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COMMUNICATIONS TO AND FROM LUNAR AND PLANETARY SPACECRAFT

Preliminary
Report to the Earth-Space Sub-Group 1
Study Group IV, C.C.I.R.

Eberhardt Rechtin
Jet Propulsion Laboratory

PRELIMINARY

Report to the Earth-Space Sub-Group 1

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COMMUNICATIONS TO AND FROM LUNAR AND PLANETARY SPACECRAFT

by

Eberhardt Rechtin, JPL

Director, NASA Deep Space Instrumentation Facility

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I. Introduction

Previous investigations have rather conclusively shown that the desirable frequencies for deep space communications using Maser receivers and directional spacecraft antennas are contained in the band of 1000 to 10,000 mc/s. Some of the references narrow the region still further, to 1000 to 3000 mc/s. Particularly complete discussions of this special problem are contained in:

1. "Tentative Evaluation of Transmission Factors for Space Vehicle Communications" Project 664, September 1958, U.S.Army Signal Radio Propagation Agency.
2. Technical Release 34-68, "Space Communications", 1960, Jet Propulsion Laboratory.
3. CCIR Report No. 115, "Factors Affecting the Selection of Frequencies for Telecommunication with and between Space Vehicles", originally published in the Journal of Research of the National Bureau of Standards, Vol. 64D, No. 2, March-April, 1960, pp. 105 - 109.

This report contains further detailed information on the deep space communication service as implemented by the Deep Space Instrumentation Facility of the NASA.

It is the function of the Deep Space Instrumentation Facility (DSIF) to provide commands, telemetering, scientific data transmission, and tracking for spacecraft destined for the Moon, the planets, and interplanetary space. This facility is managed by the California Institute of Technology Jet Propulsion Laboratory for the National Aeronautics and Space Administration. This facility occasionally, on a secondary basis, participates in earth satellite missions under the direction of the Goddard Space Flight Center, NASA. This report will concern only the deep space service; satellite service is covered by a separate report from the Goddard Space Flight Center. The DSIF, or such parts of it as existed at the time, participated in Pioneers III, IV, V (lunar and interplanetary probes); Echo (passive communication satellite); and Moonbounce (lunar reflection communications). It will participate in the future in Ranger and Surveyor (lunar landing spacecraft); Mariner (planetary probes); and Venus bounce (planetary radar reflection experiment). Proposed future programs in which the DSIF would be active would be Prospector (lunar), Voyager (planetary), and probably Apollo (lunar, manned).

The immediate plans of the DSIF are contained in an Appendix I, "System Capabilities and Development Schedule of the DSIF, 1961 - 1966." Not discussed in this appendix are quite tentative considerations for sites in the Eastern United States and in Southern Europe. The present sites -- the only mandatory sites for some years -- are located at Goldstone (Southern California desert), Woomera (Weapons Research Establishment in Australia), and near Johannesburg, South Africa.

II. The Selection of Space To Earth Frequencies for Deep Space Service

Deep Space communications must utilize low-noise-temperature components such as parametric amplifiers, Masers, and low-noise-temperature antennas. Because the spacecraft's apparent motions observed from earth stations closely resemble those of the Moon and the stars, the vast majority of the listening time at the earth stations is spent at elevation angles greater than 10 degrees.

Sky temperatures are low: a few hundred degrees at the most for lunar missions and a few tens of degrees for planetary missions. Consequently, the conclusions of almost all technical experts, that the 1000 to 10,000 mc/s band should be used with Maser systems, apply directly.

It can be shown that to obtain worthwhile amounts of information from the distances of the planets, particularly at their furthermost positions from the Earth, requires directional antennas on the spacecraft. A similar statement applies for real time television from the Moon. Directional antennas require stabilized spacecraft. Fortunately, the requirement of stabilization also applies to maneuvering, guidance, observation, and efficient solar power. Further, the requirements for stabilization accuracy for all these functions are approximately the same, namely, a few tenths of a degree. The size of the spacecraft directional antennas is limited by weight, by stowed volume and by the view angle obscured by the antenna for instruments on the spacecraft. Antenna diameters of from four feet to forty feet are presently believed practical.

On the earth, one of the controlling factors is the need for continuous listening capability. This capability is needed because of the long transient times for maneuvers and other commanded functions, because of the incidence of unexpected events at unexpected times, because of the design advantage of continuous transmission and consumption of spacecraft power, and in order to obtain the maximum amount of information from infrequent but expensive missions. On the other hand, a multitude of stations around the earth means an appreciable capital investment and significant operating costs. The combination of these factors leads to the use of a minimum number of stations (3) covering the maximum useful portion of the sky at each station (horizon to horizon to within about ten degrees). The earth antennas must therefore be able to track the spacecraft to an accuracy of a fraction of a beamwidth from horizon to horizon. The size of the earth station antenna is determined by the cost, which in turn is determined by the economics of deep space service and by the precision of construction.

Economics of deep space service show that if about ten to twelve million dollars is invested in each of three large antennas which improve the service by a factor of ten over that presently provided by the 85 foot standard antennas of the DSIF, then this investment can be written off in ten years of deep space exploration against the equivalent costs of providing the same improvement by increased spacecraft power. (Spacecraft power is the only true competitor -- sending out ten times as many vehicles to obtain ten times as much information is the least competitive solution)

The precision of antenna construction required is dictated by the frequency used; however, costs increase about as the 2.7 power of the diameter and only inversely as the mechanical tolerances for modest accuracies. A more detailed study than is given here therefore concludes that earth station antenna diameters of about 250 feet are about the largest that are economically justifiable at this time for this service. This diameter is compatible with frequencies from 1000 to 3000 mc/s.

Table I shows typical deep space communications parameters for service to the Moon, Mars, and the edge of the solar system. From this table, it can be concluded that good quality real time television is practical from the Moon, facsimile pictures from Mars at its greatest distance from the Earth are achievable, and significant data from the edge of the solar system can be acquired. The lunar application requires the greatest bandwidths; one megacycle per second of video might well be coded to occupy ten megacycles per second of the RF spectrum by utilizing signal enhancement techniques such as FM with feedback.

TABLE I: TYPICAL DEEP SPACE SERVICE

Parameter	Lunar Orbiter with TV	Lunar Lander with TV	Mars Orbiter with Facsimile	Solar Edge Probe with Cosmic Ray Counter
Range, km	4×10^5	4×10^5	4×10^8	4×10^{10}
Ground antenna gain	10^5	10^6	10^6	10^6
Ground antenna dia. (feet)	85	250	250	250
Spacecraft antenna area (meters squared)	7	2.5	25	25
Spacecraft antenna beamwidth (degrees)	2.2	3.6	1.2	1.2
System temperature (degrees Kelvin)	220	400	25	25
Spacecraft radiated power (watts)	20	10	150	150
Frequency (kmc)	2.3	2.3	2.3	2.3
Video bandwidth for S/N of 30 db (cps)	10^6	10^6	2.5×10^3	--
Bandwidth for S/N of 20 db (coded transmission)	10^7	10^7	2.5×10^4	2.5 cps
Time for spacecraft to reach destination	3 days	3 days	200 days	6 years (electric propulsion)

Tracking requirements for spacecraft in deep space service are approximately 0.05 degrees in angle, 1 meter per second in velocity, and 50 meters in range. These requirements may be met using techniques of reasonable but not difficult precision. Angle tracking of 0.05 degrees is met using tracking parabolas of reasonable precision, using computational procedures which take advantage of the long tracking periods above ten degree elevation angle and of the disturbance-free orbits of the spacecraft, and operating with sufficiently high gain to produce appropriately narrow antenna bandwidths. Velocity can be measured using coherent doppler techniques at integrally-related carrier frequencies. Ranging can be accomplished with synchronously coded modulation of about one megacycle bandwidth and with occasional position fixes followed by carrier Doppler cycle count. The principal bandwidth requirement of the tracking function is therefore that of the ranging equipment. Doppler shifts are second with a need for several hundred kilocycles in the frequency region of 1000 to 3000 megacycles/second.

The frequency bands applicable and reasonably available (ITU Geneva Conference 1959) as of the date of the frequency selection were:*

1. 1427 - 1429 mc/s
2. 1700 - 1710 mc/s
3. 2290 - 2300 mc/s
4. 8400 - 8500 mc/s

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*Reference: "Policy Planning for Space Telecommunications" Staff Report prepared for the Committee on Aeronautical and Space Sciences United States Senate December 4, 1960 - Document 59786

Of these bands, the one 2290 - 2300 was nearly optimum for deep space service for the reasons given above and for more detailed reasons given in Appendix II. This appendix contains the text of the memorandum from the implementing agency (JPL) to its headquarters (NASA) requesting that an allocation be made of the 2290 - 2300 mc/s band for deep space service. The 1427 - 1429 band was too narrow to accommodate multiple simultaneous lunar and planetary missions without interference; however, the band might be considered for overflow or special purpose transmissions such as lunar TV using a separate transmitter. The 1700 - 1710 mc/s band was practical for deep space service; performance was within a few decibels of that at 2290 - 2300. However, this band (1700 - 1710) was the first ten megacycle bandwidth in the frequency spectrum beginning at 20 mc/s and, as such, provided the first reasonable window for earth satellite use. Earth satellites, requiring inherently wider antenna beamwidths and higher tracking rates than deep space vehicles, were known to prefer lower frequencies and, in particular, to prefer 1700 - 1710 over 2290 - 2300. Since the 2290 - 2300 band was acceptable to the deep space service, provided it with narrower beamwidths for interference rejection within economically-sized antennas, and reduced sky temperatures due to cosmic disturbances from the vicinity of the Milky Way, the 1700 - 1710 band was bypassed.

The 8400 - 8500 mc/s band was incompatible with accuracies economically feasible for 250 foot diameter antennas. A reduction in the size of the antennas would have, of course, reduced the cost of the antennas. A reduction in antenna size would have appreciably reduced the communications capability with omnidirectional spacecraft antennas, however. (See Appendix II)

The 8400 - 8500 mc/s band may, at some time in the future, become useful for precision tracking and for extreme bandwidth signals from lunar distances.

III. The Selection of Earth to Space Frequencies for Deep Space Service

It is axiomatic that the performance of the earth to space circuit must be satisfactory to the same range as that demanded of the space to earth circuit. The two circuits have different demands placed on them, but the demands must be met equally well. The earth to space circuit must supply extremely reliable but comparatively narrow bandwidth commands. It must supply a good carrier for the coherent doppler system. Desirably, it should be able to use an omnidirectional rather than a directional antenna on the spacecraft. It is presently forced to use spacecraft amplifiers of appreciably higher temperature than the earth amplifiers of the space to earth circuit. On the other hand, it is practical to radiate considerably higher power from the ground than from a spacecraft. Compared to the space to earth link, the earth to spacecraft link has about a 25 db advantage in radiated power, a 30 db advantage in narrower bandwidth, but a 35 db disadvantage in spacecraft antenna gain and a 20 db disadvantage in (operational) receiver sensitivity.

The restrictions upon useable earth to space frequencies are determined by the needs of the coherent doppler and ranging functions, upon the difficulty of doppler circuit mechanization, upon the availability of spacecraft components, and upon the choice of space to earth frequencies. Of these factors, the choice of space to earth frequency as 2295 ± 5 mc/s, the need for ranging and multiple mission frequency diversity, and the technique of coherent Doppler together determine a set of 10 mc wide bands spaced throughout the spectrum. The design advantage of using the same microwave components (feeds, guides, etc.) narrows the selection to those bands within 6 to 10% of the space to earth frequency. A similar restriction is placed by the thresholding action of the coherent doppler technique which multiplies the phase noise of the received and detected carrier by the frequency transformation ratio in deriving the transmitted carrier; this factor also leads to the 10% criterion. Within the 6 to 10% bands (i.e., from 2066 to 2157 and from 2433 to 2524 mc/s) there are perhaps half a dozen reasonably workable transponder designs which will produce frequency transformations with acceptable multiplication ratios, IF frequencies, and bandwidths. The frequencies above 2400 mc result in increased earth antenna costs roughly as the ratio of frequencies referenced to 2295 mc/s and in significantly increased spacecraft and earth component costs since component development above 2400 mc has been much less than that below 2300 mc/s. In the spectrum between 2066 and 2157, the service presently occupying the spectrum to 2110 mc/s is well-established, primary, high-power heating and processing equipments whose interference with critical earth-space command transmissions is almost uncontrollable. A particularly favorable mechanization is possible at 2113 15/16 mc/s, roughly in the center of a 2110 - 2120 band, whose mutual interference with deep space service appears minimal. For this reason, the use of the 2110 - 2120 mc/s band at Goldstone, California has been requested from the Federal Communications Commission. Similar requests will be made to the governments of Australia and South Africa if the authorization requested of the FCC is granted. Appendix III contains the principal technical justification submitted by JPL to NASA for submission to the FCC.

