_{\text{weight cost of receiver tracker}}$$

$$\underbrace{K_S K_{W_{SR}} K_{P_{QR}} K_{W_{AR}} K_{d_R}}_{\text{weight cost of receiver tracker power supply}} (d_R)^{n_R} + \underbrace{K_{SR} K_{P_{QR}} K_{W_{AR}} K_{d_R}}_{\text{fabrication cost of receiver tracker power supply}} (d_R)^{n_R}$$

In simplified form

$$C_R = K_{m_R} (d_R)^{m_R} + K_{n_R} (d_R)^{n_R}$$

where

$$K_{m_R} \equiv K_{\theta_R}$$

$$K_{n_R} \equiv K_{d_R} \left\{ K_S \left[1 + K_{W_{AR}} \right] + K_{P_{QR}} K_{W_{AR}} \left[K_{SR} + K_S K_{W_{SR}} \right] \right\}$$

The expression for (C4) gives a relationship between receiver beamwidth and the cost, C_Q, of the receiver optics which is dependent upon the receiver field of view.

$$C_Q \equiv \underbrace{K_{AR} (\theta_R)^{-q_R}}_{\text{fabrication cost of receiver tracker}}$$

In simplified form

$$C_Q = K_{q_R} (\theta_R)^{-q_R}$$

where

$$K_{q_R} \equiv K_{AR}$$

The expressions for (C5) and (C8) combine to give a relationship between transmitter power and the cost, C_G of the transmitter and the associated power supply and heat exchanger which is dependent upon the transmitter power.

$$C_G = \underbrace{K_{P_T}(P_T)^{g_T}}_{\substack{\text{fabrication}\\ \text{cost of}\\ \text{transmitter}}} + \underbrace{K_S K_{W_T}(P_T)^{h_T}}_{\substack{\text{weight cost of}\\ \text{transmitter}}} + \underbrace{\frac{K_{ST}}{k_e} P_T}_{\substack{\text{fabrica-}\\ \text{tion cost}\\ \text{of trans-}\\ \text{mitter}\\ \text{power}\\ \text{supply}}} + \underbrace{\frac{K_S K_{W_{ST}}}{k_e} P_T}_{\substack{\text{weight cost}\\ \text{of transmitter}\\ \text{power supply}}}$$

$$+ \underbrace{K_H\left(\frac{1 - k_e}{k_e}\right)P_T}_{\substack{\text{fabrication cost of}\\ \text{heat exchanger}}} + \underbrace{K_S K_X\left(\frac{1 - k_e}{k_e}\right) P_T}_{\substack{\text{weight cost of heat}\\ \text{exchanger}}}$$

In simplified form

$$C_G = K_{g_T}(P_T)^{g_T} + K_{h_T}(P_T)^{h_T} + K_{j_T} P_T$$

where

$$K_{g_T} \equiv K_{P_T}$$

$$K_{h_T} \equiv K_S K_{W_T}$$

$$K_{j_T} \equiv \left\{K_S \frac{K_{W_{ST}}}{k_e} + K_X\left(\frac{1 - k_e}{k_e}\right)\right\} + \frac{K_{ST}}{k_e} + K_H\left(\frac{1 - k_e}{k_e}\right)$$

The expressions for (C3), (C4), (C6), (C7), (C8) and (C9) combine to give relationships describing the fixed system costs at the transmitter and receiver which are independent of the transmitter aperture, receiver aperture, transmitter power, and receiver field of view,

$$C_{XT} = C_{KT} + K_S W_{KT} + C_{AT} + K_S W_{BT} + C_{KP} + C_{KH} + K_S W_{KP} + K_S W_{KH} + K_{FM} R_B + C_{KM} + K_S K_M R_B + K_S W_{KM} + \left[K_{ST} + K_S K_{W_{ST}}\right]\left[K_{P_M} K_M R_B + K_{P_M} W_{KM} + K_{P_{QT}} W_{BT}\right] + K_S W_{KE} + C_{KE}$$

$$C_{XR} = C_{KR} + K_S W_{KR} + C_{AR} + K_S W_{BR} + K_{FD} R_B + C_{KD} + K_S K_D R_B + K_S W_{KM} + \left[K_{SR} + K_S K_{W_{SR}}\right]\left[K_{P_D} K_D R_B + K_{P_D} W_{KD} + K_{P_{QR}} W_{BR}\right] + K_S W_{KF} + C_{KF}$$

The total system cost is thus composed of a fixed part, which is not affected by the major system parameters and a variable part which is dependent upon the system parameters.

$$C_S = C_V + C_{XT} + C_{XR}$$

with

$$C_V = C_G + C_T + C_Q + C_R$$

where

C_S = total system cost

C_V = variable part of total system cost (optimization cost)

C_{XT} = fixed part of total transmitter cost

C_{XR} = fixed part of total receiver cost

C_G = cost of transmitter, transmitter power supply, and transmitter heat exchanger which is dependent upon transmitter power

C_T = cost of transmitter antenna, transmitter acquisition and track equipment, and associated power supply which is dependent upon transmitter aperture diameter

C_Q = cost of receiver acquisition and track equipment which is dependent upon receiver field of view

C_R = cost of receiver antenna, receiver acquisition and track equipment, and associated power supply which is dependent upon receiver aperture diameter

(E3) Optimize System Costs

The system cost allotments may be optimized by maximizing the signal-to-noise ratio as a function of the system costs for a fixed communication range and information rate under the constraint that the total system cost is constant. Since the probability of error, communication range, and information rate are all monotonically related, the maximization of the signal-to-noise ratio minimizes the probability of error and maximizes the communication range and information rate.

The optimization problem reduces to the maximization of the signal-to-noise ratio expression as a function of the variable system parameters

$$\frac{S}{N} = f\left[P_T, d_T, \theta_R, d_R\right]$$

where the system parameters are related to the system costs by

$$C_T = K_{m_T}(d_T)^{m_T} + K_{n_T}(d_T)^{n_T} + K_{q_T}(d_T)^{q_T}$$

$$C_R = K_{m_R}(d_R)^{m_R} + K_{n_R}(d_R)^{n_R}$$

$$C_Q = K_{q_R} (\theta_R)^{-q_R}$$

$$C_G = K_{g_T} (P_T)^{g_T} + K_{h_T} (P_T)^{h_T} + K_{j_T} P_T$$

under the linear constraint that the optimization cost remains constant. If the expressions for the system burdens can be inverted, the resultant expressions for the system parameters may be substituted into the formulation for the signal-to-noise ratio which then may be minimized by partial differentiation. Appendix A2. 12 discusses such a case. If the system cost expressions are not easily invertable, the optimization must be performed by numerical techniques.

By the method of Lagrange multipliers the expression

$$Q = \frac{S}{N} + \Lambda (C_V - C_T - C_R - C_G - C_Q)$$

is formed, then the partial derivatives of Q with respect to each variable system parameter are set to zero.

$$\frac{\partial Q}{\partial d_T} = \frac{\partial \left(\frac{S}{N}\right)}{\partial d_T} - \Lambda \frac{\partial C_T}{\partial d_T} = 0$$

$$\frac{\partial Q}{\partial d_R} = \frac{\partial \left(\frac{S}{N}\right)}{\partial d_R} - \Lambda \frac{\partial C_R}{\partial d_R} = 0$$

$$\frac{\partial Q}{\partial P_T} = \frac{\partial \left(\frac{S}{N}\right)}{\partial P_T} - \Lambda \frac{\partial C_G}{\partial P_T} = 0$$

$$\frac{\partial Q}{\partial \theta_R} = \frac{\partial \left(\frac{S}{N}\right)}{\partial \theta_R} - \Lambda \frac{\partial C_Q}{\partial \theta_R} = 0$$

where

$$\frac{\partial C_T}{\partial d_T} = m_T K_{m_T} (d_T)^{m_T - 1} + n_T K_{n_T} (d_T)^{n_T - 1} + q_T K_{q_T} (d_T)^{q_T - 1}$$

$$\frac{\partial C_R}{\partial d_R} = m_R K_{m_R} (d_R)^{m_R - 1} + n_R K_{n_R} (d_R)^{n_R - 1}$$

$$\frac{\partial C_G}{\partial P_T} = g_T K_{g_T} (P_T)^{g_T - 1} + h_T K_{h_T} (P_T)^{h_T - 1} + K_{j_T}$$

$$\frac{\partial C_Q}{\partial \theta_R} = -q_R K_{q_R} (\theta_R)^{-q_R - 1}$$

Equating the Λ's yields

$$\frac{\dfrac{\partial\left(\frac{S}{N}\right)}{\partial d_T}}{\dfrac{\partial C_T}{\partial d_T}} = \frac{\dfrac{\partial\left(\frac{S}{N}\right)}{\partial P_T}}{\dfrac{\partial C_G}{\partial P_T}} = \frac{\dfrac{\partial\left(\frac{S}{N}\right)}{\partial \theta_R}}{\dfrac{\partial C_Q}{\partial \theta_R}} = \frac{\dfrac{\partial\left(\frac{S}{N}\right)}{\partial d_R}}{\dfrac{\partial C_R}{\partial d_R}}$$

The simultaneous solution of these equations yields expressions for the optimum values of the system parameters, d_{TO}, d_{RO}, P_{TO}, θ_{RO}, in terms of the variable cost.

(E4) Evaluate System Weight Burdens

The weight of the system components may be determined by evaluation of the following functional relations using optimum system parameters.

(C1) Transmitter antenna weight

$$W_{d_T} = K_{d_T} (d_{TO})^{n_T} + W_{KT}$$

(C2) Receiver antenna weight

$$W_{d_R} = K_{d_R}(d_{RO})^{n_R} + W_{KR}$$

(C3) Transmitter acquisition and track system weight

$$W_{QT} = W_{BT} + K_{W_{AT}} K_{d_{TO}} (d_{TO})^{n_T}$$

(C4) Receiver acquisition and track system weight

$$W_{QR} = W_{BR} + K_{W_{AR}} K_{d_{RO}} (d_{RO})^{n_R}$$

(C5) Transmitter and transmitter heat exchanger weight

$$W_T = K_{W_T}(P_{TO})^{h_T} + W_{KP}$$

$$W_H = K_X\left(\frac{1 - k_e}{k_e}\right) P_{TO} + W_{KH}$$

(C6) Modulation equipment weight

$$W_M = K_M R_B + W_{KM}$$

(C7) Demodulation equipment weight

$$W_D = K_D R_B + W_{KD}$$

(C8) Transmitter power supply weight

$$W_{ST} = K_{W_{ST}} \left\{ K_{P_M} K_M R_B + K_{P_M} W_{K_M} + \frac{P_{TO}}{k_e} \right.$$

$$\left. + K_{P_{QT}} \left[W_{BT} + K_{W_{AT}} K_{d_T} (d_{TO})^{n_T} \right] \right\} + W_{KE}$$

(C9) Receiver power supply weight

$$W_{SR} = K_{W_{SR}} \left\{ K_{P_D} K_D R_B + K_{P_D} W_{K_D} \right.$$

$$\left. + K_{P_{QR}} \left[W_{BR} + K_{W_{AR}} K_{d_R} (d_{RO})^{n_R} \right] \right\} + W_{KF}$$

The transmitter and receiver total system component weights are

$$W_A = W_{d_T} + W_{QT} + W_T + W_H + W_M + W_{ST}$$

$$W_B = W_{d_R} + W_{QR} + W_D + W_{SR}$$

where

W_A = total transmitter weight for optimum system parameters

W_B = total receiver weight for optimum system parameters.

(E5) <u>Evaluate System Power Burdens</u>

The optimum power requirements of the system burdens may be determined by evaluation of the following functional relations using optimum system parameters.

