PARAMETRIC ANALYSIS OF MICROWAVE AND LASER SYSTEMS FOR COMMUNICATIONS AND TRACKING

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The Goddard Space Flight Center entered into a study contract on August 6, 1965, with Hughes Aircraft Company to analyze microwave and laser systems for communication and tracking. The purpose of this paper is to introduce the objectives and tasks of this contract. The paper is divided into three sections: first, an introduction to the problems of deep-space communications; second, an indication of the ultimate goal of this study; and third, an illustration of how this goal will be used in solving a typical space telecommunications problem.

A number of telecommunications choices are now available for space communications. These choices include a variety of spacecraft and ground-based hardware using frequencies from the vhf range through s-band. Future planning will undoubtedly include new frequencies and different designs. It is necessary, therefore, that a coherent and logical plan be developed enabling a space communications designer to pick the proper design configuration for an anticipated spacecraft telecommunication system. Not only is the large number of possible choices for communications design a problem for the space designer, but the continuing desire for wider and wider data bandwidth demands that the designer make his choice wisely. In those cases where a high data rate is not generated by spacecraft sensors, time competition for receiving sites will pressure the telecommunications design toward a higher data rate. That is, if a space vehicle is transmitting data at a slow rate, a rate adequate for the data being detected, it may utilize a deep-space tracking station for many hours. If, however, the data were transmitted at a much faster rate, time allotted to such a space vehicle might be arbitrarily short.

The advent of lasers as a possible communications means further compounds the nature of the communications problem. In some areas people are highly in favor of lasers and feel that this is the ultimate answer to the communications problem. In other areas people are very negative toward these new technological methods in terms of deep-space communications. The object of this study is to determine what is the net worth of lasers and then to match that net worth with the particular application for which they are best suited.

There are two major ultimate goals of this study contract. The first goal involves the ground system design. The study requires that the existing ground systems be carefully critiqued. This critiquing will document, in a convenient form, the various key parameters of ground systems. In addition, it will provide a basis for determining what additions or what changes should be made in these systems to provide suitable capability for future deep-space communications requirements. A second part of ground systems review will be the inclusion of proposed improvements or changes to the ground system, allowing both additional radio frequency capabilities and additional capability using laser frequencies. In the latter case, the ground network may be a hybrid system in the sense that the primary receiving site may be a satellite located above the earth's atmosphere working in conjunction with ground stations.

A second major goal of the study contract is to formulate a handbook for space communication design. This handbook will enable a communications designer to determine what is the best communication system based on the requirements given. The handbook will contain three major sections that deal with the solution of the problem. Interwoven with these three major sections will be a fourth, which is the communication choice available to the designer. The three major sections of this space communications handbook are: methodology, parametric studies, and state of the art. The methodology is the method of solving the space communications problem. It will include the interrelationships among the various parameters involved in the space communications problem. In addition, the methodology will contain logical methods of arriving at optimum system for a given set of space communications requirements.

The parametric studies to be documented in the space communication handbook will illustrate the parametric interrelationships of the various parameters of the space communications problem. These parametric studies will be calculated over wide ranges of parameter values and will enable the designer to realize the trade-off of his design.

The state-of-the-art portion of the space design handbook will provide limits to the parametric studies and will document the state of the art at present and will project state of the art for each parameter value for some years into the future.

This section offers a sample solution to a space communication problem in a very simplified way. The objective of this example is to show the general concepts that will be evolved through this study. It is not expected that this example will be definitive in terms of any particular application presently being envisioned. However, such an example will serve to show the method being used in the subject study.