The band 2110 - 2120 is not an ITU-discussed frequency band, but, as will be developed later in this report, it is not believed necessary because:

1. Unlike the space to earth band, the earth to space band can probably be shared with an existing service.
2. Frequency control within comparatively narrow geographical limits is sufficient and the only locations affected are the deserts of California and Australia and the back country of South Africa.
3. All deep space earth stations are located in natural bowls with 3 to 5 degree horizons, minimizing conceivable tropospheric scatter effects; additionally, normal transmitting operations seldom are carried out at elevation angles of less than 10 degrees elevation and beamwidths more than 1/2 degree.

IV. Interference on the Space to Earth Circuit

Interference by spacecraft transmissions on earth services is best computed knowing the deep space earth station parameters necessary for proper reception and then making a comparison with the equivalent parameters of the other service. Typical parameters are given in Appendix I and in Table 1. Interference into isotropic sidelobes of a conventional, 1500°K earth service receiving system will be at least 20 decibels below the noise level for the worst interference case and as much as 40 db below noise level for a typical case. If the earth service has a directional antenna pointed at the spacecraft, the interference will be determined by the ratio of antenna gains of the earth service and the deep space earth station. The spacecraft transmission will be above the earth service noise level (1500°K assumed) for earth service antenna diameters greater than six feet for the worst interference case (lunar orbiter) or greater than twenty feet for the other illustrated cases under the condition of the earth service antenna pointed directly at the spacecraft. Somewhat greater interference is conceptually possible during the time that the spacecraft is travelling from the earth to its destination; in actual practice, this interference is seldom more than 6 db worse because the use of programmed bandwidths and powers in the spacecraft for transmission efficiency maintains the signal to noise ratio per cycle per second approximately constant.

Interference from earth service transmitters into the deep space circuit can be disastrous. As can be seen from Table 1 and Appendix I, the deep space circuit is designed with very small safety margins, with only moderate radiated powers, and with spacecraft antenna beamwidths which more than illuminate the whole earth. The deep space circuit cannot compete with interference above the horizon radiating comparable powers over a more concentrated area of the earth and in comparable bandwidths. Not even the gain of the deep space earth antenna is sufficient to overcome the enormous distance advantage of an aircraft or satellite over a deep space probe. In other words, the interfering signal need not be within the beamwidth of the deep space earth antenna, only above the horizon, in order to be troublesome. This fact is confirmed in Table II following.

TABLE II: INTERFERENCE INTO DEEP SPACE CIRCUIT

Parameter	Interfering Aircraft Telemetry	Interfering Satellite Signal	Deep Space Service: Lunar TV Orbiter		Deep Space Service: Mars Orbiter	
Range (km)	4×10^1	4×10^3	4×10^5		4×10^8	
Antenna gain of signal into deep space antenna	0	0	10^5		10^6	
Radiated power (watts)	50	25	20		150	
Vehicle antenna power gain	10	10	5600		19,000	
Bandwidth	10^5	10^6	10^6		2.5×10^3	
			Aircraft	Satellite	Aircraft	Satellite
Signal to interference ratio in signal bandwidth	--	--	0.2	4400	0.002	440
Interference to receiver noise in signal bandwidth	--	--	37 db	-6 db	+57db	+4 db

The calculations of Table II are conservative in that they assume a uniform distribution of interference energy across its bandwidth. In practice, the energy will probably be distributed in sets of subcarrier channels, concentrating the interference in a way particularly harmful to the Mars orbiter. Similar calculations show that ground stations can also interfere with the deep space circuit in a way intermediate between the aircraft and satellite cases. Both the aircraft and satellite interferences are intermittent -- neither vehicle would be expected to be above the horizon for more than an hour at a time. The difficulty of suppressing interference over the horizon was the principal reason that the deep space receiving stations were located in natural bowls; this difficulty was a contributing reason for the selection of as high a frequency as practical. Rough calculations show that the natural terrain in the vicinity of the sites provides between 30 and 50 decibels of attenuation of signals over the horizon. In the Goldstone case, the present sources of possible ground interference are beyond two mountain ranges.

Airborne transmitters, even appreciably over the horizon, are just too loud. High altitude satellite transmitters, from the coverage plots of the deep space service (see Appendix I), are within the field of view of at least one deep space earth station a great portion of the time. In particular, satellites at an altitude of 2000 miles radiating over the United States, Canada, Hawaii, Mexico, and Central America are interfering sources to the DSIF. 400 miles altitude satellites radiating over the Southwestern U.S. and Mexico are also interfering. High altitude (50,000 feet) aircraft radiating in the 2290 - 2300 mc/s band within a radius of about 300 miles from Goldstone, California are potential sources of trouble.

In accomplishing its task of instrumenting deep space, the DSIF makes extensive use of contractors throughout the United States. These contractors can be expected to set up experimental stations of their own to listen to deep space probes. Collins Radio of Iowa and Texas, IT&T of the Northeastern U.S., Lincoln Laboratory of Massachusetts, and General Electric of New York have already participated either formally or informally in deep space service. A tentative consideration of a formal DSIF station on the east coast of the U.S. has been mentioned earlier in this report. To avoid interference with these stations, it therefore becomes mandatory that the 2290 - 2300 mc/s band <u>not</u> be shared with any airborne or satellite service. Sharing with ground services on a closely controlled, geographically determined basis is possible; the distances between ground transmitters at 2290 - 2300 and deep space research stations should be between 100 and 300 miles depending upon the local terrain at the deep space station. (In the Goldstone case, the 100 miles radius applies.) The use of high power, 2290 - 2300 mc/s ground transmitters to illuminate passive communication satellites, the Moon, or the planets must be carefully controlled; coordination of all such transmissions by the DSIF has been requested and approved by the FCC. Under any circumstances, the DSIF should be the primary user of this band. It is simply too expensive to abort a deep space probe, costing about $50 million each, due to lack of frequency control at critical times.

<u>It is therefore recommended</u> that the 2290 - 2300 band be allocated to deep space service as a primary service, that no airborne or satellite transmitters be authorized other than those in deep space service (testing or initial orbit use), and that no ground services be authorized within 100 to 300 miles of a station engaged in deep space service.

OK

<u>It would be highly desirable</u> if the only authorized use of the 2290 - 2300 mc/s band were for deep space service.

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V. <u>Interference on the Earth to Space Circuit</u>

Deep space service earth transmitters are planned which will radiate ten to one hundred kilowatts average power in a beam less than one half degree wide (50 to 60 db gain) at frequencies between 2110 and 2120 mc/s. The elevation angles will be no less than 3 degrees and usually more than 10 degrees above the local horizontal. Transmitters are also planned which for short periods of time will radiate 25 watts in a beam about five degrees wide (30 db gain) at elevation angles of zero degrees to the local horizontal. Continuous radiation toward the horizon is neither necessary nor desirable to the deep space service itself. Radiation is required only in the direction of the spacecraft and only when two-way communications are needed.

The orbits of deep space vehicles are such that radiation near the horizon is usually at azimuths within twenty degrees toward the equator from due east or due west. Normal acquisition procedures are such that radiation to the east is less likely than radiation to the west (radiation would not start when the spacecraft rose above the eastern horizon but might continue until it set in the west). The high power transmitters are located in natural bowls which protect surrounding ground services by no less than 30 db. Ground services would therefore hear the DSIF transmitter as an equivalent line-of-sight source radiating no more than 10 to 100 watts omnidirectionally.

The only intended high power transmitter in the United States at the present time is at Goldstone, California. This station is located on protected government land 50 miles from the nearest city (Barstow, California), and about 100 miles from Los Angeles. Los Angeles, itself, is located beyond a 7000 foot range of mountains. Interference from the Goldstone transmitter on possible ground services, particularly those using the 2110 - 2120 mc/s band, should be minimal, if even detectable. Interference with aircraft is possible, particularly if the aircraft flies through the transmitter antenna beam. The beam, however, is only 400 feet across at an altitude of 50,000 feet. Assuming that the aircraft flew directly across the beam at 300 mph, the interference would last one second; a typical aircraft antenna would intercept a fraction of a watt of power. The interference on the aircraft service by deep space service transmission through the earth antenna sidelobes would be the equivalent of a line-of-sight source radiating 1000 to 10,000 watts omnidirectionally. The source will be seen above its horizon by aircraft at 50,000 feet altitude and 140 mile range, and at 10,000 feet altitude and 30 mile range. Goldstone is located in the middle of a militarily restricted airspace; inadvertent interference with non-government services is therefore reduced. Interference with government service receivers is minimal inasmuch as this band is allocated within the United States for non-government use.

Interference from earth services into the deep space circuit via the spacecraft antenna can best be estimated by comparing the deep space earth station parameters with equivalent ground service parameters. Ground services over an enormous area of the globe must be considered because the probe very early in its trajectory sees virtually a complete hemisphere simultaneously and virtually the whole globe within a single day. Critical phases of flight occur immediately after injection of the spacecraft into orbit, during midcourse maneuvers occurring at altitudes of one hundred thousand to one million miles, and during target intercept at altitudes of 240,000 miles (lunar distance) and several tens to hundreds of millions of miles (planetary distances). Of these phases, the most critical from the standpoint of probable interferences effects are the first two phases. The first phase, fortunately, almost always occurs in the southern hemisphere at altitudes less than 1000 miles and at longitudes near South Africa and Australia. Knowledge of transmissions in their own country by the same governments that are participating in the DSIF will therefore greatly alleviate possible problems in this phase. The second phase, midcourse maneuvers, will almost always occur when the spacecraft is in view of the Goldstone station; neither European, African, Asian, or Australian sources are visible to the spacecraft at that time. Both North and South American (and adjacent ocean) sources should be considered. To be a significant interference source, the ground service must have an effective radiated power in the direction of the spacecraft within 20 decibels of 20 megawatts average (200 watts into 50 db gain is a probable mode of operation of the DSIF for lunar flights). Few, if any, such sources exist in this band.

The midcourse maneuver is carried out by the spacecraft in response to a command which may be sent at any time before several hours of the maneuver action. Consequently, by protective circuitry and multiple command transmission, interference effects could be reduced still further if necessary.

Deep Space service by the United States is unclassified and peaceful in nature. Deliberate interference with this service is of course possible, but has been assumed precluded by political considerations. In the interests of maximum reliability, therefore, a minimum of protective circuitry is presently designed into the communication service.

It is therefore recommended that the 2110 - 2120 bands be used by the deep space service on a shared basis with the presently assigned service and with primary status within 100 to 300 miles of the DSIF stations. (Primary status is necessary in order not to prevent the DSIF from communicating to its spacecraft at critical times.) It is also recommended that the DSIF be informed of other sources of radiation in this band throughout as much of the world as practical in order that the DSIF might incorporate appropriate protective circuitry and techniques should this prove necessary.

For information purposes, published frequency assignment charts should carry a footnote indicating that the Goldstone station has been authorized primary use of the requested frequency in the 2110 - 2120 band for its local area. Radiated power and bandwidth characteristics of the station would be covered in the footnote to identify the type of use involved.

It would be desirable if use of the 2110 to 2120 band were authorized for this status (primary use under controlled conditions by DSIF stations) on a world-wide basis.