(C3) Transmitter acquisition and track system power requirement

$$P_{QT} = K_{P_{QT}} \left[W_{BT} + K_{W_{AT}} K_{d_T} (d_{TO})^{n_T} \right]$$

(C4) Receiver acquisition and track system power requirement

$$P_{QR} = K_{P_{QR}} \left[W_{BR} + K_{W_{AR}} K_{d_R} (d_{RO})^{n_R} \right]$$

(C5) Transmitter power requirement

$$P_{PT} = \frac{P_{TO}}{k_e} + P_{KT}$$

(C6) Modulation equipment power requirement

$$P_M = K_{P_M} K_M R_B + K_{P_M} W_{KM}$$

(C7) Demodulation equipment power requirement

$$P_D = K_{P_D} K_D R_B + K_{P_D} W_{KD}$$

The transmitter and receiver total power requirements are

$$P_A = P_{QT} + P_{PT} + P_M$$

and

$$P_B = P_{QR} + P_D$$

where

P_A = total transmitter power requirement for optimum system parameters

P_B = total receiver power requirement for optimum system parameters

(E6) Evaluate System Fabrication Cost Burdens

The optimum fabrication cost of the system components may be determined by evaluation of the following functional relations using optimum system parameters.

(C1) Transmitter antenna fabrication cost

$$C_{\theta_T} = K_{\theta_T} (d_{TO})^{m_T} + C_{KT}$$

(C2) Receiver antenna fabrication cost

$$C_{\theta_R} = K_{\theta_R} (d_{RO})^{m_R} + C_{KR}$$

(C3) Transmitter acquisition and track system fabrication cost

$$C_{NT} = C_{AT} + \frac{K_{AT}}{(\lambda)^{q_T}} (d_{TO})^{q_T}$$

(C4) Receiver acquisition and track system fabrication cost

$$C_{NR} = C_{AR} + K_{AR} (\theta_{RO})^{-q_R}$$

(C5) Transmitter and transmitter heat exchanger fabrication cost

$$C_{FL} = K_{P_T} (P_{TO})^{g_T} + C_{KP}$$

$$C_H = K_H \left(\frac{1 - k_e}{k_e} \right) P_{TO} + C_{KH}$$

(C6) Modulation equipment fabrication cost

$$C_{FM} = K_{FM} R_B + C_{KM}$$

(C7) Demodulation equipment fabrication cost

$$C_{FD} = K_{FD}R_B + C_{KD}$$

(C8) Transmitter power supply fabrication cost

$$C_{FT} = K_{ST}\left\{K_{P_M}K_MR_B + K_{P_M}W_{KM} + \frac{P_{TO}}{k_e} + K_{P_{QT}}\left[W_{BT} + K_{W_{AT}}K_{d_T}(d_{TO})^{n_T}\right]\right\} + C_{KE}$$

(C9) Receiver power supply fabrication cost

$$C_{FR} = K_{SR}\left\{K_{P_D}K_DR_B + K_{P_D}W_{KD} + K_{P_{QR}}\left[W_{BR} + K_{W_{AR}}K_{d_R}(d_{RO})^{n_R}\right]\right\} + C_{KF}$$

The transmitter and receiver total fabrication costs are

$$C_{FA} = C_{\theta_T} + C_{NT} + C_{FL} + C_H + C_{FM} + C_{FT}$$

and

$$C_{FB} = C_{\theta_R} + C_{NR} + C_{FD} + C_{FR}$$

where

C_{FA} = total transmitter fabrication cost for optimum system parameters

C_{FB} = total receiver fabrication cost for optimum system parameters

(E7) Evaluate System Component Cost Burdens

The total system cost of the system components which includes the fabrication cost and the cost of placing the components aboard a spacecraft may be determined by evaluation of the following functional relations using optimum system parameters.

(C1) Transmitter antenna cost

$$C_{d_T} = C_{\theta_T} + K_S W_{d_T}$$

(C2) Receiver antenna cost

$$C_{d_R} = C_{\theta_R} + K_S W_{d_R}$$

(C3) Transmitter acquisition and track system cost

$$C_{QT} = C_{AT} + K_S W_{QT}$$

(C4) Receiver acquisition and track system cost

$$C_{QR} = C_{AR} + K_S W_{QR}$$

(C5) Transmitter and transmitter heat exchanger cost

$$C_{P_T} = C_{FL} + C_H + K_S W_T + K_S W_H$$

(C6) Modulation equipment cost

$$C_M = C_{FM} + K_S W_M$$

(C7) *Demodulation equipment cost*

$$C_D = C_{FD} + K_S W_D$$

(C8) Transmitter power supply cost

$$C_{ST} = C_{FT} + K_S W_{ST}$$

(C9) Receiver power supply cost

$$C_{SR} = C_{FR} + K_S W_{SR}$$

(E8) Evaluate System Cost Burdens

The system cost variables for optimum system parameters are

$$C_{TO} = K_{q_T} (d_{TO})^{q_T} + K_{m_T} (d_{TO})^{m_T} + K_{n_T} (d_{TO})^{n_T}$$

$$C_{RO} = K_{m_R} (d_{RO})^{m_R} + K_{n_R} (d_{RO})^{n_R}$$

$$C_{QO} = K_{q_R} (\theta_{RO})^{-q_R}$$

$$C_{GO} = K_{g_T} (P_{TO})^{g_T} + K_{h_T} (P_{TO})^{h_T} + K_{j_T} (P_{TO})$$

The variable system cost is then

$$C_V = C_{GO} + C_{TO} + C_{QO} + C_{RO}$$

The total system cost is

$$C_S = C_V + C_{XT} + C_{XR}$$

The total transmitter and receiver costs are

$$C_A = C_G + C_T + C_{XT}$$

and

$$C_B = C_Q + C_R + C_{XR}$$

where

C_A = total transmitter cost for optimum system parameters

C_B = total receiver cost for optimum system parameters

APPENDIX B

COPTRAN

APPENDIX B

COPTRAN

This appendix is an extract from a final report for NAS 12-566 "Study and Development of a Mathematical Analysis for the Performance Assessment of Space Communication System Parameters," dated May 1969. The basic work and initial computer tabulations were done under contract NAS 5-9637. Subsequently a contract was made between the Hughes Aircraft Company and NASA-ERC to adapt the original work such that it could be easily used by a person not familiar with computer programming. COPTRAN is a result of the contract with NASA-ERC.

A complete documentation of COPTRAN is found in the referenced final report. Pertinent sections are given here which describe what the program can do and what is necessary to make it function. A single example is also given to indicate the output which may be obtained from the program.

B.0 USER'S MANUAL FOR COPTRAN, A METHOD OF OPTIMUM COMMUNICATION SYSTEM DESIGN

B.1 Introduction

Calculations to determine communication capability of a pulse or digital transmission link are basically dependent on a single equation which specifies the probability of detection error for one way transmission. While there are variants in this equation to account for different types of noise, modulation and demodulation techniques, this one equation documents the interrelationships among the communication system parameters of range, transmitter power, antenna gains, noise, etc. In the equation describing the probability of detection error it is possible to trade one system parameter value against others while maintaining a given performance. Thus, it is difficult to determine the "best" combination of parameters for a particular application although this is an important determination, especially to space missions. It is therefore desirable to formulate an analytical method or methodology of not only selecting parameters which produce the desired performance within the regulation of the range equation but of selecting optimum parameter values which meet the desired performance.

Consider the following relatively simple optimization example for a deep space communication system. The effective radiated power from a spacecraft is to be maximized for a specified weight. Now the effective radiated power may be increased by increasing either the size of the transmitting antenna or the transmitter power, or by some suitable combination of increases in these two parameters. The problem is to determine the proper split in weight between these two elements to maximize the effective radiated power subject to the given weight constraint. It is very unlikely that a combination of an extremely large antenna using almost all the available weight with a minimal transmitter would give the best possible performance, nor would the combination of an extremely heavy transmitter with a very low-gain antenna. The optimum configuration probably lies somewhere between these two extremes. In order to determine the optimum configuration, both transmitter power and antenna gain must be expressed in terms of weight. If these two relationships are known, a straight forward optimization procedure can be employed to determine the optimum values for both transmitter power and the antenna size associated with the resulting antenna gain.

Such an optimization concept has been expanded to all applicable parameter values in the equation describing the probability of detection error for both a weight optimization and a cost optimization. The resulting methodology has been implemented in a computer program known as COPS (Communication system Optimization Program with Stops).

The COPS program optimizes the values of the Major Communication Systems Parameters which are: the transmitter antenna diameter or gain, the receiver antenna diameter or gain, the transmitter power, and the receiver field of view. The program is implemented for radio frequency homodyne detection systems, optical frequency heterodyne detection systems, and for optical frequency thermal or shot noise limited direct detection systems.

The COPS program minimizes the total system cost for a given transmission range, information rate, and probability of detection error for each communication system. The total system cost is a function of the transmitter system weight, transmitter system fabrication cost, receiver system weight, and receiver system fabrication cost either singly or in any combination. Fixed values for any of the Major System Parameters may be entered into the programs. In addition, maximum or minimum parameter values, called stops, may be placed on each of the Major System Parameters. The COPS program provides an output tabulation of optimum values of Major System Parameters as a function of information rate.

The inputs required for the COPS program are a tabulation of Systems Physical Data such as: range, sky noise background, wavelength, transmissivity losses, etc; System Burdens Data such as: constants relating transmitter power to weight; antenna size to cost; etc., and System Parameter Constraints such as the minimum, maximum, or fixed values for the Major Systems Parameters.

The COPS program has been written in Fortran IV language. In order to facilitate the use of the COPS program by persons unfamiliar with computer operation or programming, a buffer computer language called COPTRAN (Communication system Optimization Program TRANslator) has been developed.

To operate the COPS optimization program using the COPTRAN language involves answering a few simple questions which are written in the language of the user. For instance one question is: "What is the transmission range?" Following this question is a choice of six letter mnemonics and their meanings. One of these, RANMAR, may be chosen to tell the COPS methodology through the COPTRAN buffer language that the range (RAN) is a Mars (MAR) distance, 10^8 km. Similar simple questions, again using a multiple choice listing of mnemonics, are answered for such topics as the modulation type, the type of optimization desired, the type of output desired, etc. The user may also use standard sets of data for the interrelationship of transmitter cost to power, etc. (burden relationships). Or the user may change one or all the nominal constants, thus superceding the stored values.

The mnemonic instructions and data values that are selected by the user to describe the problem he wishes to solve are written down by the user on a simple COPTRAN form. This form is then used as a guide to punch computer cards, one card per mnemonic or data value. The cards become part of the COPTRAN program and are batch processed by a computer. The computer results are returned to the user either in a line printout or in Cal Comp plots.

Figure B-1 summarizes the steps used to obtain optimized communications parameters using the COPS computer program with the COPTRAN language.

The major sections of the COPTRAN User's Manual which follow, are summarized briefly for convenience.

Section B. 2 – COPTRAN Programming Structure

The COPTRAN program has several parts, some of these are changed by the user and some are not in the course of solving a problem. This section contains a description of these parts, defines the terms used to describe them and indicates which parts are changed by the user when solving a problem.

Section B. 3 – COPTRAN Program Entry

Simple forms for problem entry are provided to aid the user in describing his problem in COPTRAN language. The forms are marked to indicate where the symbols are placed and where the numerical value for the data is placed.