First, consider the various space communication concepts that might be available for a given space mission. There are the direct spacecraft-to-earth links that might use either a laser or more conventional rf transmission. Second, there is a probe-to-satellite-to-earth transmission link that again might use laser or radio or a combination of these two transmission methods. Third, instead of an intermediate satellite, the moon might be used as an intermediate station with a deep-space probe-to-moon-to-earth link using light and/or radio. Figure 1 illustrates a synchronous satellite above the earth receiving data from a deep-space vehicle. The satellite will be in view by the space vehicle continuously for large portions of the year; thus continuous communication to the synchronous satellite may be achieved with no switchover from receiving station to receiving station such as would be required if the space vehicle were transmitting directly to earth. It might be noted that the satellite shown here as a synchronous satellite may well be a lower altitude satellite, as low as 6436 km (4000 mi), and may still be continuous in view of a space vehicle over a considerable portion of a year. Comparisons of three types of bases, ground bases, moon bases, or satellite bases, are given in Figure 2.

The next step in the designer's consideration of the proper space communication concept to use is that of determining the interrelationships of various parameter values. Figures 3, 4, and 5 illustrate typical parameter values that might be considered by a space designer. In Figure 3, antenna gain versus normalized diameter is given showing the limitations for two different tolerances, one part in two thousand and one part in four thousand. A second typical parametric trade-off that a designer may consider is illustrated in Figure 4. Here the watts per pound available as a function of frequency is given for rf generators. Because of the importance of weight on spacecraft design, this type of curve is extremely important in communications analysis. Figure 5 illustrates another type of parametric consideration that will be required for each spacecraft design, the efficiency of the power supply versus the pounds required for each transmitted watt. If the power supply is very efficient, only a small amount of weight is required for the transmitted watts which corresponds to the power supply conversion equipment. As the power supply conversion equipment becomes less efficient, a larger weight is required, reflecting the increase in weight caused by heat radiators which must be carried by the spacecraft.

The designer, having reviewed spacecraft concepts and parametric interrelationships, would then apply state-of-the-art limitations on the parameter values to come to a conclusion of the type of design choices available to him. As an illustration, Figure 6 shows state of the art for system noise temperatures using various types of detectors. As a second illustration of typical state-of-the-art limitations, Figure 7 presents available cw output power as a function of frequency. Plotted here is the power available from transmitter tubes as a function of frequency. The 1960 state of the art and the current state of the art are illustrated.

Having reviewed space communications concepts, parametric value variations, and typical state-of-the-art limitations, the designer will then refer to a methodology of how to solve his particular problem. Figure 8 illustrates a very rudimentary flow chart for such a methodology. It includes four major sections: one of operation and system analysis; a second, communication theory; and third, components technology. These three sections supply inputs to the fourth major section, which is frequency trade-offs. By manipulating various functional interrelationships of the key parameter values, it is possible to obtain channel capacity for an optimized wavelength per pound of communications equipment. The calculations indicated in this flow diagram have been completed for four different transmitting frequencies: 5 GHz, 94 GHz, 3.5 μ, and 0.5 μ. These calculations are simplified by not taking account of losses due to atmospheric absorption. They have assumed a very low background noise, the case of a black sky background, and no account has been taken for the acquisition and tracking weight. A tabulation of these four calculations appears in Figure 9. The key parameters are listed in Figure 10 as is the channel capability for each system weight. This calculation is of such a rudimentary nature that the values of 5 GHz, 94 GHz, and 0.5 μ are essentially the same. The calculation for 3.5 μ shows a considerable reduction in the selected figure of merit, bits per second per pound. This low value is caused largely by the low quantum efficiency of detectors at 3.5 μ.

This paper has presented the type of study to be carried out during the contract period. It is expected that by the end of Phase I, to be completed in early February, that a definitive methodology will have been formulated. During the subsequent Phase II, definitive values of parametric studies and state-of-the-art documentation will join the methodology in formulating a space design handbook enabling the space designer to plan an optimum system configuration for a given set of space communications requirements.