VI. Conclusions

A. The 2290 - 2300 mc/s band should be allocated on a primary basis to deep space service as a space to earth tracking and communications. No airborne or satellite transmitters should be authorized other than those which are specifically designed to assist the deep space service (testing or initial orbit use). No ground services should be authorized within 100 to 300 miles of a station engaged in deep space service. Inasmuch as private experimental stations across the United States have already been, and will continue to be, listening for transmissions from deep space, a U.S.-wide allocation of this band would be desirable. The use of high-power ground transmitters to illuminate communication satellites, the Moon, or the planets must be carefully controlled; and all such transmissions must be coordinated by the Deep Space Instrumentation Facility. Desirably, this recommendation should be implemented on a world-wide basis.

B. The 2110 - 2120 mc/s band should be used by the deep space service for earth to space tracking and communications on a shared basis with presently assigned services and with primary status within 100 to 300 miles of the DSIF stations (Goldstone, California; Woomera, Australia; and Johannesburg, South Africa).

C. The 8400 - 8500 mc/s band can be foreseen in the future as a possible band for deep space use; the use would involve precision angle and range tracking and extremely wideband communications from the Moon. Research experiments are being conducted in this frequency band at the present time.

D. The 1427 - 1429 mc/s band is a conceivable band for deep space service from the Moon if the 2290 - 2300 band becomes saturated. There is no present need for this band for planetary communications.

E. Frequencies below 1000 mc/s need not be allocated for deep space-earth service if present plans for 2110 - 2120, 2290 - 2300, and 250 foot antennas materialize.

F. Frequencies above 10,000 mc/s need not be allocated for deep space-earth service because of atmospheric effects.

E. Rechtin/bdm
February 14, 1961

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SYSTEM CAPABILITIES AND DEVELOPMENT SCHEDULE OF THE DEEP SPACE INSTRUMENTATION FACILITY

1961 - 1966

Prepared by J. R. Hall

approved

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PASADENA, CALIFORNIA
February 13, 1961

FOREWORD

The purpose of this publication is to familiarize those agencies anticipating use of the Deep Space Instrumentation Facility (DSIF) with both its existing capabilities and those programmed in the immediate future. In general, the DSIF capability is matched to the requirements of the missions of the Jet Propulsion Laboratory in its exploration of outer space; however, the capability can be adapted to the needs of other programs without undue difficulty.

The capabilities shown in this Memorandum fall into three categories: existing facilities, authorized and funded projects, and proposed but not funded facilities.

N. A. Renzetti, Deputy
Program Director, DSIF

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FIGURES (Cont'd)

I. INTRODUCTION

An integral requirement in the conduct of scientific investigations of outer space is the establishment of a precision tracking and communications system capable of providing command, telemetering, and positional tracking of the space probe. The Deep Space Instrumentation Facility (DSIF) has been established to satisfy this requirement in lunar and planetary programs for which the Jet Propulsion Laboratory (JPL) has been assigned responsibility by the National Aeronautics and Space Administration (NASA). The DSIF is primarily intended for use in experiments conducted at lunar distances and beyond; however, certain experiments in cislunar space may utilize the DSIF stations when schedules permit.

The DSIF is comprised of three Deep Space Stations (DSS), a mobile station, and the intersite communication links providing for transfer of data and for administration of operations by JPL. A second mobile station is planned for operational use in 1963. The DSS's are presently equipped with 85-ft-diameter reflectors, and can track at angular rates to 1 deg/sec. These large reflectors are used mainly for deep-space experiments. The mobile station is equipped with a 10-ft diameter reflector, and can track at angular rates to 10 deg/sec. The mobile station is used mainly for command, telemetering, and tracking of space probes from injection to about 10,000-mi altitude.

The design philosophy of the DSIF is to provide a precision radio-tracking system which measures two angles, radial velocity and range, and then to utilize this tracking system to send radio commands and to receive radio telemetry in an efficient and reliable manner. The DSIF is scheduled to undergo long-term improvement and modernization consistent with the state of the art and spacecraft requirements. One of the basic design requirements of the DSIF is that it be possible to incorporate these improvements quickly, easily, and economically.

NASA is the cognizant United States agency responsible for the DSIF. JPL, of the California Institute of Technology, is under contract to NASA for the research, development, and fabrication of the DDS's and mobile stations for the technical coordination and liaison necessary to establish and operate the DSIF throughout the world. Overseas DSS's at Woomera, Australia, and Johannesburg, South Africa, will be operated by personnel provided by cooperating agencies in the respective countries. The Goldstone station and the mobile stations will be operated by United States personnel.

The Goldstone station, in addition to its participation as a member of the DSIF, is utilized for extensive research and development in space tracking and communications. In most cases, new equipment will be installed and tested at Goldstone before it is integrated into the DSIF.

II. STATION GEOMETRY

The three DSS's are spaced at approximately equal intervals of longitude around the Earth and are located as shown in Table 1.

Table 1. Deep Space Station locations

DDS location	Code	Geodetic latitude	Longitude
Goldstone, Calif., U.S.A.	GS	35.389°N	116.848°W
Woomera, Australia	W	31.382°S	136.886°E
Johannesburg, South Africa	J	25.891°S	27.675°E

The mobile stations will, in most cases, be located so as to cover the injection point and immediate post-injection trajectory of the spacecraft, which tend at the present time to be centered in the Southern Hemisphere. Typical DSS and mobile station installations are shown in Fig. 1 and 2.

The loci of subvehicle points, with 5-deg horizon mask angles at Woomera and Johannesburg, and the natural mask at Goldstone, are shown in Fig. 3. This figure indicates the field of view of each DSS as a function of vehicle altitude, as well as showing the region of overlapping coverage. The field of view of mobile stations is somewhat less restricted because they are normally emplaced on elevated locations.

Fig. 1. Typical Deep Space Station
(Goldstone receiver site)

Fig. 2. Typical mobile station

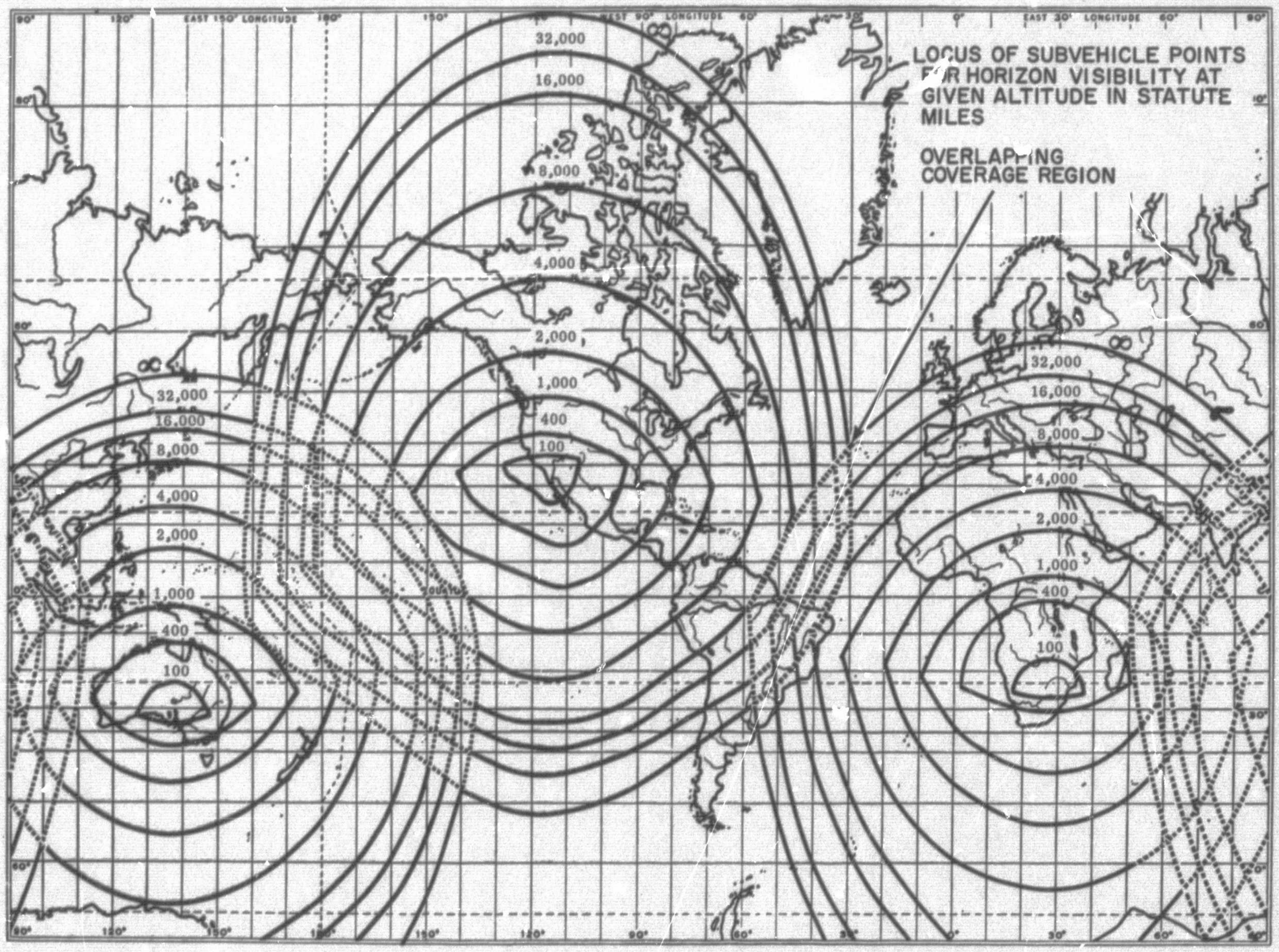


Fig. 3. Station coverage for 85-ft polar-mount DSIF antennas (Goldstone, Woomera, and Johannesburg)

III. SYSTEM CAPABILITIES

In the charts and text in this Section, the code (I) after the year designates existing installed facilities, (A) designates authorized and funded projects, and (P) designates proposed but not yet funded projects. Particular station configurations will vary somewhat from site to site and are not described in this Memorandum. Such configurations are shown in applicable program documents.

A. Tracking Data

1. Angle Tracking

The automatic-angle-tracking systems used in the DSIF are of the simultaneous lobing type. The 85-ft Ha-Dec antenna has two maximum tracking-rate capabilities, 1.0 deg/sec and 0.03 deg/sec, depending on tracking-system bandwidth requirements. During the periods in which angle-tracking accuracy is most significant (e.g., when data for midcourse-maneuver computation and for initial ephemeris calculation are acquired), the strong signal levels available result in a root-mean-square (rms) angle-tracking error from 0.01 to 0.02 deg. The rms tracking error at receiver threshold increases to approximately 0.05 deg. Bias errors are also of this magnitude; however, results of star-tracking data have, for the most part, made possible the stripping out of these bias errors.

The 10-ft Az-El antenna has a maximum tracking-rate capability of 10 deg/sec. Angle errors during post-injection tracking are usually no greater than 0.1 deg rms. Angle data from all DSIF antennas are digitally encoded directly from the servo-positioning system and routed to the data-handling facility. Angle data as sent to the

Central Computer Facility are smoothed only by the noise bandwidth of the servo-tracking system.

2. Range Tracking

A ranging system is presently under development by JPL and is planned for operational use with a 2115/2295-Mc transponder. The system measures the time difference between two identical, separately generated, pseudo-random noise codes (one generated at the transmitter for modulation and the other at the receiver for correlation detection) to represent range. The spacecraft transponder utilizes the same correlation technique to reconstruct the code sequence before retransmission to Earth. Unambiguous ranging at interplanetary distances is planned, with a range resolution equivalent to 0.1 μsec. The standard transmitting and receiving equipment located at the DSS's will be adaptable to the ranging mode. The ranging detection system is operable as long as carrier coherence is maintained in the two-way system. The general mode of operation for the ranging system will be to establish range lock, and then to remove range modulation and count carrier doppler cycles to maintain the range tally. Present plans require that telemetry, television, and command systems be inoperative during ranging modulation.

DSIF ranging capability at all stations is planned for March 1963 (P). An advanced-development prototype of the ground portion of the ranging system is expected to be in operation at Goldstone in July 1962 (I). The spacecraft portion is expected to be operational in 1964-1965 (P) to satisfy flight-program requirements arising at that time.