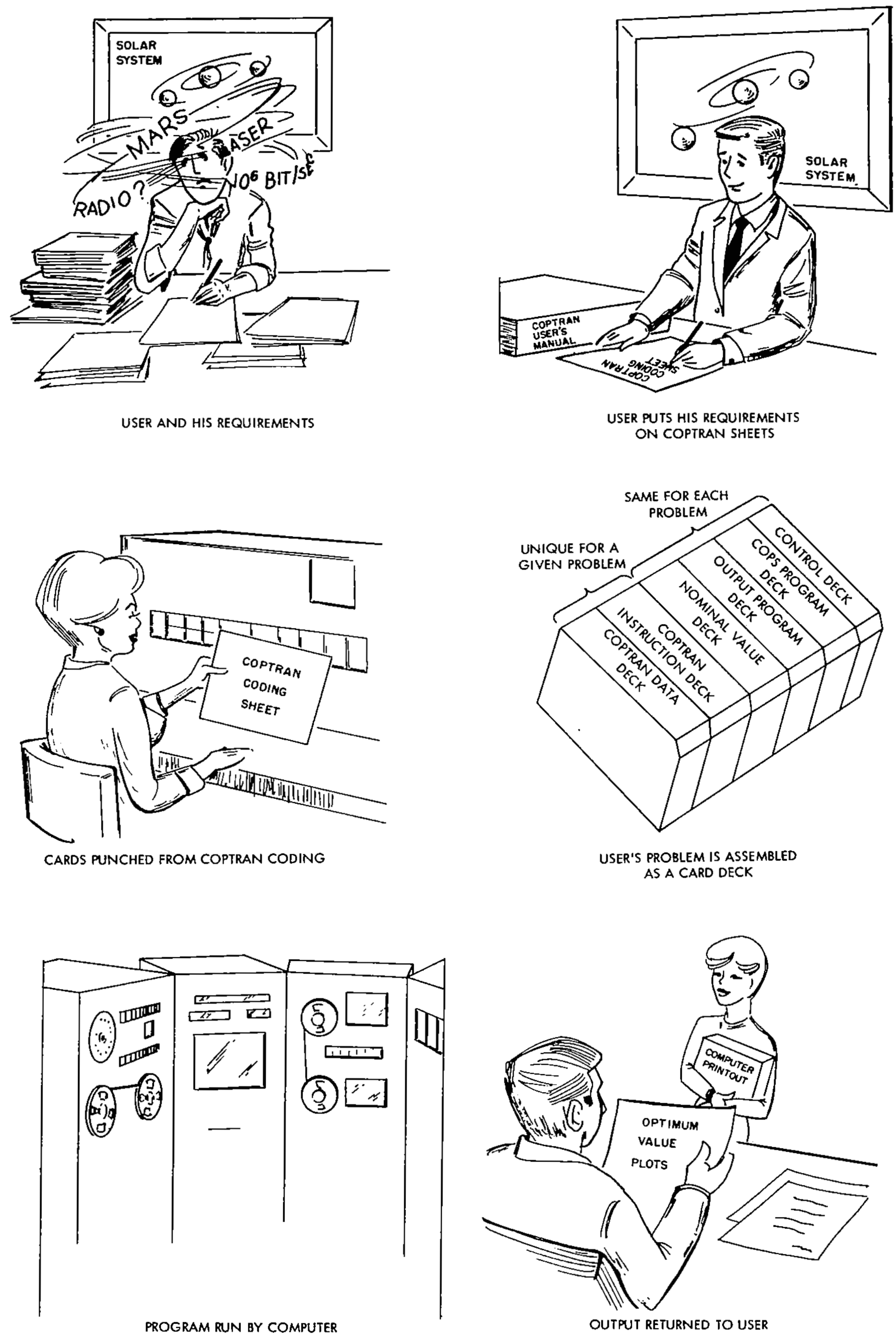


Figure B-1. COPTRAN Programming

The program entry procedure needed for a computer facility using the IBM 7094/IBSYS or the GE 635/GECOS III is also given.

Section B. 4 — COPTRAN Use

This section is the one used by the user's to put his problem in COPTRAN language. The user considers each of the several categories and enters mnemonics on the COPTRAN forms (see Section 4. 3) as appropriate. Section 4. 4 is complete, containing all of the COPTRAN mnemonic values.

Section B. 5 — COPTRAN Use Simplified

The simplified version of COPTRAN does not provide all the flexibility of the general program. As such it limits the problems that may be solved. Its advantage is it allows a user to obtain optimized solutions without the general program complexity.

Section B. 6 — COPTRAN Examples

Seven examples are given in COPTRAN solutions. These examples have been designed to indicate the capabilities of COPTRAN by using its various features.

All program solutions published except Example E have been obtained from the IBM 7094/IBSYS computer and verified on the GE 635/GECOS III computer. The published solution for Example E has been obtained from the GE 635/GECOS III computer.

Section B. 7 — COPTRAN Multiple Case

COPTRAN multiple case subprograms include the "Increment" subprogram, the "Repeat" subprogram, the "Worth" subprogram and the "New Set" subprogram. These are briefly described in Section B. 4, COPTRAN Use, but are given in further detail here.

Section B. 8 — COPTRAN Error Messages

The use of error messages is noted in Section B. 4. The actual messages are given.

Section B. 9 — COPTRAN Automatic Data Selection

Many values used in the COPTRAN optimum solutions are taken from data storage. This section lists the values used and the conditions under which they become part of the COPTRAN program.

Section B. 10 — COPTRAN Nominal Value Decks

The mnemonics selected by the user or by the COPTRAN program in turn select numerical values for a large number of constants (e.g., those relating transmitter power to weight) used in a given solution. The numerical values are listed in this section. Also given are means for changing or adding to the data storage.

B. 2 COPTRAN Structure

B. 2. 1 Introduction. – The COPTRAN programming language is a specialized, simple computer language used in the design of communication systems. COPTRAN allows a user to determine the optimum configuration of a complex communication system with relatively few instructions phrased in the context of his problem and without the necessity of supplying large quantities of data to the computer. This is accomplished by storing nominal values of the program data in the computer data banks. The pertinent data for a particular problem is then automatically fetched by the COPTRAN program unless countermanded by particular user selections.

A COPTRAN job is composed of six main parts which are subdivided as follows:

COPTRAN Control Program COPS Program Output Program Nominal Value Data	COPTRAN System Program
COPTRAN Instructions COPTRAN Data	COPTRAN User Program

The first four parts of a COPTRAN job comprise the COPTRAN System Program. This program is configured for a particular computer installation; it is not changed by the general user. The last two parts of a COPTRAN job are the COPTRAN User Program, which is written by the user for each problem. This manual is largely a description of the COPTRAN User Program.

Table B-I summarizes the nomenclature for the COPTRAN structure while Table B-II gives the COPTRAN programming nomenclature used in this manual.

The following two parts of this section describes the basic use of COPTRAN instructions and COPTRAN data, which are the user supplied parts of a COPTRAN job.

TABLE B-I
COPTRAN STRUCTURE NOMENCLATURE

COPTRAN System Program	The COPTRAN System Program is composed of FORTRAN IV programming language statements and is in four basic parts: 1) the COPTRAN Control Program, 2) the COPS Program, 3) the Output Program, and 4) the Nominal Value Data. The COPTRAN System Program may be in either FORTRAN source or object format for a particular computer installation.
COPTRAN Control Program	A program which decodes the COPTRAN User Program instructions and provides linkages between COPTRAN System Programs.
COPS Program	A program which provides optimum values of system parameters and evaluation of associated cost, weight, and power burdens of a communication system as a function of information rate.
Output Program	A program which controls the format and presentation of output tabulations and plots.
Nominal Value Data	Lists of System Physical Data, System Burdens Data, and System Parameter Constraints Data from which automatic selections are made.
COPTRAN	A User Program list of instruction mnemonics and data entries which automatically provides information for the performance of the COPS program.
COPTRAN Instructions	Lists of mnemonics selected by the user to describe his problem, the method of optimization, and the presentation of the results.
COPTRAN Data	COPTRAN Data selected by the user to incorporate individual burdens, physical data, and parameter contraints into the COPTRAN solution.

TABLE B-II
COPTRAN PROGRAMMING NOMENCLATURE

Job	That which is submittal to the computer. It consists of a COPTRAN System Program, a COPTRAN User Program, and whatever submittal information is required by a computer installation.
Case	A single solution of optimization equations by COPS program.
Run	The results of one or more cases obtained by repeated performance of COPS program under direction of the increment or repeat subprograms or the new instruction/data set.
Instruction/data set	A list of COPTRAN instruction mnemonics and data entries.
Instruction/data category	A grouping of related instructions or data entries.

B.2.2 COPTRAN Instructions. – COPTRAN instructions are single mnemonics which describe the communication problem to be solved, the method of optimization, and the presentation of results. The instructions are divided into the following five classifications.

1. Physical Environment, which includes:

   Transmitter location (spacecraft)

   Receiver location (earth)

   Transmission range (one of a set of selected ranges may be chosen to indicate physical environment or another range choice may be made and the environment specified)

   Background (choice of physical source of background radiation)

2. Communication System, which includes:

   Transmission wavelength (one selected wavelength may be chosen)

   Modulation and demodulation methods (choice of one of several sets available).

3. Optimization Basis, which includes:

   Weight/fabrication cost optimization: (transmitter system weight, transmitter system fabrication cost, receiver system weight, and receiver system fabrication cost may be minimized individually or in any combination).

   Antenna Parameter Optimization: (Transmitter antenna gain or diameter and receiver antenna gain or diameter may be optimized).

4. Processing, which includes:

   Computation format (choice of initial and final values of information rate and number of information rate data points calculated).

   Print format (choice of data and results to be printed in tabular form).

   Plot format (choice of results to be plotted by Cal Comp plotter).

5. Nominal System Burdens* (see Section B. 10 for description)

   Choices of system burdens may be made from a data bank list if automatic selections are not desired. (Section B. 9 describes automatic data selection.) System burdens values may also be entered as new data if desired.

B. 2. 3 COPTRAN Data. – COPTRAN data is the means by which individual burdens, physical data, and parameter constraints are inserted into the COPTRAN User Program. If the automatic burdens and physical data selections provided by the COPTRAN instructions are acceptable to the user, and no parameter constraints are specified, there will be no COPTRAN Data for the COPTRAN User Program. The COPTRAN User Program has been developed so that user supplied COPTRAN Data automatically replaces items of data normally selected from data banks. The program data is of three types.

*Burdens represent the modeled relationship between system parameters and the weight, fabrication cost, and power requirement of a component. For example, the transmitter system weight, W_X, may be modeled in terms of the transmitter power, P_T as $W_X = K_{W_T}(P_T)^{h_T} + W_{KP}$ where K_{W_T}, h_T, and W_{KP} are burden constants.

1. <u>System Physical Data</u>

   Physical data such as signal-to-noise ratio, atmospheric transmissivity, receiver temperature, etc.

2. <u>System Burdens Data</u>

   Weight, fabrication cost, and power requirement burdens for communication system components.

3. <u>System Parameter Constraints</u>

   These are fixed and stop values of the Major Communication System Parameters, namely transmitting or receiving antenna gains or diameters, transmitter power, and receiver field of view. (A "fixed" parameter value is one that remains fixed throughout all portions of the optimization. A "stop" in the parameter value is the minimum or maximum value the parameter may take. For instance, a communication problem may require a fixed antenna diameter for a receiving antenna on earth of 64 meters and have a stop value for a space antenna diameter of 10 meters. The optimization program will determine the optimum split between the spacecraft antenna size and spacecraft power as a function of data rate. As the data rate requirements increase, the transmitter power and transmitting antenna size will increase until the antenna size of 10 meters is reached. For larger data rates, the antenna size will remain at 10 meters and the transmitter power will increase, at a faster rate now, to meet the demands of higher data rates.)

B. 3 COPTRAN Program Entry

B. 3. 1 Introduction. — The main concern of the COPTRAN user relative to program entry, is how to place the COPTRAN instruction mnemonics and data values in the proper location on the COPTRAN coding sheets. This coding is unique for each COPTRAN job. It is described in Section B. 3. 2 below.