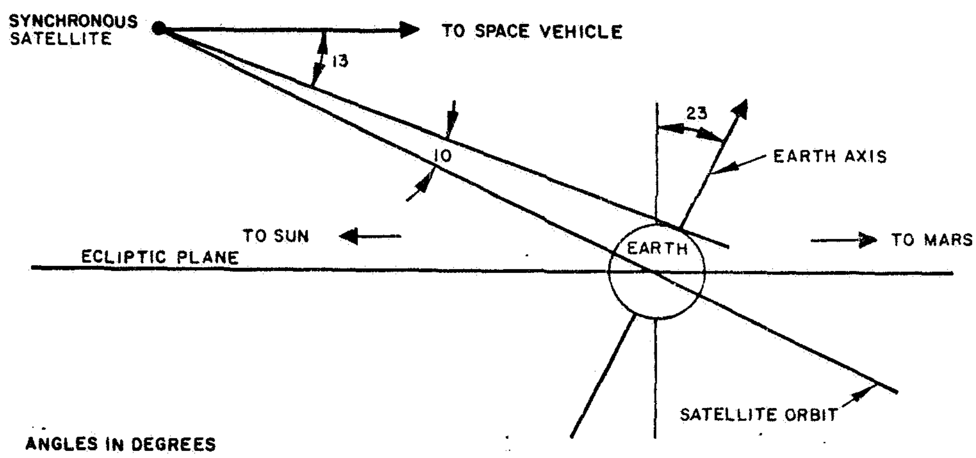

FIGURE 1. FIELD OF VIEW OF EQUATORIAL SYNCHRONOUS SATELLITE

Base	Advantages	Disadvantages
Ground	Power limited only by laser state of art Antenna size limited only by variable flexure of structure Logistics and maintenance Sophisticated data processing and trajectory prediction equipment available	Pointing accuracy limited by image motion, beam spread Power reduced by absorption and scattering High background noise during daytime operation Possibility of operation depends on meteorological condition Several ground stations required for continuous coverage Switchover and reacquisition problems difficult Long and frequent switchover time
Moon	No atmospheric effects Low background noise Large antenna size possible Possibility of continuous coverage	Pointing accuracy limited by lunar thermal environment Additional ground station required Inter-lunar communication difficulties Sophistication of base(s) dependent on earth-moon transportation and development of manned lunar colonies Most expensive
Satellite	No atmospheric effects Low background noise Continuous coverage probable from single base Reacquisition problems eliminated Cost less than moon link Excellent pointing accuracy	Power and antenna size limited in near future by payload requirements Monitoring and control ground station required Complex equipment Poor maintenance facilities Switchover and reacquisition difficult if occultations occur