3. Doppler

One-way and two-way radial doppler measurement capability is to be included in the DSIF. Two-way doppler requires a ground transmitter in the vicinity of the receiver to achieve frequency control by a single exciter. The distance at which the DSIF stations can obtain doppler data is, of course, dependent on the sensitivity of the spacecraft receiver and power output of the spacecraft transponder; as long as the carrier can be locked, doppler can be made available. (See Appendix for a discussion of the communications-range capability.)

The accuracy of one-way doppler data is limited because of unknown spacecraft oscillator drift. In the two-way system, the frequency control is maintained by the ground-transmitter exciter and is precisely known. One-way doppler is extracted at an equivalent 31-Mc carrier frequency; two-way doppler is extracted at an equivalent 32-Mc carrier frequency. Two-way precision doppler is available with the shift at the RF carrier frequency (960 Mc or 2300 Mc). Because of the increasing percentage effects of systematic errors (e.g., refraction), it appears that 0.17 m/sec rms is the practical radial-velocity measurement accuracy at present (see Table 2).

Table 2. DSIF programmed doppler capability

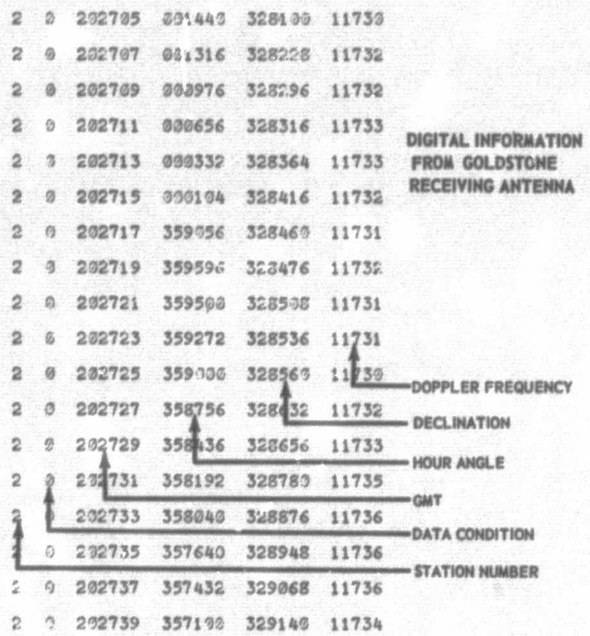
Type	Equipment resolution m/sec	Year operational in DSIF			Mobile station
		GS	W	J	
One-way	10	1960 (I)	1960 (A)	1961 (A)	1960 (I)
Two-way	5	1960 (A)	1962 (P)	1962 (P)	1960 (A)
One-way precision	0.34	1961 (A)	1962 (P)	1962 (P)	1961 (A)
Two-way precision	0.17	1961 (A)	1962 (P)	1962 (P)	1961 (A)

Cumulative doppler counts can be supplied to eliminate round-off error.

4. Data Handling

Automatic data-handling equipment is presently operational at Goldstone, Woomera, and the mobile tracking station; it will be operational at all DSIF stations in 1961. Data format is such that 120 characters can be printed out per line. The system is presently capable of tape-punching 60 characters per second; however, the intersite teletype communication system can transmit a maximum of 6 characters per second. The present system transmits doppler data, data condition, station identification, time, and two angles every 10 sec (see Fig. 4a). Sample rates from one per second to one per 90 min are available. When the ranging capability is added to the DSIF, range will be included in the teletype format (see Fig. 4b).

Transfer of telemetering data from overseas DSS's to JPL may be accomplished in several ways, depending on the urgency of its use. The normal method will be to airmail the telemetry tapes to JPL, with the attendant delay of approximately 72 hr. Other more rapid methods include use of the teletype system after the completion of the particular DSS tracking mission, and use of commercial radio-telephone facilities. At the present time, local reduction and re-transcription of data is necessary when teletype or radio-telephone methods are used.



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2 0 202709 000976 328296 11732
2 0 202711 000656 328316 11733
2 0 202713 000332 328364 11733
2 0 202715 000104 328416 11732
2 0 202717 359056 328460 11731
2 0 202719 359596 328476 11732
2 0 202721 359500 328508 11731
2 0 202723 359272 328536 11731
2 0 202725 359000 328568 11730
2 0 202727 358756 328632 11732
2 0 202729 358436 328656 11733
2 0 202731 358192 328780 11735
2 0 202733 358040 328876 11736
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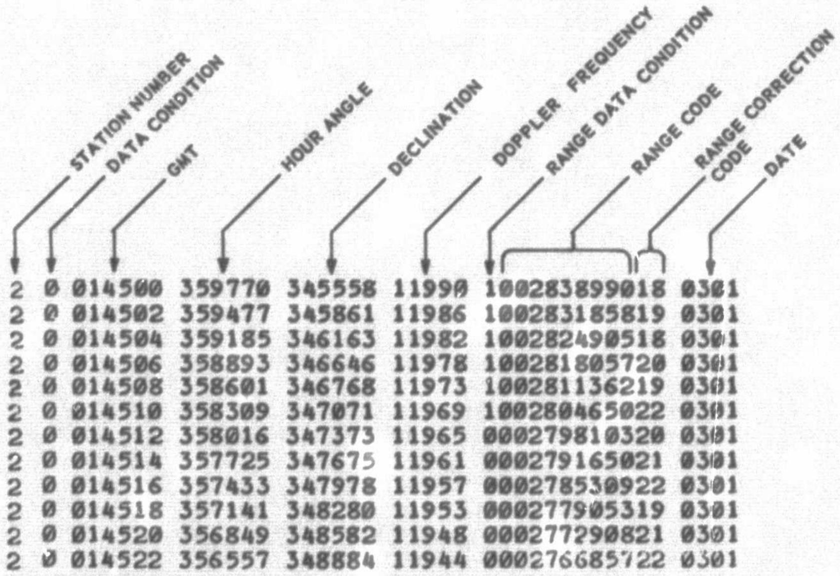
```

a. Present format

b. With ranging



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2 0 014502 359477 345861 11986 100283185819 0301
2 0 014504 359185 346163 11982 100282490518 0301
2 0 014506 358893 346646 11978 100281805720 0301
2 0 014508 358601 346768 11973 100281136219 0301
2 0 014510 358309 347071 11969 100280465022 0301
2 0 014512 358016 347373 11965 000279810320 0301
2 0 014514 357725 347675 11961 000279165021 0301
2 0 014516 357433 347978 11957 000278530922 0301
2 0 014518 357141 348280 11953 000277905319 0301
2 0 014520 356849 348582 11948 000277290821 0301
2 0 014522 356557 348884 11944 000276685722 0301
```

Fig. 4. Teletype format

B. Communications Data

1. Telemetry

The present ground-telemetering system can accept transmission bandwidths of 3.5 kc and is designed to process FM/PM modulation. A wide-bandwidth (1-3 Mc) detection capability is presently under consideration and is planned for integration into the DSIF as part of the 2295-Mc receiver. In most instances, the method of subcarrier detection and the logical design of the ground-station telemetering system will be dictated by the requirements of a particular space-probe experiment, and will vary from mission to mission. As a minimal capability, however, IRIG subcarrier channels 1 through 3 are presently incorporated in the DSIF. Goldstone and the mobile station have available IRIG channels 4 through 7 also. Phase-lock subcarrier detection techniques are utilized.

2. Command

To provide for the interrogation or command of a space probe, an initial command capability consisting of three audiofrequency tones will be provided in the 1961-62 (A) period. Future command requirements appear to favor a digital technique, and this digital command system will probably be introduced to the DSIF in 1962 (P). Again, as in telemetering, command capability is closely related to the requirements of individual space-probe experiments, and in most instances the command unit—DSIF interface will consist of a transmitter phase-modulator.

3. Recording Equipment

The recording equipment installed or programmed for installation at each DSIF site is designed to allow recording of a variety of signals, both spacecraft and locally generated. The types of available equipment are shown in Table 3. Signal-conditioning equipment of various types is also provided.

Table 3. DSIF programmed recording equipment

Location	Year operational in DSIF					
	Direct writing (8-channel)	Photographic oscillograph (36-channel)	Photographic oscillograph (14-channel)	Tape recorder (CEC-752 type)[a]	Video tape recorder (FR-700 type)	Digital recorder
GS	Jan 1960[b] (I)	Dec 1960[c] (I)	Dec 1960[d] (I)	Dec 1960[e] (I)	Jul 1961 (A)	Jan 1962 (P)
W			Dec 1960 (I)	Dec 1960[e] (I)	Jan 1962 (P)	Jan 1963 (P)
J			Apr 1961 (A)	Apr 1961[e] (I)	Jan 1962 (P)	Jan 1963 (P)
Mobile station		Dec 1960 (I)		Dec 1960 (I)		

[a] May be frequency-multiplexed.

[b] Available at transmitter and receiver sites.

[c] Available at transmitter site only.

[d] Available at receiver site only.

[e] Two each per site.

The timing system available at each site is stable over a one-day period to 5 parts in 10^{10}. Local-time readout is synchronized to WWV to at least 10 ms, and, at Goldstone, WWV synchronization is usually better than 1 ms. Time readout is available locally in digital and visual display, and serial coded time is available at 1-sec, 1-min, or 1-hr readout intervals. Maser timing and frequency control systems are under consideration for use in the DSIF in the 1963-64 period.

4. Special-Purpose Equipment

The major part of the DSIF equipment is or will be standardized for the purpose of reducing spares costs; insuring equalized high performance; and allowing standard training, maintenance, checkout, and countdown procedures to be utilized. Such standardized equipment is designated as Goldstone Duplicate Standard (GSDS). Certain situations exist, however, in which fund limitations and/or program and schedule requirements preclude a GSDS designation; such equipment may be peculiar to any of the DSS's, depending on the need of a particular program.

In general, special-purpose communications equipment is limited to modulation, demodulation, and data-handling equipment specifically required to satisfy a particular program need. Funding and engineering of this special-purpose equipment is handled as part of, and is the responsibility of, the program using it; however, spares requirements, interface configurations, operational procedures, etc., must be coordinated through the DSIF. Facility negotiations and schedules are the responsibility of the DSIF. Operation of specialized equipment is decided by mutual agreement. Some of this specialized equipment, if its use has shown it to be efficient and reliable and it appears to be versatile in its application to many programs, may later be integrated into the DSIF as GSDS.

5. Intersite Communications

A NASA-operated communication net linking the DSIF stations is utilized for data transfer and for operational control of the DSIF by JPL. The capability that will exist in the 1960-62 (A) period is shown in Fig. 5.