The necessary program entry cards to make COPTRAN operate on a given computer need be worked out only once for a given facility. The cards necessary for the IBM 7094/IBSYS and the GE635/GOCOS III are described in Section B. 3. 3 below.

B. 3. 2 Instruction and Data Format. — A COPTRAN program is composed of mnemonic instructions and data values which are entered on COPTRAN coding sheets (see Figures B-2 to B-5). Punched cards are then produced from these coding sheets to obtain the COPTRAN program card deck.

COPTRAN instruction mnemonics, six characters in length, are placed in columns 1 to 6 of a COPTRAN coding sheet. Columns 25 to 80 may be used for user comments. The program ignores entries in these columns. Examples of COPTRAN instructions are given below.

Transmitter location: spacecraft (SPXMTR)

Instruction (1-6)							Description (25-80)			
1	2	3	4	5	6	25	26	. . .	79	80
S	P	X	M	T	R					

Modulation method: PCM amplitude modulation (PCM/PL)

Instruction (1-6)							Description (25-80)			
1	2	3	4	5	6	25	26	. . .	79	80
P	C	M	/	P	L					

COPTRAN data is in two parts, a label consisting of characters and a field consisting of up to fourteen characters in either fixed or floating point form. Small amounts of data are usually entered on COPTRAN Coding Sheet A (see Figure B-2) by the user for subsequent key punching with the COPTRAN instructions. If a large amount of data is to be entered, COPTRAN Coding

Sheets B, C, and D shown in Figures B-3 and B-5 respectively may be utilized. These later coding sheets contain preprinted data labels. Each data parameter will be punched on a single card.

The data label must be justified left in columns 1 to 6 on the coding sheet. Columns 7, 8, 23, and 24 are left blank. The data value is entered in columns 9 to 22. Columns 25 to 80 may be employed for users comments.

Examples of fixed and floating point entries in the data field are given below. The decimal point in both cases is always in column 14. For floating point numbers the letter E must appear in column 19 followed by the sign (±) in column 20. The exponent must be justified right to column 22.

Floating point entry: QBEE = 7.5×10^{13}

Data label (1-6) | Data value (9-22) | Description (25-80)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	. . .	79	80
Q	B	E	E									7	•	5				E	+	1	3							

Fixed point entry: TAUR = 0.95

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	. . .	79	80
T	A	U	R										•	9	5													

COPTRAN CODING SHEET A

NAME ______________________ DATE __________ PROBLEM ______________________________

COPTRAN INSTRUCTIONS AND DATA

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19 (E)	20	21	22	23	24
1																								
2																								
3																								
4																								
5																								
6																								
7																								
8																								
9																								
10																								
11																								
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24																								
25																								
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19 (E)	20	21	22	23	24
1																								
2																								
3																								
4																								
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22																								
23																								
24																								
25																								
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

Figure B-2. COPTRAN Coding Sheet A

COPTRAN CODING SHEET B

NAME ____________________ DATE __________ PROBLEM ______________________________

COPTRAN INSTRUCTIONS AND DATA

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	E 19	20	21	22	23	24
1	K	T	H	T										•										
2	H	T	H	T										•										
3	K	D	T											•										
4	H	D	T											•										
5	C	K	T											•										
6	W	K	T											•										
7	M	T												•										
8	N	T												•										
9	K	A	T											•										
10	K	W	A	T										•										
11	K	P	Q	T										•										
12	C	A	T											•										
13	W	B	T											•										
14	Q	T												•										
15	K	F	M											•										
16	K	M												•										
17	K	P	M											•										
18	C	K	M											•										
19	W	K	M											•										
20	K	S	T											•										
21	K	W	S	T										•										
22	C	K	E											•										
23	W	K	E											•										
24																								
25																								

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	E 19	20	21	22	23	24
1	K	T	H	R										•										
2	H	T	H	R										•										
3	K	D	R											•										
4	H	D	R											•										
5	C	K	R											•										
6	W	K	R											•										
7	M	R												•										
8	N	R												•										
9	K	A	R											•										
10	K	W	A	R										•										
11	K	P	Q	R										•										
12	C	A	R											•										
13	W	B	R											•										
14	Q	R												•										
15	K	F	D											•										
16	K	D												•										
17	K	P	D											•										
18	C	K	D											•										
19	W	K	D											•										
20	K	S	R											•										
21	K	W	S	R										•										
22	C	K	F											•										
23	W	K	F											•										
24																								
25																								

Figure B-3. COPTRAN Coding Sheet B

COPTRAN CODING SHEET C

NAME ____________________ DATE __________ PROBLEM ____________________

COPTRAN INSTRUCTIONS AND DATA

Line	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19 (E)	20	21	22	23	24
1	K	P	T											.										
2	K	W	T											.										
3	K	H												.										
4	K	X												.										
5	K	D												.										
6	C	K	P											.										
7	C	K	H											.										
8	W	K	P											.										
9	W	K	H											.										
10	G	T												.										
11	H	T												.										
12	J	T												.										
13	K	S	A											.										
14	K	S	B											.										
15																								
16																								
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19																								
20																								
21																								
22																								
23																								
24																								
25																								

Line	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19 (E)	20	21	22	23	24
1	R	A	N	G										.										
2	L	M	D	A										.										
3	S	N	R	R										.										
4	P	E	R	R										.										
5	T	A	U	T										.										
6	T	A	U	R										.										
7	T	A	U	A										.										
8	E	T	A	A										.										
9	R	L	L	L										.										
10	L	M	D	I										.										
11	Q	B	E	E										.										
12	R	H	Ø	T										.										
13	R	H	Ø	R										.										
14	T	E	M	P										.										
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25																								

Figure B-4. COPTRAN Coding Sheet C

COPTRAN CODING SHEET D

NAME ______________________ DATE __________ PROBLEM ______________________________

SYSTEM PARAMETER CONSTRAINTS DATA

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	E 19	20	21	22	23	24
1	D	T	M											.										
2	G	T	M											.										
3	D	R	M											.										
4	G	R	M											.										
5	P	T	M											.										
6	T	R	M											.										
7	D	T	B											.										
8	G	T	B											.										
9	D	R	B											.										
10	G	R	B											.										
11	P	T	B											.										
12	T	R	B											.										
13	D	T	L											.										
14	G	T	L											.										
15	D	R	L											.										
16	G	R	L											.										
17	P	T	L											.										
18	T	R	L											.										
19																								
20																								
21																								
22																								
23																								
24																								
25																								

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	E 19	20	21	22	23	24
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Figure B-5. COPTRAN Coding Sheet D

B. 3. 3 Job Entry for Computer Installations. – The COPTRAN job card deck consists of the COPTRAN System Program card deck, the COPTRAN User Program card deck, and any submittal control cards required for a particular computer installation. The COPTRAN System Program card deck should not be altered by the general user. COPTRAN job deck structures for an IBM 7094/IBSYS and a GE 635/GECOS III computer installation are shown in Figures B-6 and B-7. The submittal control cards required for these installations are identified by a "$" in card column 1.

As presently implemented COPTRAN on the IBM 7094/IBSYS Version 13 computer installation does not execute the North Subprogram due to memory (3 limitations. The GE 635/GECOS III computer installation provides all of the COPTRAN features.

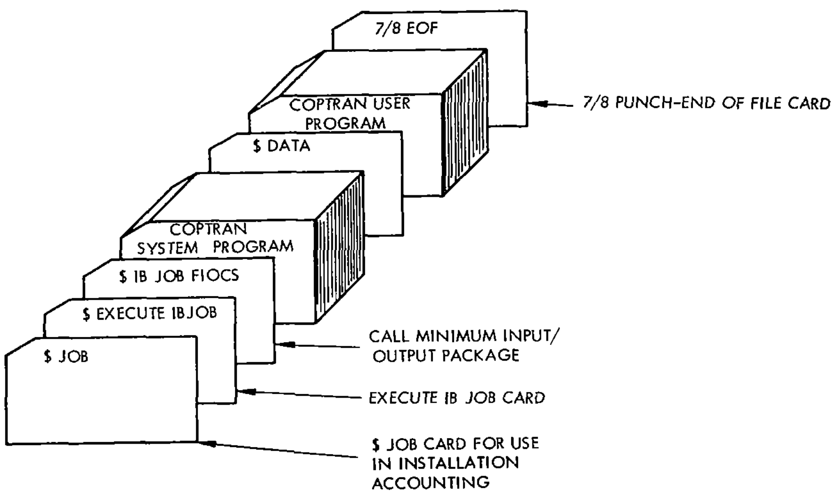

Figure B-6. COPTRAN Job Deck Structure for an IBM 7094/IBSYS Version 13 Computer Installation

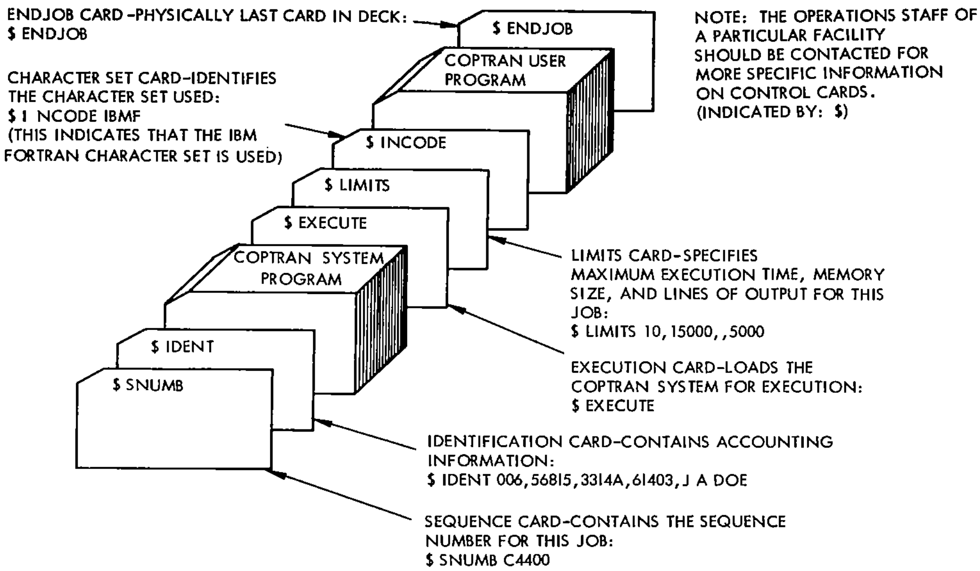

Figure B-7. COPTRAN Job Deck Structure for a GE 635/GECOS III Computer Installation

B.4 COPTRAN Use — A Complete Listing of COPTRAN Instructions and Data Mnemonics

This section contains a complete listing of COPTRAN instruction and data mnemonics including a brief description of all of the COPTRAN subprograms. In order to specify a problem properly the user must consider each COPTRAN category sequentially. In some instances several instructions or data entries must be selected in each category. The notes associated with each category indicate the restrictions that must be observed.

The user's attention is called to: Section B. 5, which describes a simplified version of COPTRAN use. A version that does not require consideration of the subprograms (Increment, Repeat, Worth, etc.), but does provide complete optimization; to Section B. 6 which give examples of COPTRAN use; and to Section B. 7 which describes the multiple case subprograms in greater detail. The categories and their titles are as follows:

Category	
1	Transmitter Location
2	Receiver Location
3	Transmission Range
4	Background
5	Transmission Wavelength
6	Modulation and Demodulation Methods
7	Optimization Basis
8	Computational Format
9	Case Title
10	Print Format
11	Plot Format
*12	Worth Subprogram
13	Nominal System Burdens
14	System Physical Data
15	System Burdens Data
16	System Parameter Constraints Data
17	Increment Subprogram
18	Process
19	Repeat Subprogram
20	New Set
21	End of Run

*Not presently implemented on the IBM 7094/IBSYS Version 13 computer installation.