FIGURE 2. COMPARISON BETWEEN OPTICAL LINKS

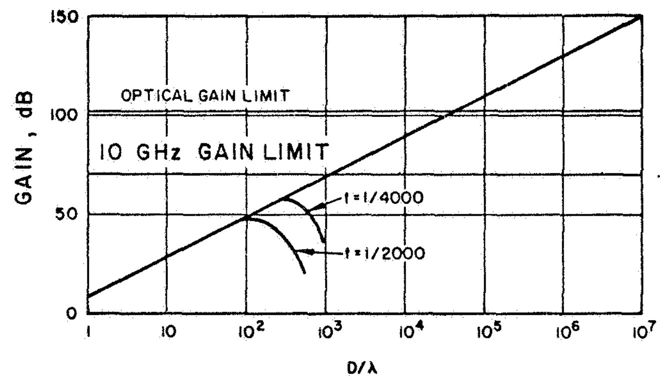

FIGURE 3. PARABOLIC ANTENNA
GAIN VERSUS SIZE

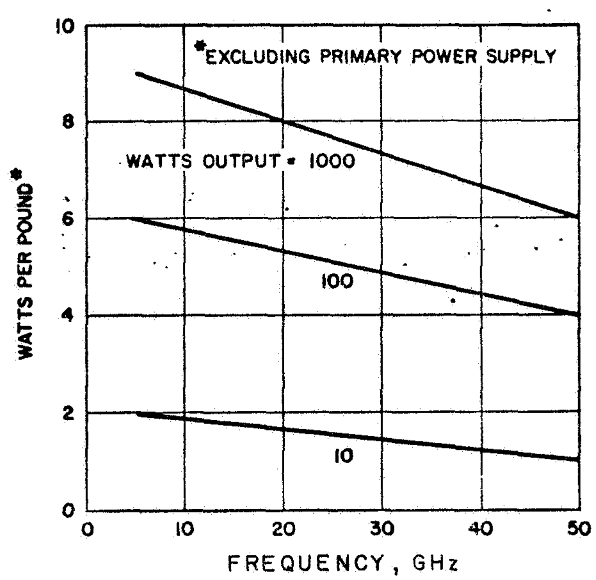

FIGURE 4. ESTIMATED TRANSMITTER WEIGHTS IN
SPACE SYSTEM APPLICATIONS

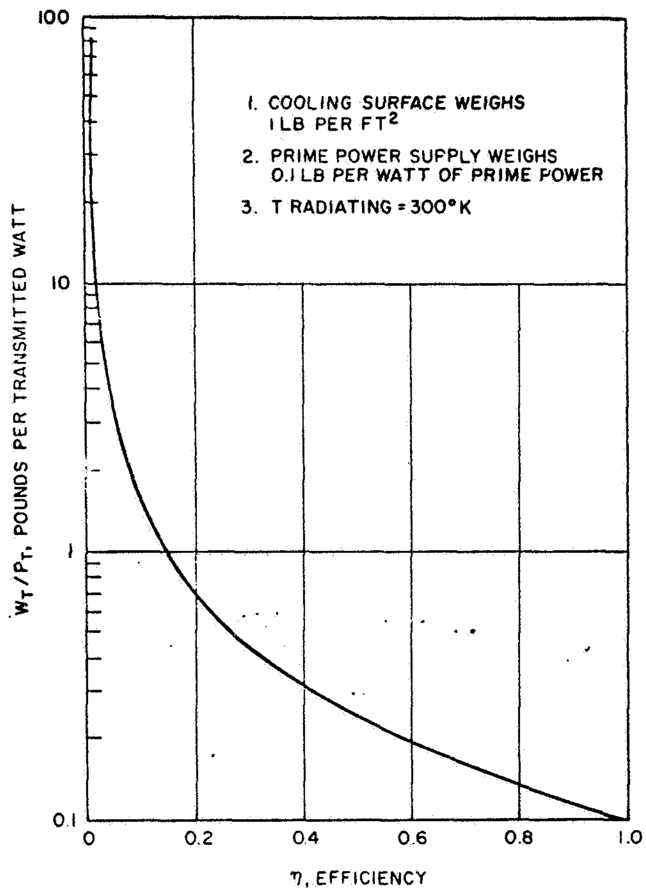

FIGURE 5. WEIGHT OF TRANSMITTER PRIME POWER AND COOLING SURFACE VERSUS EFFICIENCY