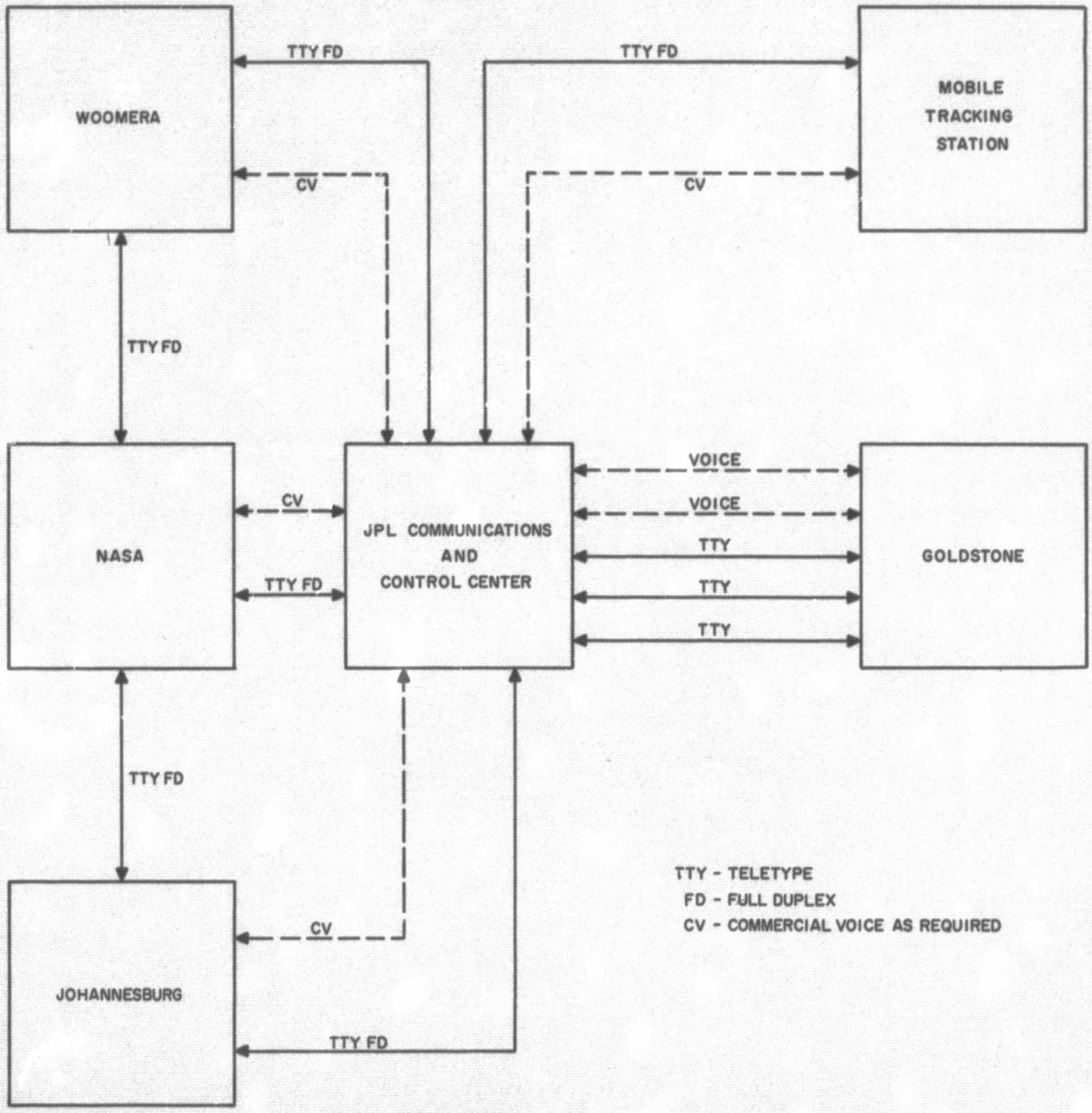


Figure 5. Communications net linking the DSIF stations

A high-frequency system linking the DSIF stations is under consideration for operational use in the 1963-65 (P) period. Bandwidth capability for this system is planned to be in excess of 3 kc. Communications reliability of 85 to 90% is anticipated.

C. Communications Systems

1. DSIF Frequencies

Frequencies assigned to JPL for use on DSIF missions fall into two general categories: ground-transmitter frequencies and spacecraft-transmitter frequencies. Table 4 shows the allocated and tentatively allocated JPL space-mission frequencies.

Table 4. JPL space-mission frequencies

Frequency, Mc	Year operational in DSIF[a]	Use
890	1960-63[b]	Transmitter frequency for DSIF equipment (25 w to 10 kw). Receiver frequency for spacecraft equipment.
960	1960-63[b]	Receiver frequency for DSIF equipment. Transmitter frequency for spacecraft equipment (1/4 to 100 w).
2115 ± 5[c]	1963-	Transmitter frequency for DSIF equipment (25 w to 100 kw). Receiver frequency for spacecraft equipment. The exact frequencies have not yet been chosen, but are expected to be from 6 to 10% lower than the assigned 2290 to 2300-Mc band. (Six to ten per cent higher frequency is also under consideration.)
2295 ± 5	1963-	Receiver frequency for DSIF equipment. Transmitter frequency for spacecraft equipment (to 1 kw).

[a] Operational capability of DSIF may not include all DSS's at the earlier dates listed.

[b] Use of the 890 to 960-Mc band will be terminated in January 1963.

[c] Allocation applied for, not yet authorized as of the date of this report.

A general receiving capability is under consideration for the purpose of receiving and recording telemetry data in the 20-Mc to 10-kMc region. Initially, it is planned to develop and/or incorporate broadband feeds, tunable receivers, wideband-telemetry detection channels, and wide-bandwidth recording systems into the DSIF. This capability is being considered so that the DSIF may react efficiently to requirements for tracking space probes other than those under JPL-mission cognizance.

2. DSIF Transmitters

Transmitter capability is incorporated in the DSIF for the purpose of providing two-way doppler data and ranging data and for command of the spacecraft. Depending on the particular mission, power outputs from 25 w to 10 kw are planned. In general, the transmitters will have a phase-modulation capability and will be excited with a voltage-controlled oscillator operated in the 30-Mc region. In some instances, diplexed operation, with a receiver operating at a different frequency, will be employed. Presently under consideration is a 100-kw-transmitter installation for the DSIF. Table 5 indicates the present and future planned transmitter capability.

Table 5. DSIF programmed transmitter capabilities

Frequency Mc	Power output	GS	Year operational in DSIF		Mobile station	Antenna
			W	J		
890	25 w				Dec 1960 (I)	10-ft Az-El
890	200 w [a]	Jun 1961[b] (I)				85-ft Az-El
890/960[c]	10 kw	Dec 1960 (I)				85-ft Az-El
890	200 w[a]		Aug [b] 1962	Aug [b] 1962		85-ft Ha-Dec
2115 ± 5	10 kw	Dec 1960 (I)				85-ft Az-El
2115 ± 5	25 200 w[e]				Jan 1963 (P)	10-ft Az-El
2115 ± 5	10 kw	Jul 1962[b] (P)	Jan 1963[b] (P)[d]	Jan 1963[b] (P)[d]		85-ft Ha-Dec
2115 ± 5	100 kw	1963 (P)	1965 (P)	1965 (P)		85-ft Az-El

[a] Either 10-kw, 890-Mc transmitter will be installed and operated with 200-w output, or separate 200-w power amplifier will be provided.

[b] Diplexed.

[c] Transmitter will be utilized for interstation Moon-bounce communication.

[d] Initially, the overseas 10-kw transmitters will be installed on the 85-ft polar-mount receiving antenna; they will be moved to the 85-ft Az-El antenna when it is installed.

[e] Actual power not decided.

3. DSIF Receivers

The DSIF stations incorporate extremely sensitive and stable receivers which are designed for the purpose of tracking the received RF carrier in phase, and for amplitude and phase-sensitive detection of the sidebands. The various receivers listed in Table 6 are comprised of a low-noise preselector/mixer, carrier and sideband IF amplifiers, detectors, and a voltage-controlled local oscillator, the combination comprising a double superheterodyne receiver, which is locked in phase to the received signal. Doppler data are derived from the local oscillator, telemetry data from either the phase error in the tracking loop or from a separate detection channel, and angle data from separate angle-error detection channels.

Minor modifications of the receiver will be necessary to incorporate the ranging system. In general, correlation detection of the range code will be accomplished at the first mixer, with the bulk of the ranging equipment being separate from the receiver.

Table 6. DSIF programmed receiver capabilities

Frequency Mc[a]	Year operational in DSIF						Mobile station	Receiver-system excess noise °K	Type	Bandwidth[b]	
	Goldstone		Woomera		Johannesburg					Carrier loop noise[c] cps	Telemetry channel information
	1	2	1	2	1	2					
960	Dec 1960(I)	May 1961(A)	Dec 1960(I)		May 1961(A)		Dec 1960(I)	1430	Track	20-250	0-3.5 kc
960	Jan 1962(A)	Jan 1962(A)	Jan 1962(P)		Jan 1962(P)			220/70[d]	Track	20-250	0-5 kc
2295 ± 5	Jul 1962(P)	Jan 1963(P)	Jan 1963(P)	Oct 1963(P)	Jan 1963(P)	Oct 1963(P)		235/50[e]	Track	3-250	0-1 Mc
2295 ± 5							Jan 1963(P)	1000	Track	20-250	0-1 Mc
2295 ± 5	Jul 1964(P)		Dec 1966(P)		Dec 1966(P)			20[f]	Listen	3-250	0-1 Mc

[a] In general, the receivers listed are capable of operation within several megacycles of the nominal center frequency by replacing a series of quartz crystals within the receiver system.

[b] The ranging system requires preselector and mixer bandwidths in excess of 5 Mc.

[c] Phase-lock loop-noise bandwidth is a function of the received signal level; hence, the frequency tracking-rate capability is a function of received signal level. The minimum bandwidths are limited because of the inherent phase instability of quartz crystals used in the communication system.

[d] A nominal 150°K excess-noise parametric amplifier will be installed at the Goldstone transmitter site and at the overseas DSS's; a 40°K excess-noise maser amplifier will be installed at the Goldstone receiver site.

[e] A nominal 200°K excess-noise parametric amplifier will be provided for receiver No. 1 and a nominal 30°K excess-noise maser amplifier will be provided for receiver No. 2. Diplexing may increase maser system temperature to approximately 100°K.

[f] Complete system excess-noise temperature, using 250-ft antenna (design goal).

4. DSIF Antennas and Feeds

a. Antenna temperature. Figure 6 shows antenna-temperature contours vs pointing angles recorded for the Goldstone 85-ft polar antenna at 960 Mc, using the sum channel output of a circularly polarized, simultaneous lobing tracking feed. The temperatures were recorded at the output of a feedline whose attenuation contributed approximately 45°K excess-noise temperature. A Dicke-type radiometer was used in this measurement. Similar data will be available from the Woomera and Johannesburg Deep Space Stations in 1961. DSIF temperature profiles will be available for 2290 to 2300 Mc in 1962. At 960 Mc, estimated Moon brightness temperatures vary between 210 and 250°K. The effective excess-noise temperature of the Moon depends on the beamwidth of the receiving antenna.

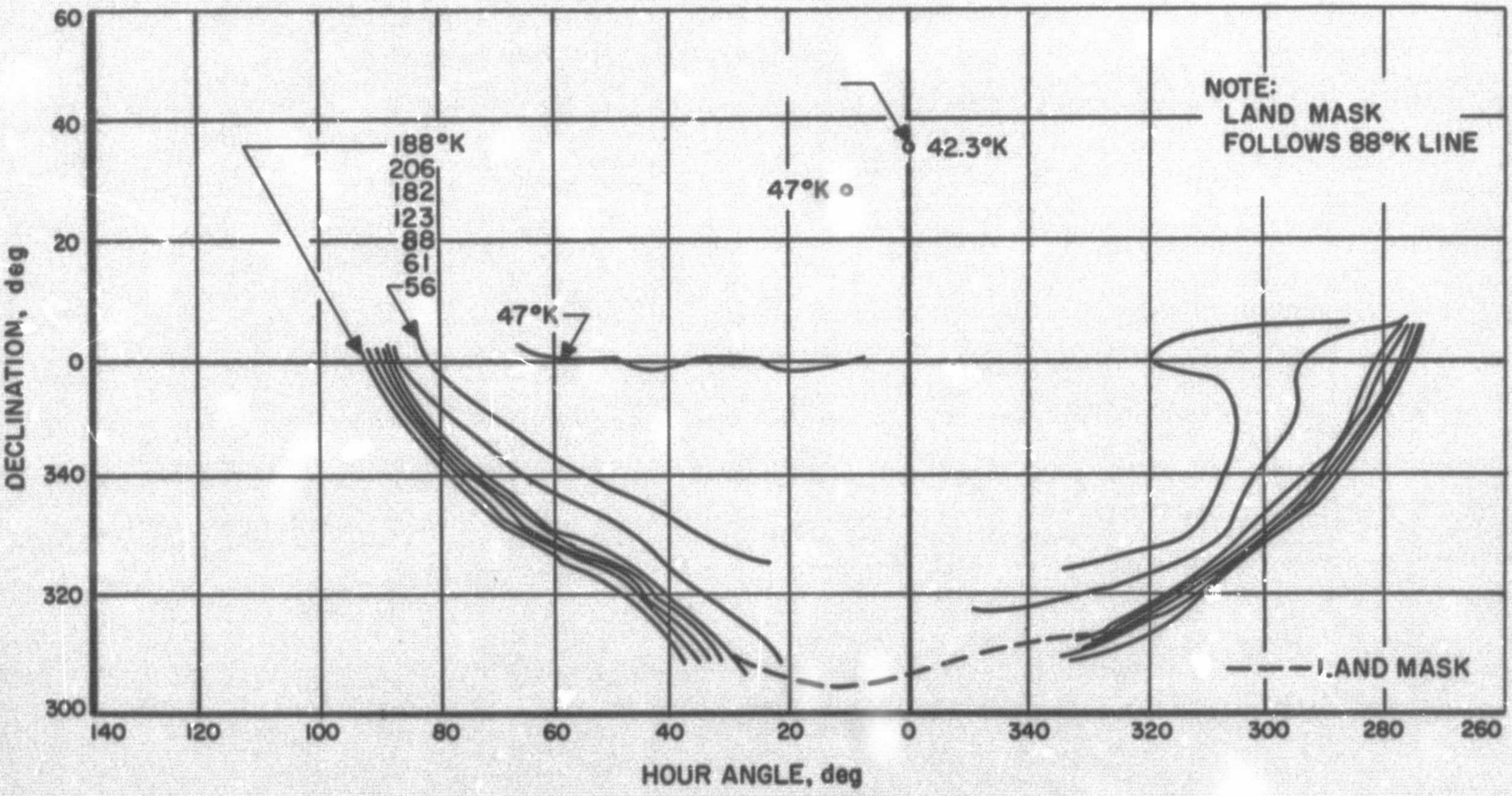


Figure 6. Goldstone antenna-temperature contours vs pointing angles recorded for the 85-ft polar antenna at 960 Mc

b. DSIF antenna reflectors. Antenna reflectors installed or programmed for installation in the DSIF are shown in Table 7.