Complete Listing of COPTRAN Instruction and Data Mnemonics

Note: 1. Circled entries indicate instruction and date categories that must be supplied for every COPTRAN User Program

2. Descriptions of instructions and data in columns 25 to 80 may be changed or omitted without affecting program.

Category 1 — Transmitter Location (Choose only one)

Note: If no choice is made, program selects SPXMTR instruction.

Instruction (1-6)*	Description (25-80)
SPXMTR**	Spacecraft transmitter

Category 2 — Receiver Location (Choose only one)

Note: If no choice is made, program selects EARCVR instruction.

Instruction (1-6)	Description (25-80)
EARCVR**	Earth receiver

*Indicates column numbers, see Section B. 3. 2.

**If Earth transmitter and/or space receiver are desired, these mnemonics may be used and appropriate changes can be made using categories 13, 14, 15.

Category (3) — Transmission Range (Choose only one)

Note: 1. If no choice is made, program prints an error message and proceeds to next case specified by NEWSET (see Category 20) instruction.

2. If RANØTH instruction is selected, range value must be included with COPTRAN data in Category 14 statement. In addition, power supply burdens in Category 13 and/or 15 statements indicated by dagger (†) that are affected by range must be supplied. Failure to comply with this rule causes an error message to be printed. The program then proceeds to next case specified by NEWSET (see Category 20) instruction.

Instruction (1-6)	Description (25-80)
RANMAR	Mars range (1. 0 E + 13 cm)
RANJUP	Jupiter range (7. 5 E + 13 cm)
RANSAT	Synchronous satellite range (3. 6 E + 9 cm)
RANØTH*	Other range value

Category (4) — Background (Choose only one)

Note: If no choice is made, program prints an error message and proceeds to next case specified by NEWSET (see Category 20) instruction.

Instruction (1-6)	Description (25-80)
BKDSKY	Day sky (for optical transmission)
BKNSKY	Night sky (for optical transmission)
BKGALT	Galactic (for radio transmission)

*If desired, RANMAR, RANJUP or RANSAT may be chosen in order to select burdens pertinent to these general ranges and then specify the exact range by use of the RANG data value change (see Category 14).

Category	Transmission Wavelength (Choose only one)
(5)	Note: 1. If no choice is made, program prints an error message and proceeds to next case specified by NEWSET (see Category 20) instruction. 2. If LAMØTH instruction is selected, the following must also be done: (a) the wavelength value must be included with COPTRAN data in Category 14 statement, (b) system physical data in Category 13 and/or 15 statements indicated by asterisk (*) that are affected by wavelength must be supplied. (c) stop values must be supplied for the non-fixed maximum and minimum values of the four major system parameters (see Figure B-5 and see Category 16). Failure to comply with these rules causes an error message to be printed. The program then proceeds to next case specified by NEWSET (see Category 20) instruction.

Instruction (1-6)	Description (25-80)
LAM051	λ = 0.51 micron
LAM084	λ = 0.84 micron
LAM106	λ = 10.6 microns
LAM13C	λ = 13 cm (2.3 GHz)
LAMØTH*	Other wavelength value

*If desired, LAM051, LAM084, LAM06 or LAM13C may be chosen in order to select burdens pertinent to these general frequencies and then specify the exact frequency by use of the LMDA data value change (see Category 14.)

Category ⑥ — <u>Modulation and Demodulation Methods</u> (Choose only one modulation and demodulation <u>pair</u>)

Note:
1. If no choice is made program prints an error message and proceeds to next case specified by NEWSET (see Category 20) instruction.
2. Systems burdens are available for automatic data selection only for those modulation and demodulation methods indicated by "available" in the table below. If any other selections of modulation and demodulation methods are made system burdens in Category 13 and/or 15 statements must be supplied. Shaded squares in the table below indicate that modulation and demodulation methods are not compatible with transmission frequency. Failure to comply with this rule causes an error message to be printed. The program then proceeds to next case specified by NEWSET (see Category 20) instruction.

System Burdens Availability

Modulation Demodulation Method	Transmission Wavelength			
	λ = 0.51 micron	λ = 0.84 micron	λ = 10.6 micron	λ = 13 cm
PCM/AM ØPTDIR	not currently available	not currently available	available	(shaded)
PCM/PS ØPTDIR	available	not currently available	not currently available	(shaded)
PCM/PL ØPTDIR	available	not currently available	not currently available	(shaded)
PCM/FM ØPTHET	not currently available	not currently available	available	(shaded)
PCM/PM RADHØM	(shaded)	(shaded)	(shaded)	available

Instruction (1-6)	Description (25-80)
PCM/AM	PCM amplitude modulation
ØPTDIR	Optical direct detection
PCM/PL	PCM polarization modulation
ØPTDIR	Optical direct detection
PCM/FM	PCM frequency modulation
ØPTHET	Optical heterodyne detection
PCM/PM	PCM phase modulation
RADHØM	Radio homodyne detection
PCM/PS	PCM pulse shift modulation
ØPTDIR	Optical direct detection

Category ⑦ **Optimization Basis** (Choose from each of the two subcategories)

Note: If indicated choices are not made, program prints an error message and proceeds to next case specified by NEWSET (see Category 20) instruction.

7a Weight/Fabrication Cost Optimization (Choose at least one; multiple choices provide joint optimization.)

Instruction (1-6)	Description (25-80)
XMWTØP	Transmitter weight optimization
RCWTØP	Receiver weight optimization
XMFCØP	Transmitter fabrication cost optimization
RCFCØP	Receiver fabrication cost optimization

Note: If receiver parameters d_R or G_R and θ_R or transmitter parameters d_T or G_T and P_T are not to be optimized in weight or fabrication cost, their fixed values must be given in Category 15 statement. Selection of more than one instruction in this subcategory provides joint optimization of burdens (i. e., fabrication cost or weight) selected.

7b Antenna Parameter Optimization (Choose only one as indicated)

Instruction (1-6)	Description (25-80)
DTDRØP	Transmitter antenna diam. and receiver antenna diam. opt.
GTDRØP	Transmitter antenna gain and receiver antenna diam. opt.
DTGRØP	Transmitter antenna diam. and receiver antenna gain opt.
GTGRØP	Transmitter antenna gain and receiver antenna gain opt.

Note:
1. Transmitter or receiver antenna gain optimization is to be used only for radio frequency systems.
2. If no choice is made, DTDRØP is automatically selected.

Category	Computation Format (Choose one of each)
8	Note: 1. If no choice is made, program selects RBINT0, RBFIN9, RBFRQ2 instructions.
	2. Final information rate, R_B, must be greater than initial information rate. Failure to comply with this rule causes an error message to be printed. The program then proceeds to next case specified by NEWSET (see Category 20) instruction.

Instruction (1-6)	Description (25-80)
RBINT __	Initial information rate
RBFIN __	Final information rate
RBFRQ __	Number of computations per decade

Initial Information Rate Instructions

RBINT0	RBINT1	RBINT2	RBINT3	RBINT4
$R_B = 10^0$	$R_B = 10^1$	$R_B = 10^2$	$R_B = 10^3$	$R_B = 10^4$
RBINT5	RBINT6	RBINT7	RBINT8	
$R_B = 10^5$	$R_B = 10^6$	$R_B = 10^7$	$R_B = 10^8$	

Final Information Rate Instruction

RBFIN1	RBFIN2	RBFIN3	RBFIN4	RBFIN5
$R_B = 10^1$	$R_B = 10^2$	$R_B = 10^3$	$R_B = 10^4$	$R_B = 10^5$
RBFIN6	RBFIN7	RBFIN8	RBFIN9	
$R_B = 10^6$	$R_B = 10^7$	$R_B = 10^8$	$R_B = 10^9$	

Number of Computations per Decade Instruction

RBFRQ1	RBFRQ2	RBFRQ4	RBFRQ5	RBFRQ8	RBFRQ9
10^n	10^n	10^n	10^n	10^n	10^n
10^{n-1}	0.5×10^n	0.75×10^n	0.8×10^n	0.875×10^n	0.9×10^n
	10^{n-1}	0.50×10^n	0.6×10^n	0.750×10^n	0.8×10^n
		0.25×10^n	0.4×10^n	0.625×10^n	0.7×10^n
		10^{n-1}	0.2×10^n	0.500×10^n	0.6×10^n
			10^{n-1}	0.375×10^n	0.5×10^n
				0.250×10^n	0.4×10^n
				0.125×10^n	0.3×10^n
				10^{n-1}	0.2×10^n
					10^{n-1}

Category   Case Title (Choose if desired)

9

Instruction (1-6)	Description (25-80)
TITLEE	(Title to be printed on tabulation and plots for each instruction/data set.)

Category 10 — Print Format (Choose instructions desired)

Note:

1. If no choice is made, program selects PRTALL instruction.
2. See Worth subprogram, Section 4.7.4, description for further information on PRTWTH instruction.

Instruction (1-6)	Description (24-80)
PRTBUR	Print system burdens data
PRTSPD	Print system physical data
PRTSNC	Print signal-to-noise ratio constants
PRTBRC	Print system burden constants
PRTSPC	Print parameter constraints
PRTØPT	Print optimum system parameters
PRTWGT	Print weight burdens for opt. system parameters
PRTPWP	Print power burdens for opt. system parameters
PRTFAB	Print fab cost burdens for opt. system parameters
PRTSYC	Print system cost burdens for opt. system parameters
PRTALL	Print all data and results
PRTDAT	Print all data
PRTWTH	Print Worth instruction results

Category   Plot Format (Choose up to five as desired)

11   Note:

1. If no choice is made, program does no plotting.
2. If more than five choices are made, program selects only first five choices.
3. See worth subprogram description, Section 4.7.4, for further information on PLTWTH instruction.

Instruction (1-6)	Description (25-80)
PLTØPT	Plot optimum system parameters
PLTDTØ	Plot optimum value of transmitter antenna diameter
PLTGTØ	Plot optimum value of transmitter antenna gain
PLTDRØ	Plot optimum value of receiver antenna diameter
PLTGRØ	Plot optimum value of receiver antenna gain
PLTPTØ	Plot optimum value of transmitter power
PLTTRØ	Plot optimum value of receiver field of view
PLTWDT	Plot transmitter antenna weight
PLTWDR	Plot receiver antenna weight
PLTWQT	Plot transmitter acquisition and track equipment weight
PLTWQR	Plot receiver acquisition and track equipment weight
PLTWXM	Plot transmitter weight
PLTWHX	Plot transmitter heat exchanger weight
PLTWMD	Plot modulation equipment weight
PLTWDM	Plot demodulation equipment weight
PLTWST	Plot transmitter power supply weight
PLTWSR	Plot receiver power supply weight
PLTWAY	Plot transmitter system weight
PLTWBY	Plot receiver system weight
PLTPQT	Plot transmitter acq. and track equipment power req.
PLTPQR	Plot receiver acq. and track equipment power req.
PLTPXM	Plot transmitter power requirement
PLTPMD	Plot modulation equipment power requirement
PLTPDM	Plot demodulation equipment power requirement
PLTPAY	Plot transmitter system power requirement

PLTPBY	Plot receiver system power requirement
PLTCDT	Plot transmitter antenna fabrication cost
PLTCDR	Plot receiver antenna fabrication cost
PLTCQT	Plot transmitter acq. and track equipment fab. cost
PLTCQR	Plot receiver acq. and track equipment fab. cost
PLTCXM	Plot transmitter fabrication cost
PLTCHX	Plot transmitter heat exchanger fabrication cost
PLTCMD	Plot modulation equipment fabrication cost
PLTCDM	Plot demodulation equipment fabrication cost
PLTCST	Plot transmitter power supply fabrication cost
PLTCSR	Plot receiver power supply fabrication cost
PLTCAY	Plot transmitter system fabrication cost
PLTCBY	Plot receiver system fabrication cost
PLTCTY	Plot transmitter antenna cost burden
PLTCRY	Plot receiver antenna cost burden
PLTCQY	Plot receiver field of view cost burden
PLTCGY	Plot transmitter power cost burden
PLTCVY	Plot optimization cost
PLTCSY	Plot total system cost
PLTWTH	Plot worth instruction results

Category 12 — <u>Worth Subprogram</u> (Choose instruction if it is desired to evaluate the effect of varying a single data entry)

Note:
1. (Worth parameter) entry must follow immediately after WORTHE instruction.
2. The Worth subprogram requires the use of either the Increment or Repeat subprograms to vary a data entry.
3. Failure to comply with the above rules causes an error message to be printed. The program then proceeds to next case specified by NEW SET instruction.
4. See Worth subprogram description, Section 4.7.4, for further information.