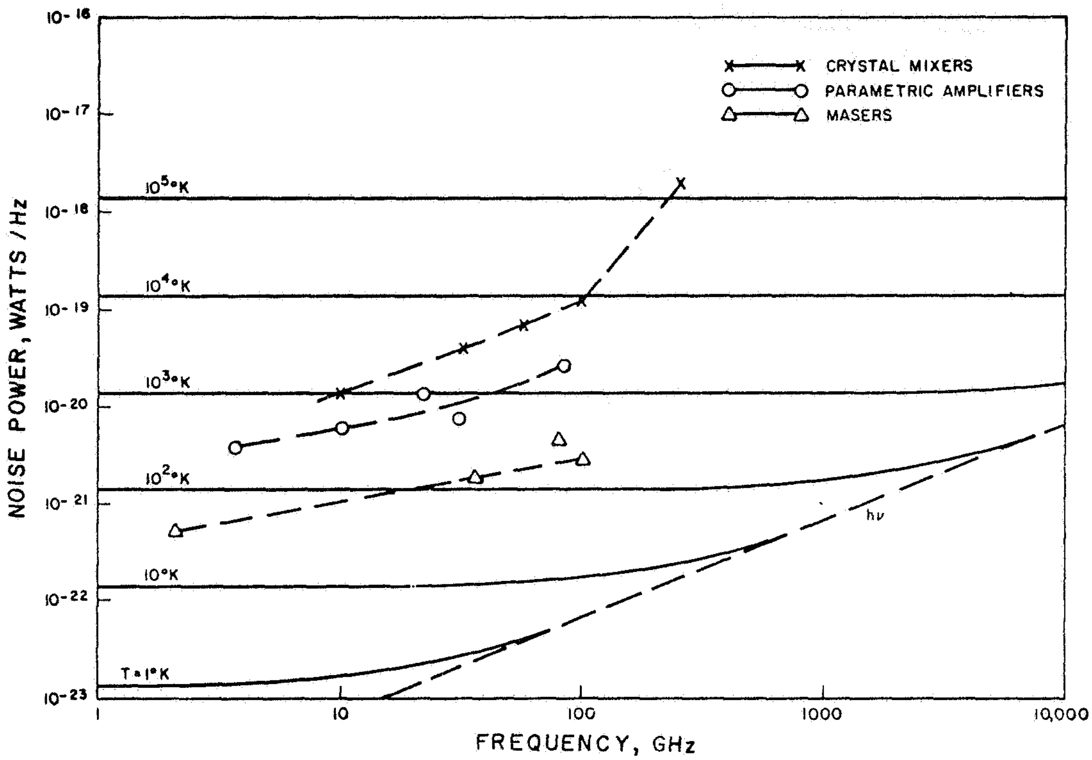

FIGURE 6. SYSTEM NOISE TEMPERATURE

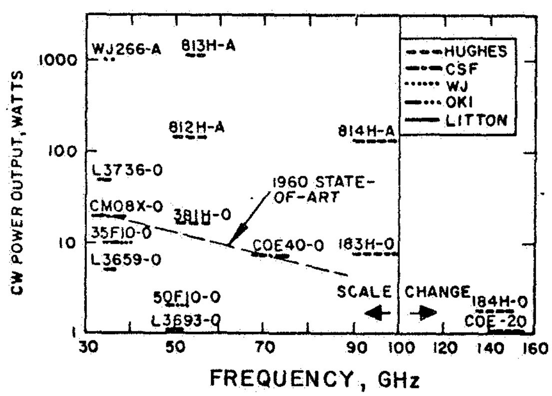

FIGURE 7. POWER CHARACTERISTICS OF AVAILABLE HIGH POWER CW SOURCES. MOST SIGNIFICANT IS 35 PERCENT EFFICIENCY ACHIEVED IN THE 813H AND MARKED INCREASE IN AVAILABLE POWER WHICH HAS OCCURRED SINCE 1960