Table 7. DSIF programmed antenna reflectors

Pointing accuracy[c] deg	Diameter ft	Type	Maximum angular rate deg/sec	Year operational in DSIF			
				GS	W	J	Mobile station
0.05	10	Az-El	20				Dec 1960 (I)
0.01	85	Ha-Dec	1	Jan 1960 (I)	Dec 1960 (I)	Apr 1961 (A)	
0.01	85	Az-El	2	May 1960 (I)	Dec 1963 (P)	Dec 1963 (P)	
0.02[a]	200-300	—[b]	0.2-0.5[a]	Dec 1963 (P)	Dec 1966 (P)	Dec 1966 (P)	

[a] Design goal.

[b] Not determined.

[c] The capability of pointing the radio beam in a specified direction within a specified peak error is defined as the pointing accuracy.

c. DSIF antenna feeds. The antenna feeds listed in Table 8 are planned for specific program support. As a general rule, tracking antennas are circularly polarized, transmitter antennas are circularly polarized, and spacecraft antennas are linearly polarized. Tracking feeds utilized are exclusively of the simultaneous lobing type.

d. Typical DSIF system. A typical DSIF system embodying all of the capabilities discussed above is shown in Fig. 7.

Table 8. DSIF programmed feed capability

Frequency Mc	Output power	Type	Gain[a]	Reflector diameter ft	Feed-line loss db[b]	Est. noise °K[c]	Polarization	Approx. beam-width deg	Year operational in DSIF			
									GS	W	J	Mobile station
960/890	200 w[d]	Track Trans.	43.5/43	85	0.7	80	Right Circ.	1.0	Jan 1960 (I)	Nov 1960 (I)	Apr 1961 (A)	
960/890	25 w[d]	Track Trans.	22.5/22	10	0.7	-	Right Circ.	9.0				Dec 1960 (I)
960/890	10 kw	Listen Trans.	45.8/45	85	0.4	60	Right Circ.	0.9	Aug 1962 (A)			
960/890	200 w	Listen Trans.	45.8/45	85	0.2	60	Linear[e]	0.85	Jan 1962 (A)	Aug 1962 (P)	Aug 1962 (P)	
2295 ± 5/ 2115 ± 5	10 kw[d]	Track Trans.	51.8/51	85	0.1	50	Right Circ.	0.4	Aug 1962 (P)	Jan 1963 (P)	Jan 1963 (P)	
2295 ± 5/ 2115 ± 5	10 kw	Listen Trans.	52.8/52	85	0.4	-	Linear[e]	0.38	Aug 1962 (P)			
2295 ± 5/ 2115 ± 5	25 w[d]	Track Trans.	33/32	10	0.5	-	Right Circ.	3.0				Jan 1963 (P)
2115 ± 5	100 kw	Trans.	51	85	0.4	-	Right Circ.	0.4	Jan 1963 (P)			
2115 ± 5	100 kw	Trans.	62	200-300	0.2	-	Right Circ.	0.13	Dec 1964 (P)	Dec 1966 (P)	Dec 1966 (P)	
2295 ± 5	-	Track	61	200-300	0.1	15	Right Circ.	0.15	Dec 1964 (P)	Dec 1966 (P)	Dec 1966 (P)	

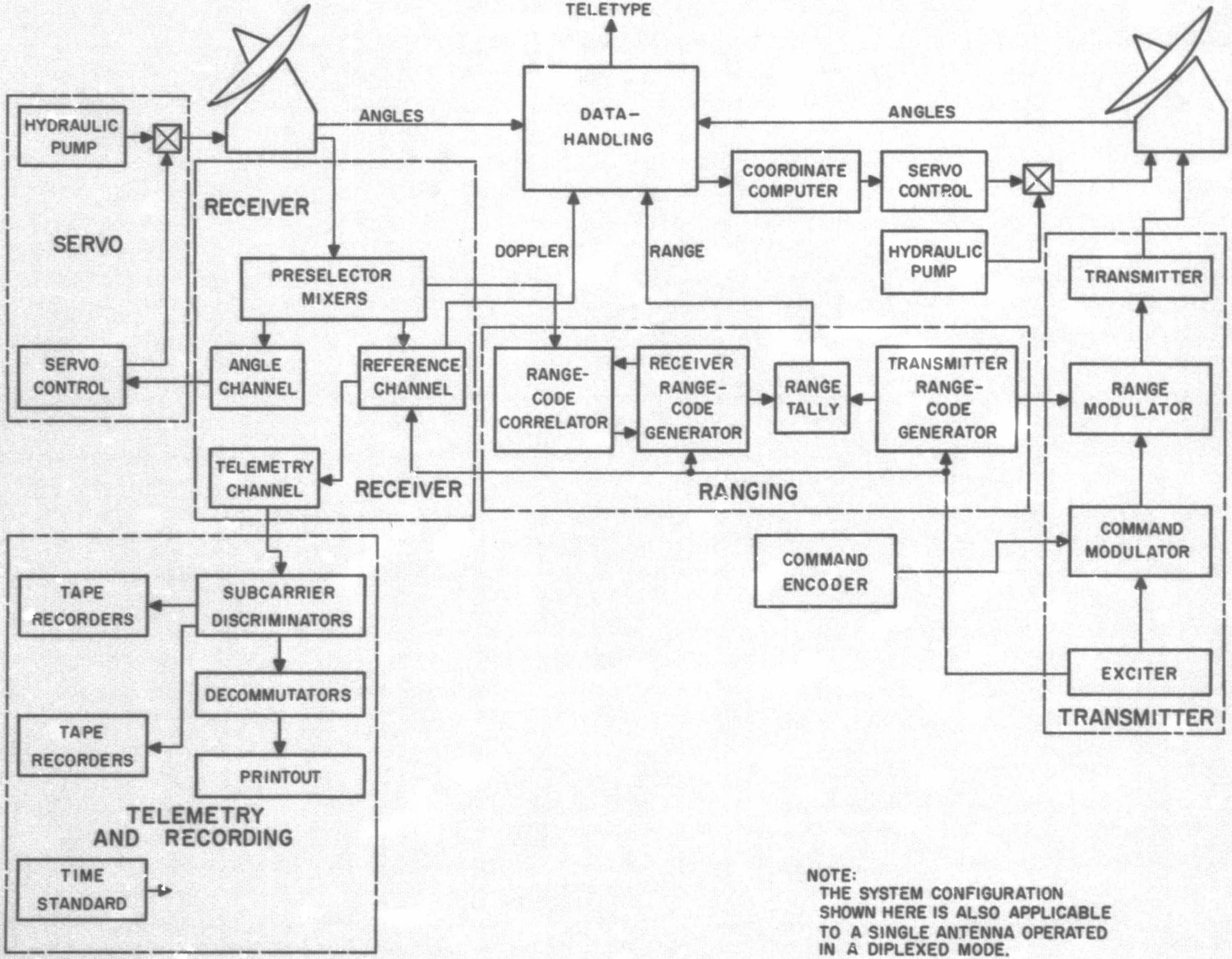
[a] Gain is in decibels above isotropic radiator of matching polarization. Dual-frequency, circularly polarized feeds may have as much as 6-db ellipticity at the transmitting frequency and as much as 3-db ellipticity at the receiving frequency.

[b] Indicated loss is included in antenna gain.

[c] Includes excess noise due to losses in feed lines and antenna temperature at zenith with 0°K sky temperature.

[d] Diplexed. Diplexer loss is approximately 0.2 to 0.3 db in addition to that indicated.

[e] Rotatable.



NOTE:
THE SYSTEM CONFIGURATION SHOWN HERE IS ALSO APPLICABLE TO A SINGLE ANTENNA OPERATED IN A DIPLEXED MODE.

Figure 7. Typical deep space tracking station block diagram

5. DSIF Acquisition Procedures

DSIF spacecraft-acquisition requirements can be separated into the following modes: pointing, frequency, and code acquisition, or combinations of them. The requirement for continuity of data from the spacecraft necessitates that acquisition be made as promptly as possible; to this end, the DSIF provides automatic scan equipment in the three modes to minimize acquisition time. However, certain minimum time requirements still exist which may affect the results of spacecraft experiments:

a. Angle. Pointing information is usually provided for a tracking station; however, it is still necessary to search the area about which the probe position is predicted to be. Supplied ephemeris data are usually accurate to within a degree; however, as noted below, the combined requirement for both angle and frequency search may necessitate several minutes for complete acquisition.

b. One-way doppler. Lock in this mode can usually be achieved in 1 to 2 min. *A priori* information as to the expected received frequency considerably reduces the acquisition time to lock to the carrier. It is usually necessary, in any case, to be at least 3 to 6 db above threshold to establish carrier lock. Care must be exercised to avoid reference-channel phase lock on the subcarrier sidebands.

c. Two-way doppler. Two-way radio-frequency lock on a spacecraft transponder requires that the ground receiver first be locked on the spacecraft transmitter; then the ground-transmitter frequency is swept through the spacecraft-receiver frequency. The spacecraft receiver then acquires and switches from internal frequency control of the spacecraft transmitter to ground-transmitter frequency control, which then requires relocking of the ground receiver to the spacecraft transmitter. Periods involved could be in excess of 10 min.

d. Ranging. This is similar to two-way doppler; however, there is the additional complexity of acquiring range-code lock. Periods involved could be in excess of 15 min.

e. Telemetry subcarrier. The acquisition time of subcarrier channels is usually dependent on the system used. In general, once the carrier has been acquired, the subcarrier acquisition and synchronization (if digital) will take several minutes.

D. Testing and Checkout

At the present time, approximately 10 hr are required to ready a tracking station to support a tracking mission. All checkout, calibration, and testing are performed manually and much data reduction and interpretation is necessary before the station is adjudged satisfactory.

A program is underway to automate many of the procedures now performed manually, and it is estimated that the total time necessary to ready the station will be less than one hour. Included in this automatic equipment will be go-no-go indicators, fault-locating indicators, automatic-calibration equipment, and checkout sequencers. It is expected that the addition of this equipment will materially increase the operational reliability of the station and will enable the tracking stations to participate in a much higher percentage of total tracking hours.

IV. DSIF MISSION SCHEDULES

The existing facilities and programmed expansion of the DSIF are expected to provide adequate tracking and communications capability for the lunar and planetary programs, for which JPL is responsible, during the next five years.

In general, it is expected that any one tracking station can, as a maximum, track 70% of the time, which leaves 30% of the time for maintenance. However, it is doubtful that this tracking percentage can be maintained during the next five years, when one considers the time required for modification or up-dating the tracking stations and the time required to change tracking feeds and equipment necessary to track other experiments within a 24-hr tracking period.