Instruction or Data Label (1-6)	Description (25-80)
WORTHE	Worth instruction
(Worth parameter)	Worth output parameter

Category 13 — Nominal System Burdens (Choose desired system burdens data from subcategories 13A through 13I as indicated)

Note:

1. If no choices are made in a subcategory program automatically selects values for system burdens data, unless superseded by a Category 15 (Systems Burden Data) statement.
2. If a choice is made in a subcategory, it supersedes automatic selection unless superseded by Category 15 statement.
3. If more than one choice is made per subcategory program selects first choice.
4. Entries with dagger (‡) are transmission range dependent and must be supplied by either Category 13 or 15 statements when RANØTH instruction is selected.
5. Entries with asterisk (*) are transmission wavelength dependent and must be supplied by either Category 13 or 15 statements when LAMØTH instruction is selected.
6. Failure to comply with above rules causes an error message to be printed. The program then proceeds to next case specified by NEWSET (see Category 20) instruction.

Instruction (1-6)	Description (25-80)
13A	*Transmitter Antenna Burdens (Choose only one)
NXANTA	λ = 0.51 micron, spacecraft
NXANTC	λ = 0.84 micron, spacecraft
NXANTD	λ = 10.6 microns, spacecraft
NXANTF	λ = 13 cm, diameter burdens, spacecraft
NXANTG	λ = 13 cm, gain burdens, spacecraft
13B	*Receiver Antenna Burdens (Choose only one)
NRANTA	λ = 0.51 micron, optical direct detection, earth
NRANTB	λ = 0.51 micron, optical heterodyne, earth
NRANTC	λ = 0.84 micron, optical direct detection, earth

*See note 5 above.

NRANTD	λ = 10.6 microns, optical direct detection, earth
NRANTE	λ = 10.6 microns, optical heterodyne, earth
NRANTF	λ = 13 cm, diameter burdens, earth
NRANTG	λ = 13 cm, gain burdens, earth
13C	Transmitter Acquisition and Track Burdens (Choose only one)
NXACTA	Optical frequencies, spacecraft
NXACTB	Radio frequencies, spacecraft, diameter burdens
NXACTC	Radio frequencies, spacecraft, gain burdens
13D	Receiver Acquisition and Track Burdens (Choose only one)
NRACTA	Optical frequencies, earth
NRACTB	Radio frequencies, earth, diameter burdens
NRACTC	Radio frequencies, earth, gain burdens
13E	*Modulation Equipment Burdens (Choose only one)
NMØDEA	λ = 0.51 micron, CW laser, spacecraft
NMØDEB	λ = 0.84 micron, CW laser, spacecraft
NMØDEC	λ = 0.84 micron, pulsed laser, spacecraft
NMØDED	λ = 10.6 microns, CW laser, spacecraft
NMØDEE	λ = 13 cm, spacecraft
NMØDEF	λ = 0.51 micron, CW laser, earth
NMØDEG	λ = 0.84 micron, CW laser, earth
NMØDEH	λ = 0.84 micron, pulsed laser, earth
NMØDEI	λ = 10.6 microns, CW laser, earth
NMØDEJ	λ = 13 cm, earth
13F	*Demodulation Equipment Burdens (Choose only one)
NDMØDA	Optical direct detection, earth
NDMØDB	Optical heterodyne detection, earth
NDMØDC	Optical homodyne detection, earth
NDMØDE	13 cm radio homodyne detection, earth
NDMØDF	Optical direct detection, spacecraft
NDMØDG	Optical heterodyne detection, spacecraft

*See note 5 above.

NDMØDH	Optical heterodyne detection, spacecraft
NDMØDI	13 cm radio direct detection, spacecraft
NDMØDJ	13 cm radio homodyne detection, spacecraft
13G	*Transmitter Burdens (Choose only one)
NXMTRA	λ = 0.51 micron, spacecraft
NXMTRB	λ = 0.51 micron, earth
NXMTRE	λ = 10.6 microns, spacecraft
NXMTRF	λ = 10.6 microns, earth
NXMTRG	λ = 13 cm, spacecraft
NXMTRH	λ = 13 cm, earth
13H	‡Transmitter System Power Supply Burdens (Choose only one)
NXPWSA	RTG, spacecraft
NXPWSB	Reactor, spacecraft
NXPWSC	Solar cell, Mars, spacecraft
NXPWSD	Generator, earth
NXPWSE	Solar cell, satellite, spacecraft
NXPWSF	Solar cell, Venus, spacecraft
NXPWSG	Solar cell, Mercury, spacecraft
13I	‡Receiver System Power Supply Burdens (Choose only one)
NRPWSA	RTG, spacecraft
NRPWSB	Reactor, spacecraft
NRPWSC	Solar cell, Mars, spacecraft
NRPWSD	Generator, earth
NRPWSE	Solar cell, satellite, spacecraft
NRPWSF	Solar cell, Venus, spacecraft
NRPWSG	Solar cell, Mercury, spacecraft

*See note 5 above.

‡See note 4 above.

Category 14

System Physical Data (Choose desired system physical data such as signal-to-noise ratio atmospheric transmissivity, receiver temperature, etc. as indicated.)

Note:

1. If no choice of an entry is made, program automatically selects a value.
2. If a choice of an entry is made, it supersedes automatic selection.
3. Entries with dagger (‡) are transmission range dependent and must be supplied when RANØTH instruction is selected.
4. Entries with asterisk (*) are transmission wavelength dependent and must be supplied when LAMØTH instruction is selected.
5. Failure to comply with above rules causes an error message to be printed. The program then proceeds to next case specified by NEWSET (see Category 20) instruction.

Data Label (1-6)	Data Value (9-22)	Description (25-80)
‡ RANG	YY...Y	Transmission range
* LMDA	YY...Y	Transmission wavelength
* TAUT	YY...Y	Transmitter system transmissivity
* TAUR	YY...Y	Receiver system transmissivity
* TAUA	YY...Y	Atmospheric transmissivity
* RHØT	YY...Y	Transmitter antenna efficiency
* RHØR	YY...Y	Receiver antenna efficiency
* TEMP	YY...Y	Receiver equivalent temperature
** ETAA	YY...Y	Detector quantum efficiency
RLLL	YY...Y	Receiver output load resistance
** LMDI	YY...Y	Optical filter bandwidth
** QBEE	YY...Y	Background radiation photon spectral radiance
PERR	YY...Y	Required probability of detection error
SNRR	YY...Y	Required signal-to-noise power ratio

**Not Required for Radio Frequency

*See note 4 above.
‡See note 3 above.

Category 15 — System Burdens Data (Choose desired system burdens data as indicated. See Section 4.2 for definition of system burdens data.)

Note:
1. If no choice of an entry in a subcategory is made, program automatically selects a value unless superseded by a Category 13 statement.
2. If a choice of an entry in a subcategory is made it supersedes values selected by Category 13 statement and automatic selection.
3. Entries with dagger (‡) are transmission range dependent and must be supplied by either Category 13 or Category 15 statements when RANØTH instruction is selected.
4. Entries with asterisk (*) are transmission wavelength dependent and must be supplied by either Category 13 or Category 15 statements when LAMØTH instruction is selected.
5. Failure to comply with above rules causes an error message to be printed. The program then proceeds to next case specified by NETSET (see Category 20) instruction.

Label (1-6)	Value (9-22)	Description (25-80)
	15A	*Transmitter Antenna Burdens

CDT = KTHT*(DT)**MT + CKT
= HTHT*(GT)**MT + CKT

WDT = KDT*(DT)**NT + WKT
= HDT*(GT)**NT + WKT

Label (1-6)	Value (9-22)	Description (25-80)
KTHT	YY...Y	Note equations above and Section 3.0, Symbols
HTHT	YY...Y	
KDT	YY...Y	
HDT	YY...Y	
CKT	YY...Y	
WKT	YY...Y	
MT	YY...Y	
NT	YY...Y	

*See note 4 above.

15B *Receiver Antenna Burdens

```
CDR = KTHR*(DR)**MR + CKR
    = HTHR*(GR)**MR + CKR

WDR = KDR*(DR)**NR + WKR
    = HDR*(GR)**NR + WKR
```

KTHR	YY...Y	Note equations above and Section 3.0, Symbols
HTHR	YY...Y	
KDR	YY...Y	
HDR	YY...Y	
CKR	YY...Y	
WKR	YY...Y	
MR	YY...Y	
NR	YY...Y	

15C Transmitter Acquisition and Track Burdens

```
CQT = KAT*(DT/LMDA)**QT + CAT
    = KAT*(GT**.5/(3.1416*SQRTF(RHOT)))**QT + CAT
WQT = KWAT*(WDT) + WBT
PQT = KPQT*(WQT)
```

KAT	YY...Y	Note equations above and Section 3.0, Symbols
KWAT	YY...Y	
KPQT	YY...Y	
CAT	YY...Y	
WBT	YY...Y	
QT	YY...Y	

15D Receiver Acquisition and Track Burdens

```
CQR = KAR*(DR/LMDA)**QR + CAR
    = KAR*(1./GR)**QR + CAR
    = KAR*(GR**.5/(3.1416*SQRTF(RHOR)))**QR + CAR
WQR = KWAR*(WDR) + WBR
PQR = KPQR*(WQR)
```

*See note 4 above.

KAR	YY...Y	Note equations above and Section 3.0, Symbols
KWAR	YY...Y	
KPQR	YY...Y	
CAR	YY...Y	
WBR	YY...Y	
QR	YY...Y	

15E *Modulation Equipment Burdens

CM = KFM*(RB) + CKM

WM = KM*(RB) + WKM

PM = KPM*(WM)

KFM	YY...Y	Note equations above and Section 3.0, Symbols
KM	YY...Y	
KPM	YY...Y	
CKM	YY...Y	
WKM	YY...Y	

15F *Demodulation Equipment Burdens

CD = KFD*(RB) + CKD

WD = KD*(RB) + WKD

PD = KPD*(WD)

KFD	YY...Y	Note equations above and Section 3.0, Symbols
KD	YY...Y	
KPD	YY...Y	
CKD	YY...Y	
WKD	YY...Y	

15G *Transmitter Burdens

CX = KPT*(PT)**GT + CKP

CH = KH*((1.-KE)/KE)*(PT)**JT

WX = KWT*(PT)**HT + WKP

WH = KX*((1.-KE)/KE)*(PT)**JT + WKH

PX = (1./KE)*(PT)**JT

*See note 4 above.