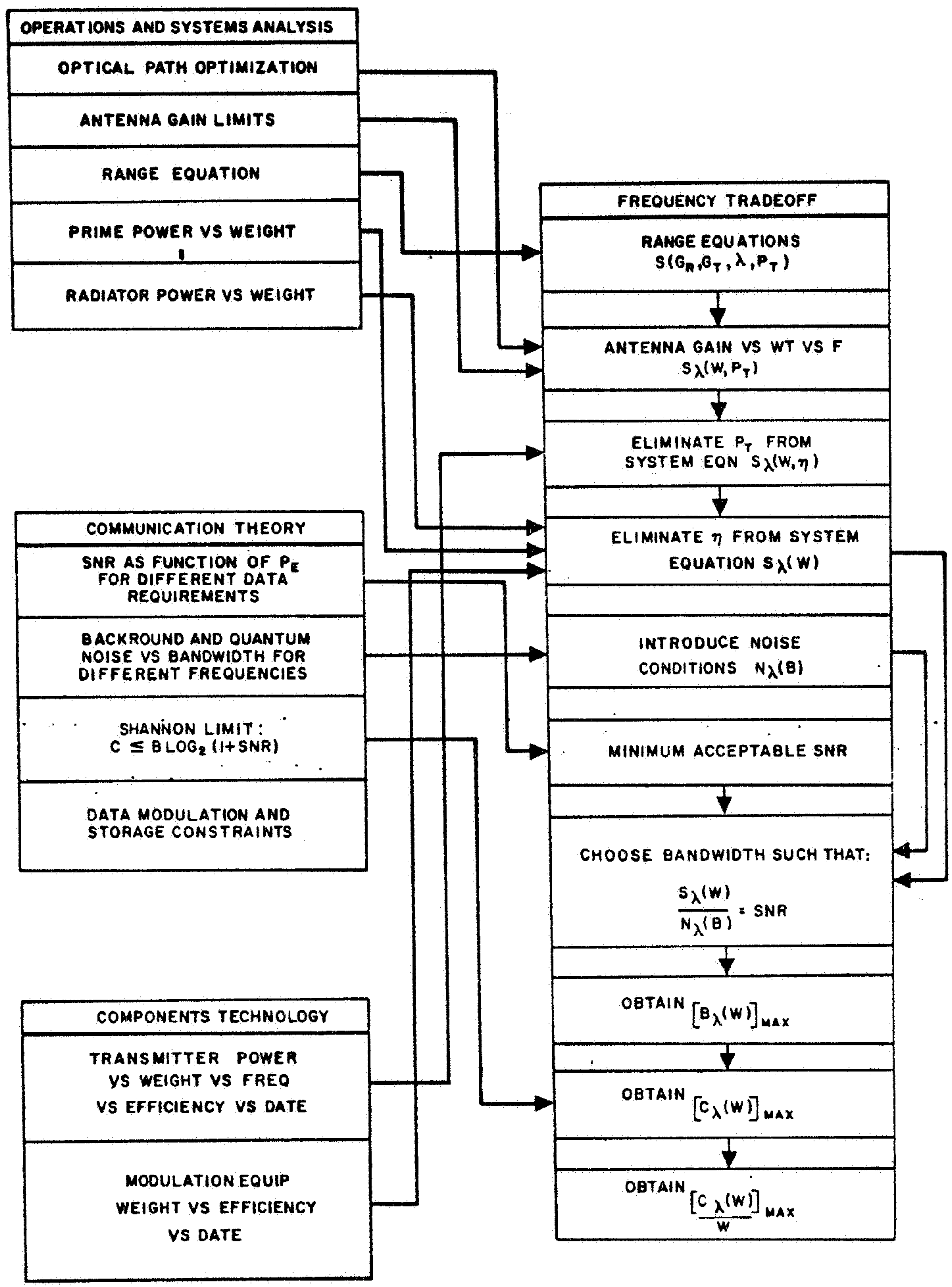

FIGURE 8. FREQUENCY TRADEOFF FLOW CHART

E. M. Wave	5 GHz	94 GHz	3.5 μ	0.5 μ
Transmitter Power (watts)	100	100	1	1
Efficiency	0.2	0.2	0.002	0.002
W_T/P_T*	0.68	0.68	74	74
Prime Power and Heat Radiator Weight (kg)	30.84	30.84	33.57	33.57
Transmitter Weight (kg)	7.71	22.68	4.54	4.54
Antenna Weight (kg)	45.36	27.22	45.36	45.36
Total System Weight (kg)	83.92	80.74	83.46	83.46

FIGURE 9. TYPICAL TRANSMITTER SYSTEM WEIGHT COMPARISON

E. M. Wave	5 GHz	94 GHz	3.5 μ	0.5 μ
Transmitter Power (watts)	100	100	1	1
Range (meters)	10^{11}	10^{11}	10^{11}	10^{11}
Transmitter Antenna Size (meters)	4	3	.1	1
Receiver Antenna Size (meters)	40	20	10	10
Maximum Bandwidth (MHz)	26	258	0.06	520
Transmitter Prime Power (Watts)	500	500	500	500
Total Transmitter Weight* (kg)	83.92	80.74	83.46	83.46
Channel Capacity (bits/sec)	9×10^7	8.9×10^8	2.1×10^5	1.8×10^9
Figure of Merit (bps/kg)	2.18×10^5	2.26×10^6	0.5×10^3	4.4×10^6

*Includes prime power, radiator, and antenna weight.

FIGURE 10. MICROWAVE-OPTICAL COMMUNICATION SYSTEM COMPARISON