The types of space explorations to be supported include 24-hr satellites, lunar probes, planetary probes, and extra-ecliptic probes. As indicated previously, the Goldstone Station will also be utilized for research and development studies; it is expected that approximately half of the Goldstone activity will be directed to this end. Also, it is expected that about 5% of the Woomera and Johannesburg schedule will be devoted to local research and development studies.

The tracking and communications scheduling requirements vary greatly, depending on the type of mission to be supported. A few examples of the requirements for specific missions are shown below.

1. High-density tracking requirements for several days
    a. Photographing lunar or planetary surfaces during encounter
    b. Obtaining trajectory data for midcourse maneuvers
2. Low-density tracking requirements for several months or years
    a. Deep-space ranging experiments for refinements of the astronomical unit
    b. Particle or radiation experiments in deep space (using data storage)

3. High-density tracking requirements for several weeks
    - a. Mobile lunar explorations
    - b. Dual-vehicle (satellite and soft-lander) planetary exploration
4. High-density tracking requirements for several months
    - a. Lunar mapping, using an orbital camera
    - b. Measurements of lunar or planetary surfaces by means of soft-landed capsules

APPENDIX

Communications Capabilities of the Deep Space Instrumentation Facility

The figures shown in this Appendix are representative of the systems capability of the DSIF in the period 1961-66. The spacecraft communications capability shown is based on existing and planned equipment to be utilized in JPL space missions. The combinations shown are also typical of those planned and are given for the Goldstone site capability.

The following assumptions are made:

1. A 6-db loss pad is included to compensate for various small losses and inaccuracies in the assumed parameters.
2. Sky temperature is assumed to be 0° K.
3. Total transmitter power is divided equally between the carrier and the sidebands; therefore, the value of P_T used in Fig. A-1, A-2, and A-3 is 3 db less than that shown in Table A-1.
4. The maximum tracking range is limited by the minimum possible loop-noise bandwidth of the carrier phase-locked system. Realizable values for this parameter are as follows:

Year	Spacecraft Receiver	Ground Receiver
1961	100 cps	20 cps
1963	20 cps	3 cps
1965	10 cps	3 cps

Table A-1. Communications parameters[a-1]

Year	Frequency Mc	P_T w	G_T db	T °K	G_R db
Spacecraft to Earth (see Fig. A-1)					
1961	960	3	18	1500	44
1962	960	25	18	300	44
1963-64	2295	250	30	100	50
1965-66	2295	250	35	20	62
Earth to spacecraft (see Fig. A-2 and A-3)					
1961-62	890	10^4	44	2600	18/0[a-2]
1963-64	2115	10^4	50	1000	30/0[a-2]
1965-66	2115	10^5	61	400	35/0[a-2]

[a-1] Values shown are nominal.

[a-2] Values are shown in Fig. A-3 for an isotropic receiving antenna on the spacecraft.

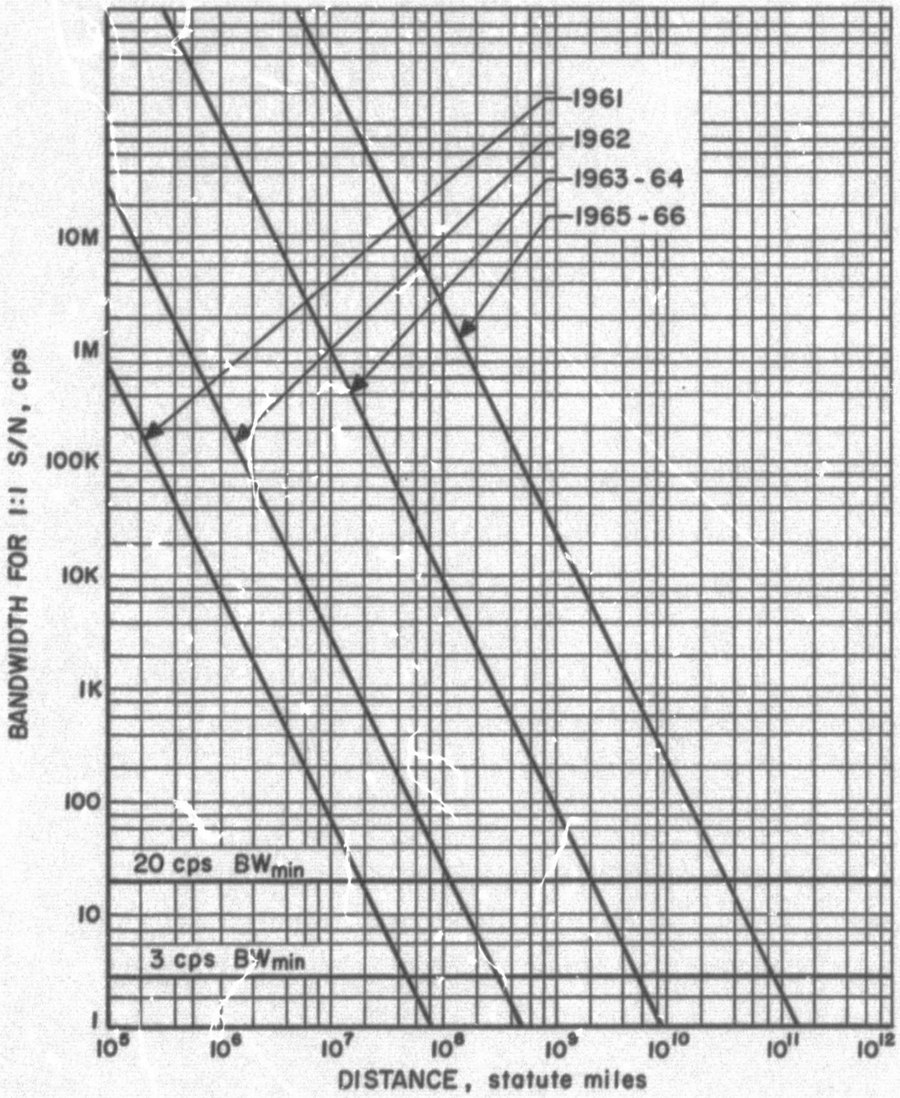


Fig. A-1. Spacecraft-to-Earth communications capabilities

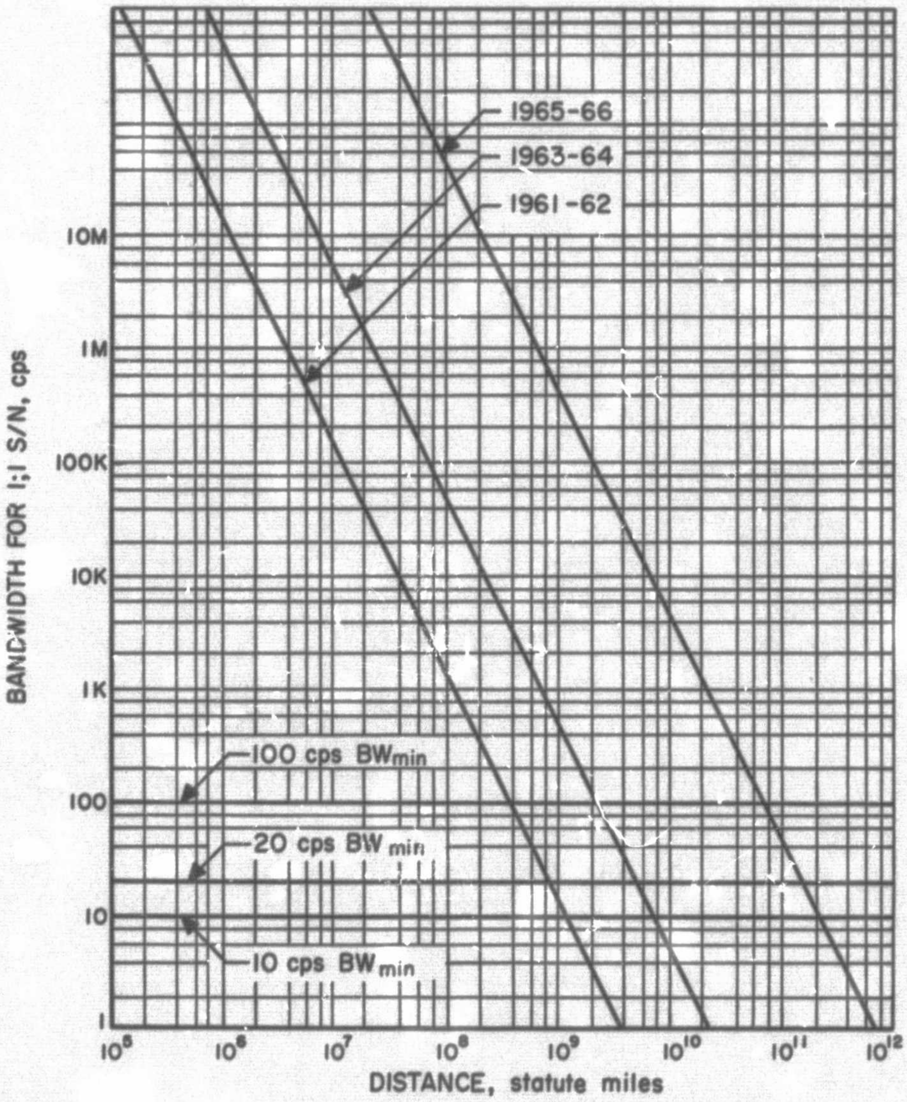


Fig. A-2. Earth-to-spacecraft communications capabilities, spacecraft directional antenna

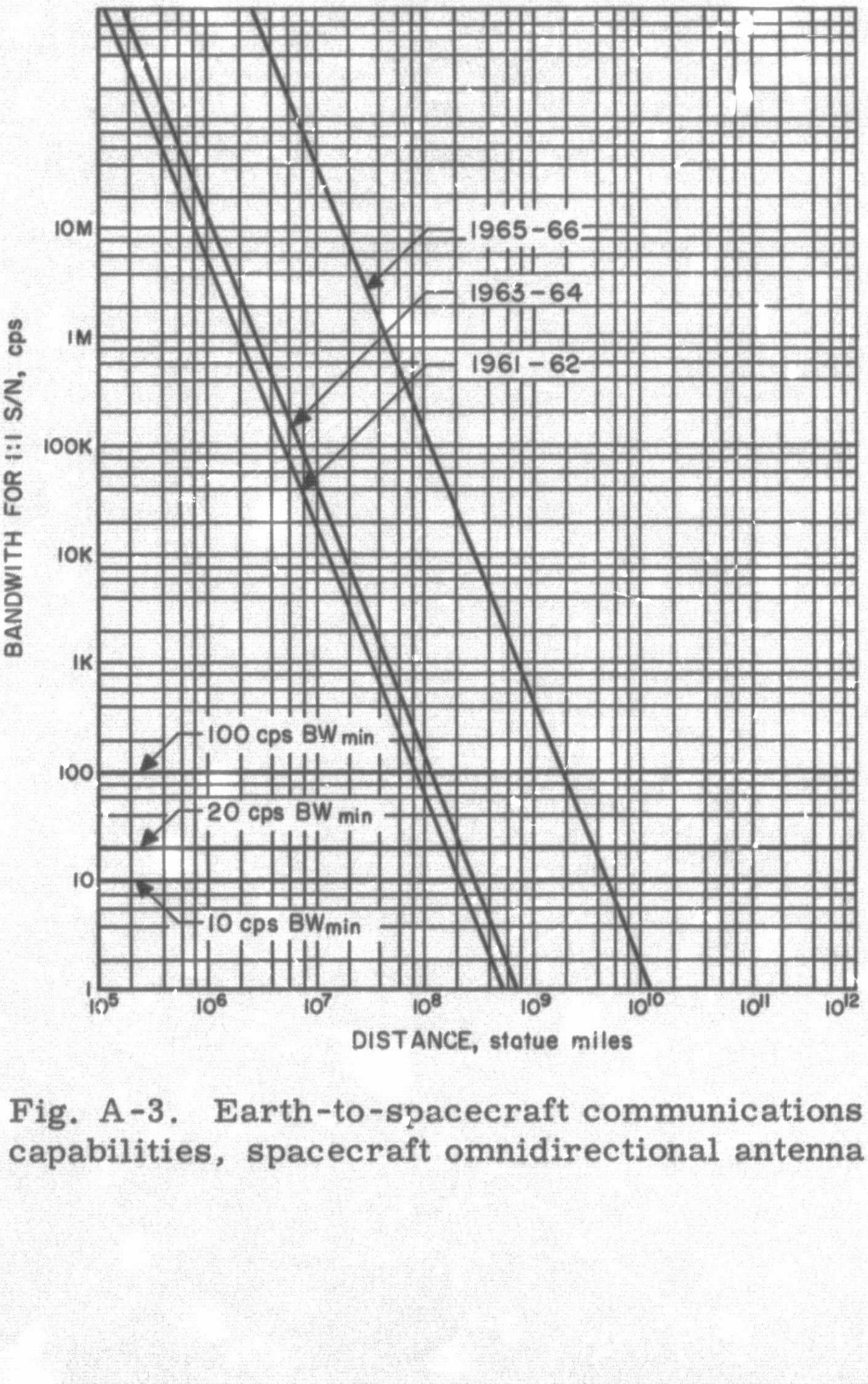


Fig. A-3. Earth-to-spacecraft communications capabilities, spacecraft omnidirectional antenna