KPT	YY...Y	Note equations above and Section 3.0, Symbols
KWT	YY...Y	
KH	YY...Y	
KX	YY...Y	
KE	YY...Y	
CKP	YY...Y	
CKH	YY...Y	
WKP	YY...Y	
WKH	YY...Y	
GT	YY...Y	
HT	YY...Y	
JT	YY...Y	

15H ‡Transmitter System Power Supply Burdens

CST = KST*(PQT + PM + PX) + CKE

WST = KWST*(PQT + PM + PX) + WKE

KST	YY...Y	Note equations above and Section 3.0, Symbols
KWST	YY...Y	
CKE	YY...Y	
WKE	YY...Y	

15I *Receiver System Power Supply Burdens

CSR = KSR*(PQR + PD) + CKF

WSR = KWSR*(PQR + PD) + WKF

KSR	YY...Y	Note equations above and Section 3.0, Symbols
KWSR	YY...Y	
CKF	YY...Y	
WKF	YY...Y	

‡See note 3 above.

*See note 4 above.

Category 16 — System Parameter Constraints Data (Choose system parameter constraints data as indicated. See Section 4.2 for definition of system parameter constraints data.)

Note:
1. Choose DTM, DTB, and DTL for transmitter antenna diameter optimization and GTM, GTB, and GTL for transmitter antenna gain optimization.
2. Choose DRM, DRB, and DRL for receiver antenna diameter optimization and GRM, GRB, and GRL for receiver antenna gain optimization.
3. Choose the maximum and minimum stop values for the non-fixed system parameters when LAMØTH is chosen. Fixed system parameters require no stop values.
4. Maximum stop value of receiver field of view must be smaller than minimum value, TRB TRL. For all other parameters maximum stop value must be larger than minimum value, XXB>XXL.

Data Label (1-6)	Data Value (9-22)	Description (25-80)
DTM	YY...Y	Fixed value of transmitter antenna diameter
GTM	YY...Y	Fixed value of transmitter antenna gain
DRM	YY...Y	Fixed value of receiver antenna diameter
GRM	YY...Y	Fixed value of receiver antenna gain
PTM	YY...Y	Fixed value of transmitter power
TRM	YY...Y	Fixed value of receiver field of view
DTB	YY...Y	Maximum stop value of transmitter antenna diameter

Data Label (1-6)	Date Value (9-22)	Description (25-80)
GTB	YY...Y	Maximum stop value of transmitter antenna gain
DRB	YY...Y	Maximum stop value of receiver antenna diameter
GRB	YY...Y	Maximum stop value of receiver antenna gain
PTB	YY...Y	Maximum stop value of transmitter power
TRB	YY...Y	Maximum stop value of receiver field of view
DTL	YY...Y	Minimum stop value of transmitter antenna diameter
GTL	YY...Y	Minimum stop value of transmitter antenna gain
DRL	YY...Y	Minimum value of receiver antenna diameter
GRL	YY...Y	Minimum stop value of receiver antenna gain
PTL	YY...Y	Minimum stop value of transmitter power
TRL	YY...Y	Minimum stop value of receiver field of view

Category 17 — <u>Increment Subprogram</u> (Choose instruction if it is desired to change a single data entry in a systematic manner for a subsequent case, otherwise instruction is not needed)

Note:
1. No other instructions or data entries of previous case are changed except for those specified by Increment instruction.
2. Increment subprogram statements must be arranged in the order shown.
3. Final value must be greater than initial value.
4. Failure to comply with rule 3 causes program to print an error message. The program then proceeds to next case specified by NEWSET (see Category 20) instruction.
5. See Increment subprogram, Section 4.7.2, description for further information.

Instruction or Data Label (1-6)	Data Value (9-22)	Description (25-80)
NCRMNT		Increment instruction
(Data name)		Data parameter to be incremented
INITAL	YY...Y	Initial value of data parameter
STPSZE	YY...Y	Increment step size
FINALE	YY...Y	Final value of data parameter

Category (18) — <u>Process</u> (A PRØCES instruction must be included to cause program to compute.)

Instruction (1-6)	Description (25-80)
PRØCES	Begin to process instructions

Category 19	Repeat Subprogram (Choose instruction if it is desired to change a few instructions or data entries for a subsequent case otherwise the instruction is not needed)

Note:
1. Only those instructions or data entries of previous case specified by the Repeat instruction are changed.
2. See Repeat subprogram description, Section 4.7.3, for further information.

Instruction (1-6)	Description (25-80)
REPEAT	first repeat instruction
XXXXXX XXXXXX . . . XXXXXX PRØCES	new instructions and data for first repeat instruction
REPEAT	second repeat instruction
XXXXXX . . . XXXXXX PRØCES	new instructions and data for second repeat instruction
REPEAT . . .	third repeat instruction
REPEAT	last repeat instruction
XXXXXX . . . XXXXXX PRØCES	new instructions and data for last repeat instruction

Category 20

New Set (Choose instruction if a new set of instructions and data is desired for computing additional cases; otherwise the instruction is not needed. This instruction is to be used if the next case to be processed differs markedly from the previous case.)

Note:
1. A NEWSET instruction is required before every group of instructions and data defining a new case or series of cases (see Table 4-2 for definitions).
2. The instruction automatically erases all previous instructions and data.

Instruction (1-6)	Description (25-80)
NEWSET	first new set instruction
XXXXXX XXXXXX . . . XXXXXX PRØCES	new instructions and data for first new set instruction
NEWSET	second new set instruction
XXXXXX . . . XXXXXX PRØCES	new instructions and data for second new set instruction
NEWSET . . .	
NEWSET	last new set instruction
XXXXXX . XXXXXX PRØCES	new instructions and data for last new set instruction

Category (21) — End of Run (An ENDRUN instruction must follow all other instructions and data entries)

Instruction (1-6)	Description (25-80)
ENDRUN	End of processing run

Example C

Example C illustrates the optimization of a heterodyne detection optical communication system (HOPS example) using the complete listing of COPTRAN instructions and data with the Repeat subprogram. The communication system optimization problem is summarized below.

Jupiter Spacecraft Transmitter to Earth Receiver Link

10.6 micron transmission wavelength

PCM frequency shift keying and optical heterodyne detection receiver

Transmitter system weight optimization

Parameters to be optimized:

a. Transmitter antenna diameter
b. Receiver antenna diameter
c. Transmitter power

Fixed parameters:

a. Receiver field of view at 1 milliradian

Parameter stops:

a. Transmitter power at 1 kw
b. Receiver antenna diameter at 1 meter
c. Transmitter antenna diameter at 50 cm and 80 cm

A COPTRAN coding sheet for this example is shown on the next page followed by the computer tabulation and plots for the example.

EXAMPLE C HOPS

*** 'DTDROP' ASSUMED ***

```
*** COPTRAN PROGRAM ***

SPXMTR
EARCVR
RANJUP
BKDSKY
LAM106
PCM/FM
OPTHET
XMWTOP
RBINTO
RBFIN7
RBFR09
TITLEE
PRTDAT
PLTOPT
PTB                  0.100E 04
DRM                  0.100E 03
DTB                  0.500E 02
TRM                  0.100E-02
PROCES
```

SPACECRAFT TRANSMITTER
EARTH RECEIVER
JUPITER RANGE(7.5E8 KM)
TRANSMISSION WAVELENGTH LAMBDA = 10.6 MICRONS
DAY SKY BACKGROUND
PCM FREQUENCY MODULATION
OPTICAL HETERODYNE DETECTION
TRANSMITTER WEIGHT OPTIMIZATION
TRANSMITTER ANTENNA DIAMETER AND RECEIVER ANTENNA DIAMETER OPTIMIZATION

SYSTEM BURDENS DATA

TRANSMITTER ANTENNA	KTHT	14.00000	KDT	0.01200	CKT	20000.00	WKT	5.00	MT	2.00	NT	2.20000
RECEIVER ANTENNA	KTHR	8.75000	KDR	0.0230000	CKR	25000.00	WKR	20.00000	MR	2.00000	NR	2.00000
TRANSMITTER ACQUISITION AND TRACK SYSTEM	KAT	71000.	KWAT	0.13000	KPQT	0.48000	CAT	40000.	WRT	40.000	QT	0.30000
RECEIVER ACQUISITION AND TRACK SYSTEM	KAR	71000.	KWAR	0.46000	KPQR	0.48000	CAR	20000.	WRR	5.000	QR	0.30000
TRANSMITTER	KPT	1.43000	KWT	2.00000	KH	1.97000	KX	0.02500	KE	0.10000	CKP	10000.00
	CKH	13800.	WKP	25.000	WKH	0.000	JT	1.000	GT	1.00000	HT	1.00000
MODULATION EQUIPMENT	KFM	0.00050	KM	0.00000	KPM	5.00000	CKM	15000.	WKM	10.00		
DEMODULATION EQUIPMENT	KFD	0.0001000	KD	0.0000020	KPD	3.33000	CKD	27500.	WKD	55.000		
TRANSMITTER POWER SUPPLY	KST	500.000	KWST	0.625000	CKE	1200000.	WKF	400.000				
RECEIVER POWER SUPPLY	KSR	25.000	KWSR	0.0000000	CKF	5000.	WKF	0.0000				
BOOSTER BURDENS	KSA	1640.000	KSR	1640.000								

****

SYSTEM PHYSICAL DATA

R	0.75000E 14	LAMBDA	0.10600E-02	S/N	0.15000E 02	PERR	0.10000E-03	TAUT	0.80000E 00	TSMP	-0.10000E 21		
TAU-R	0.60000E 00	TAU-A	0.80000E 00	TE	-0.10000E 21	FTA	0.50000E 00	RL	0.10000E 03	LMBD-I	0.10000E-02		
WB	-0.10000E 21	RHO-T	0.90000E 00	RHO-R	0.90000E 00	TRMP	-0.10000E 21						

SIGNAL-TO-NOISE RATIO CONSTANTS

K	0.00000E-38	KN	0.16202E-04	KP	0.00000E-38	KR	0.00000E-38	KS	0.00000E-38

SYSTEM BURDEN CONSTANTS

KMT	0.00000E-38	KNT	0.23006E 02	KOT	0.00000E-38	KMR	0.00000E-38	KNR	0.00000E-38	KOR	0.00000E-38
KGT	0.00000E-38	KHT	0.32800E 04	KJT	0.10619E 05						

PARAMETER CONSTRAINTS

DTL	0.20000E 01	GTL	0.00000E-38	DRL	0.10000E 03	GRL	0.00000E-38	PTL	0.10000E 01	THERL	0.10000E-02
DTM	0.00000E-38	GTM	0.00000E-38	DRM	0.10000E 03	GRM	0.00000E-38	PTM	0.00000E-38	THERM	0.10000E-02
DTB	0.50000E 02	GTB	0.00000E-38	DRB	0.10000E 03	GRB	0.00000E-38	PTB	0.10000E 04	THERB	0.10000E-02
DTI	0.26000E 02	GTI	0.00000E-38	DRI	0.10000E 03	GRI	0.00000E-38	PTI	0.25050E 03	THERI	0.10000E-02

EXAMPLE C HOPS

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*** COPTRAN PROGRAM ***

SPXMTR
EARCVR
RANJUP
BKDSKY
LAM106
PCM/FM
OPTHET
XMWTOP
RBINTO
RBFIN7
RBFRQ9
TITLEE
PRTDAT
PLTOPT
PTB                 0.100E 04
DRM                 0.100E 03
DTB                 0.500E 02
TRM                 0.100E-02
PROCES
REPEAT
DTB                 0.800E 02
PROCES
```

SPACECRAFT TRANSMITTER
EARTH RECEIVER
JUPITER RANGE(7.5E8 KM)
TRANSMISSION WAVELENGTH LAMBDA = 10.6 MICRONS
DAY SKY BACKGROUND
PCM FREQUENCY MODULATION
OPTICAL HETERODYNE DETECTION
TRANSMITTER WEIGHT OPTIMIZATION
TRANSMITTER ANTENNA DIAMETER AND RECEIVER ANTENNA DIAMETER OPTIMIZATION

SYSTEM BURDENS DATA

TRANSMITTER ANTENNA	KTHT	14.00000	KDT	0.01200	CKT	20000.00	WKT	5.00	MT	2.00	NT	2.20000
RECEIVER ANTENNA	KTHR	8.75000	KDR	0.0230000	CKR	25000.00	WKR	20.00000	MR	2.00000	NR	2.00000
TRANSMITTER ACQUISITION AND TRACK SYSTEM	KAT	71000.	KWAT	0.13000	KPQT	0.48000	CAT	400000.	WRT	40.000	QT	0.30000
RECEIVER ACQUISITION AND TRACK SYSTEM	KAR	71000.	KWAR	0.46000	KPQR	0.48000	CAR	200000.	WRR	5.000	QR	0.30000
TRANSMITTER	KPT	1.43000	KWT	2.00000	KH	1.97000	KX	0.02500	KF	0.10000	CKP	10000.00
	CKH	13800.	WKP	25.000	WKH	0.000	JT	1.000	GT	1.00000	HT	1.00000
MODULATION EQUIPMENT	KFM	0.00050	KM	0.00000	KPM	5.00000	CKM	15000.	WKM	10.00				
DEMODULATION EQUIPMENT	KFD	0.0001000	KD	0.00000020	KPD	3.33000	CKD	27500.	WKD	55.000				
TRANSMITTER POWER SUPPLY	KST	500.000	KWST	0.625000	CKE	1200000.	WKE	400.000				
RECEIVER POWER SUPPLY	KSR	25.000	KWSR	0.0000000	CKF	5000.	WKF	0.0000				
BOOSTER BURDENS	KSA	1640.000	KSB	1640.000								

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SYSTEM PHYSICAL DATA

R	0.75000E 14	LAMBDA	0.10600E-02	S/N	0.15000E 02	PERR	0.10000E-03	TAUT	0.80000E 00	TSMP	-0.10000E 21
TAU-R	0.60000E 00	TAU-A	0.80000E 00	TE	-0.10000E 21	ETA	0.50000E 00	RL	0.10000E 03	LMHO-I	0.10000E-02
QB	-0.10000E 21	RHO-T	0.90000E 00	RHO-R	0.90000E 00	TRMP	-0.10000E 21				

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SIGNAL-TO-NOISE RATIO CONSTANTS

K	0.00000E-38	KN	0.16202E-04	KP	0.00000E-38	KR	0.00000E-38	KS	0.00000E-38

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SYSTEM BURDEN CONSTANTS

KMT	0.00000E-38	KNT	0.23006E 02	KQT	0.00000E-38	KMR	0.00000E-38	KNR	0.00000E-38	KQR	0.00000E-38
KGT	0.00000E-38	KHT	0.32800E 04	KJT	0.10619E 05						

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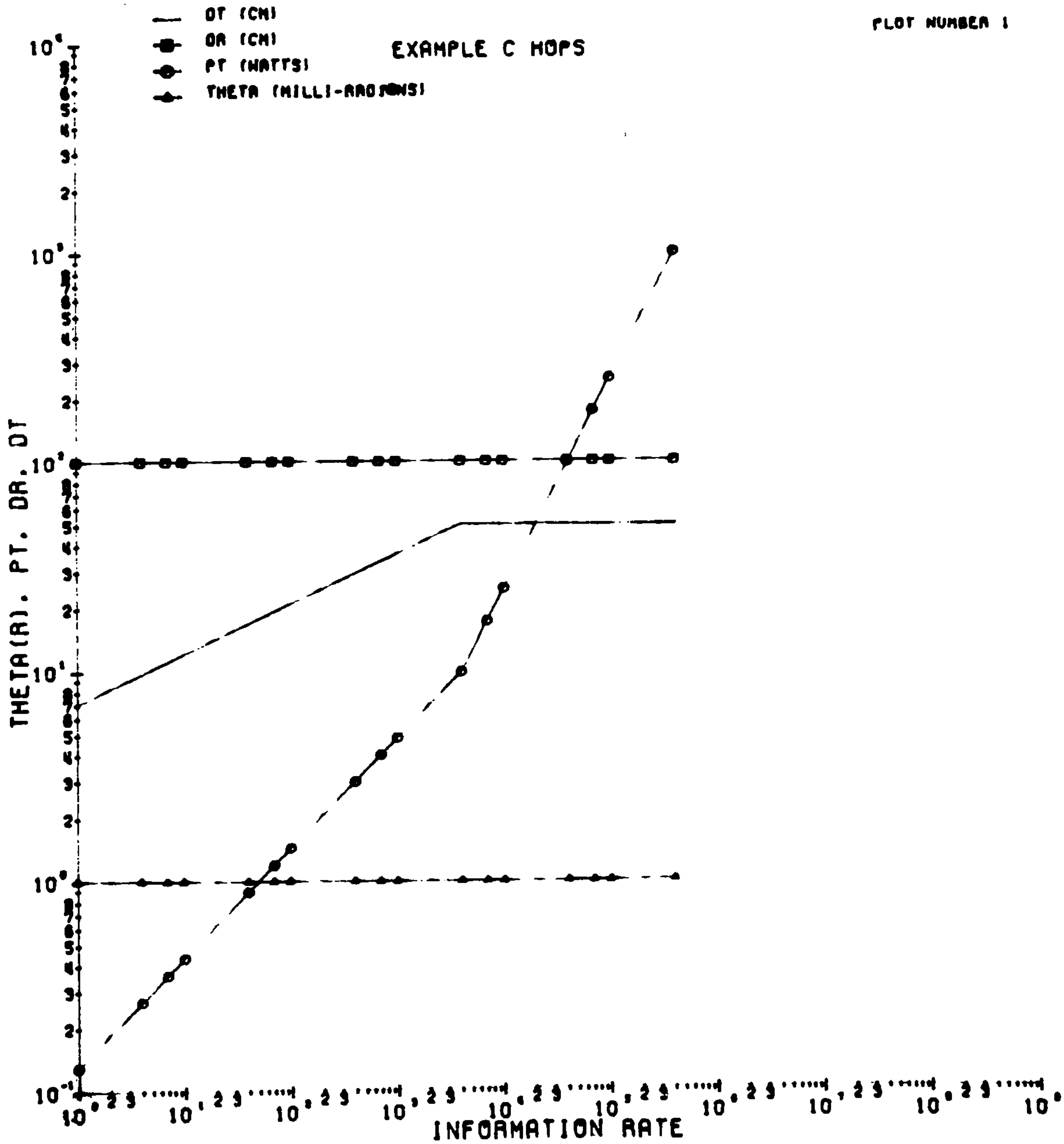
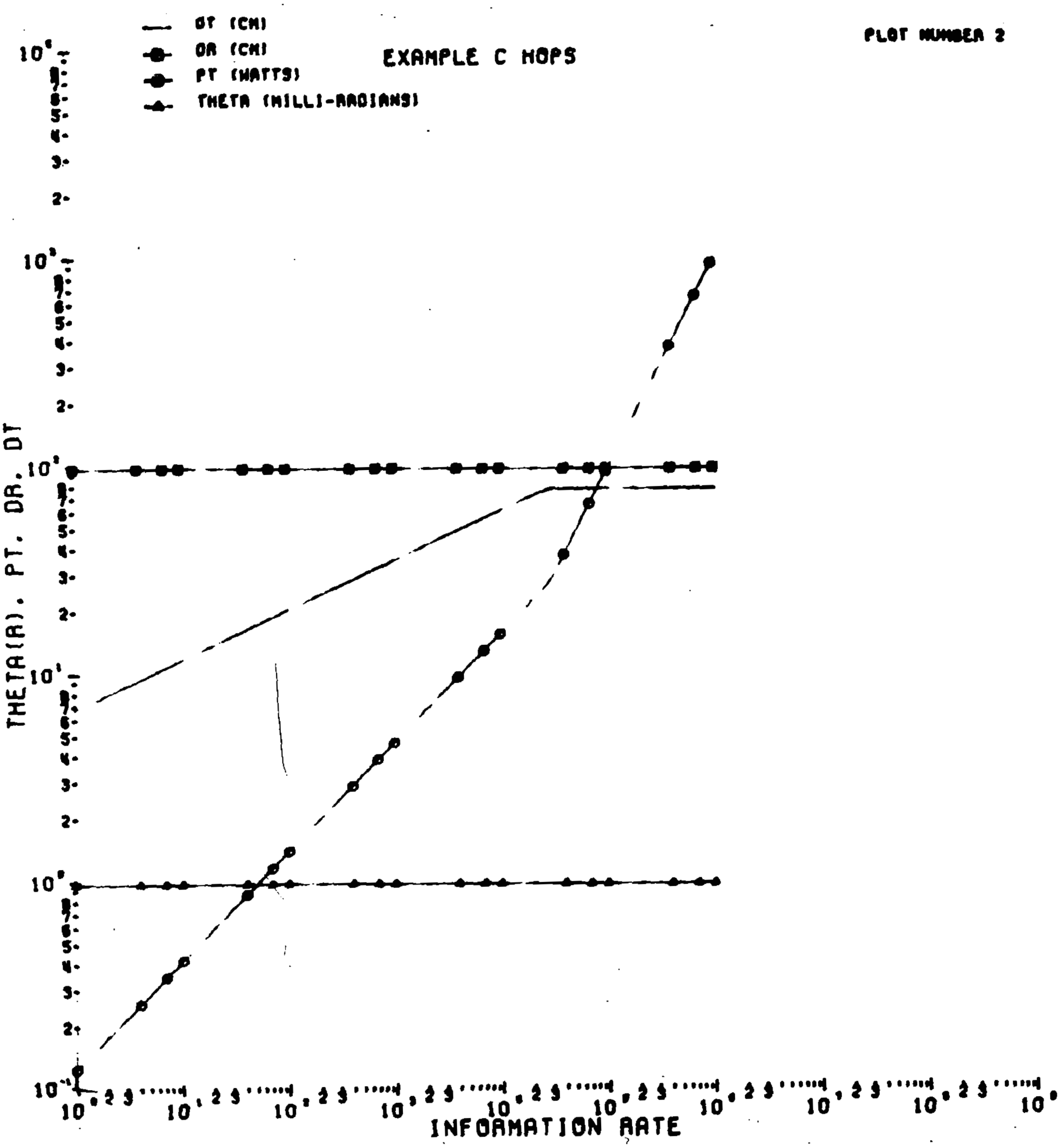
PARAMETER CONSTRAINTS

DTL	0.20000E 01	GTL	0.00000E-38	DRL	0.10000E 03	GRL	0.00000E-38	PTL	0.10000E 01	THERL	0.10000E-02
DTM	0.00000E-38	GTM	0.00000E-38	DRM	0.10000E 03	GRM	0.00000E-38	PTM	0.00000E-38	THERM	0.10000E-02
DTB	0.80000E 02	GTB	0.00000E-38	DRB	0.10000E 03	GRB	0.00000E-38	PTB	0.10000E 04	THERB	0.10000E-02
DTI	0.41000E 02	GTI	0.00000E-38	DRI	0.10000E 03	GRI	0.00000E-38	PTI	0.25000E 03	THERI	0.10000E-02

****



DT (CM)
DR (CM)
PT (WATTS)
THETA (MILLI-RADIANS)
EXAMPLE C HOPS
PLOT NUMBER 1
THETA(R). PT. DR. DT
INFORMATION RATE



DT (CM)
DR (CM)
PT (WATTS)
THETA (MILLI-RADIANS)
EXAMPLE C HOPS
PLOT NUMBER 2
THETA(R). PT. DR. DT
INFORMATION RATE