The calculations on which Fig. A-1, A-2, and A-3 are based are derived from the familiar line-of-sight transmission equation

$$P_R = P_T + G_T + G_R - L_{FS} - L_P \tag{1}$$

where

P_R = power at the receiver input, dbm

P_T = transmitter power output, dbm

G_T = transmitter antenna gain, db over isotropic

G_R = receiver antenna gain, db over isotropic

L_{FS} = loss between isotropic radiators in free space, db

L_P = loss pad to account for various system losses, db

The loss between isotropic radiators in free space is given by

$$L_{FS} = 36.6 + 20 \log D + 20 \log f \tag{2}$$

where

D = distance, statute miles

f = frequency, Mc

Thermal noise power is related to source temperature and bandwidth by the following equation:

$$P_N = KTB \tag{3}$$

where

P_N = noise power, mw

$K = 1.38 \times 10^{-20} \frac{(\text{mw x sec})}{°\text{K}}$ (Boltzmann's constant, -198.6 dbm)

T = receiver-system excess-noise temperature, °K

B = Bandwidth, cps

For a 1:1 signal-to-noise ratio,

$$P_R = P_N$$

Using Eq. (3), P_N may be expressed in dbm:

$$P_N = 10 \log k + 10 \log T + 10 \log B$$

$$P_N = -198.6 + 10 \log T + 10 \log B \tag{4}$$

To find maximum tracking range, Eq. (4) and (2) are substituted into Eq. (1), and D is solved for:

$$\begin{aligned} P_R &= -198.6 + 10 \log T + 10 \log B \\ &= P_T + G_T + G_R - 36.6 - 20 \log D - 20 \log f - L_P \end{aligned}$$

$$20 \log D = P_T + G_T + G_R - 20 \log f - L_P - 10 \log T - 10 \log B + 162.0 \tag{5}$$

In evaluating various systems, assumptions are made for all parameters except D and B. Then B is varied, and Eq. (5) is solved for D. To simplify Eq. (5), a system gain G_S is defined:

$$G_S = P_T + G_T + G_R - 20 \log f - L_P - 10 \log T + 162.0 \tag{6}$$

Equation (5) then becomes:

$$20 \log D = G_S - 10 \log B \tag{7}$$

Figures A-1, A-2, and A-3 show tracking distance vs bandwidth for a 1:1 signal-to-noise ratio. For ease in using the figures, it should be noted that a tenfold change in bandwidth results in a 10-db change in signal-to-noise ratio, whereas a tenfold change in distance results in a 20-db change in signal-to-noise ratio.

Distances from Earth to various astronomical objects are given in Table A-2.

Table A-2. Distances from Earth to various astronomical objects

Object	Distance, statute miles	
	Minimum	Maximum
Moon	2.2×10^5	2.5×10^5
Venus	2.4×10^7	1.63×10^8
Mars	3.7×10^7	2.5×10^8
Mercury	6.2×10^7	1.39×10^8
Jupiter	3.7×10^8	6.0×10^8
Saturn	7.5×10^8	1.03×10^9
Pluto	2.7×10^9	4.7×10^9
Alpha Centauri	2.6×10^{13}	–

APPENDIX II

THE SELECTION OF THE SPACE TO EARTH FREQUENCY FOR THE DSIF

TO: Dr. A. Silverstein
DATE: May 20, 1960
FROM: Dr. E. Rechtin via Dr. W. H. Pickering
SUBJECT: DEEP SPACE INSTRUMENTATION FREQUENCY

The DSIF report outlining the design principles and proposed future programming of the DSIF has passed a significant milestone: the completion of a technical financial study to determine the choice of frequency and the closely related choice of antenna diameter. The heart of the problem was to obtain the best overall communications capability at the least risk within the proposed cost of $12 million per ground antenna.

One of the first technical conclusions that we reached was that there were two different communication problems involved rather than one. One communication problem is concerned with communication either to or from a space vehicle which has an omnidirectional gain antenna or a very low gain antenna. The second problem involves the transmission of great quantities of data from the distance of the Moon and the planets, a problem which can only be solved by use of directional antennas aboard the spacecraft.

The first problem is encountered in low altitude satellites, in non-stabilized space probes, and in vehicles requiring omnidirectional receiving antennas (regardless of their use of directive transmitting antennas). An omnidirectional receiving antenna permits the vehicle to be turned off for large periods of time and then reactivated by command, an option not available if the receiving antenna is highly directional (and consequently demanding of continuous attitude control). In those applications, it can be shown that the desired antenna on the earth is as large as practical. In order to gain great size without excessive construction difficulties, the usual solution is to use as low a frequency as is practical without encountering excessive external noise. The choice of about 400 to 1000 mc and the use of the 250' Jodrell Bank type antenna is therefore consistent for this particular type of communication. For antennas whose surface tolerances would be better than those of Jodrell Bank, higher frequencies could be used with some slight increase in system performance.

The second case, the one involving directive antennas aboard the vehicle, is sharply different. It can be shown that in this case the principal constraint on the vehicle antenna is its size, inasmuch as if the vehicle attitude control system works at all, it will work to sufficient precision to satisfy the needs of directive antennas. It almost immediately follows that the critical parameter for the ground antenna is its gain and that in order to do really successful communications, this gain should be between 3×10^5 and 10^6. Gains of this magnitude are virtually impossible to achieve at the low frequencies without almost fantastic costs, costs well over one hundred million dollars per antenna. Gains of this order of magnitude, on the other hand, are not at all unreasonable to expect from antennas working at x-band frequencies (the allocation is 8400 to 8500 mc). Indeed, a Goldstone-type antenna with a refined surface could achieve such gains. Unfortunately, a choice of x-band would require a great deal of component development , a postponement of an increased space communications capability for about five years, and a decided incompatibility with the communication problem posed by the omnidirectional vehicle antenna. In addition, a very high order of vehicle attitude stabilization would be required (0.1 degrees) which, while practical, would be some years in arriving. On the other hand, the choice of x-band would minimize the antenna costs, considered alone.

The next lowest frequency from x-band is 2290 to 2300 mc. (This frequency is the proposed choice.) The appropriate gains at these frequencies would require antennas between 150 and 250 feet in diameter; however, because such high gains require antenna surface precisions three to six times as fine as the present Goldstone precisions, the construction problem will not be simple. A choice of a still lower frequency would require that the antenna diameter be still greater. Since the cost of an antenna increases approximately as the 2.7 power of the diameter and (probably) as the inverse of the relative tolerance, we price ourselves out of business as we go to frequencies lower than about 2300 mc. The next available band, 1700 mc approximately, would require antenna diameters proportionately greater and capital investments about 2.4 times as great. Alternatively, we could use lower frequencies, retain the same antenna diameter, reduce the tolerances required, and therefore reduce the system capability proportional to the square of the relative frequencies.

The advantages of a 2300 mc choice appear to be

1. An antenna diameter which we can(probably)afford.
2. An antenna diameter large enough to satisfy the omnidirectional vehicle communication problem (either for transmitting or receiving).
3. An antenna precise enough to satisfy the directional vehicle antenna communication problem.
4. By slightly modifying the existing Blaw-Knox 85' dishes, we can immediately improve system performance by a factor of four.

5. Vehicle transmitters in the 2300 mc band radiating 25 to 250 watts are competitive in efficiency with transmitters at lower frequencies and consequently system performance is not lessened by the choice of frequency.

6. The "allocated" bandwidth of 10 mc between 2290 and 2300 mc is compatible with band-sharing between probes, with TV transmission from the Moon, and with precision ranging. This band would be to the DSIF what 136-137 mc is to Minitrack, and should be coordinated by JPL much like Minitrack handles 136-137.

7. The network would be self-sufficient for the two types of communication problems it faces.

8. The coming of electric propulsion with the associated availability of great quantities of electrical power aboard the vehicle will require vehicle RF transmitters which can take advantage of this windfall. Transmitters at about 2300 mc can perform well in a minimum size without severe arc-over or transmission line loss difficulties common to x-band.

9. High-stability carrier frequencies can be generated and amplified at 2300 mc by use of klystron amplifiers, a technique well developed by JPL/Varian in the past.

10. Optimum frequency for space communications based on galactic noise and atmospheric absorption.

11. Complementary to the probable frequency assignments of the various satellite programs (reference: Coates speech to ISA, San Diego, May 4, 1960).

12. One of best for interference rejection -- a serious DSIF problem.

Eberhardt Rechtin
Eberhardt Rechtin
DSIF Program Director

February 15, 1961

APPENDIX III

THE SELECTION OF THE EARTH TO SPACE FREQUENCY FOR THE DSIF

The lunar and planetary communication system must provide two-way doppler velocity and range information, to telemeter engineering and scientific information from the spacecraft and to send commands from earth.

The ground complex employed is the Deep Space Instrumentation Facility (DSIF) consisting of a mobile tracking station with a 10' parabolic antenna and three tracking stations with 85' parabolic antennas located near Barstow, California; Woomera, Australia; and Johannesburg, South Africa. The RF system now in the detailed design stage consists of a crystal controlled transmitter at a nominal 2113 5/16* mc, a narrow band, double superheterodyned automatic phase tracking receiver operating at a nominal 2295* mc, and a coherent frequency shifter to provide an absolute reference between the transmitter and the receiver. The flight equipment, which of necessity must be compatible with the DSIF, employs an S-band transponder consisting of an extremely narrow band, double superheterodyned automatic phase tracking receiver operating at 2113 5/16 mc and an integrally related transmitter operating at 2295 mc. Thus, the overall communication system provides a coherent phase relationship between the transmitted and received signal via the earth-to-space-to-earth link.

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*To accommodate several active flight missions, frequency diversity is required. Each flight equipment uses 1 mc/s to 5 mc/s of bandwidth, depending upon the operating mode. Hence, the several carrier frequencies must be separated by 1 to 5 mc/s, in turn requiring bands from 2110 to 2120 mc/s and 2290 to 2300 mc/s.

As mentioned previously, this system mechanization not only provides coherency which is absolutely necessary for precision doppler and ranging measurements, but also has telemetry and command capabilities. The telemetry information is sent by phase modulating the spacecraft-to-earth carrier with audio or video information. In a similar manner, commands are sent by phase modulating the earth-to-spacecraft carrier with audio tones. The ranging system is mechanized by phase modulating the earth-to-spacecraft link with a psuedo noise (PN) code*, detecting and reconstructing this code in the airborne receiver, retransmitting the code back to earth and finally detecting and comparing its phase with the phase of the original code to determine range.

Many factors were considered in the selection of the RF frequencies. The most important of which are listed below:

1. Antennas, feeds, and diplexers.
2. Airborne equipment, mechanization and reliability.
3. DSIF receiver and transmitter mechanization.
4. Receiver sensitivity degradation due to N/S ratio.
5. Cost of new development.
6. Schedules.

The antenna characteristics are the most severely affected by the frequency selection. During the immediate future, the two DSIF stations at Woomera and Johannesburg will each be equipped with an 85' parabolic monopulse tracking antenna. Their mode of operation will be to diplex both the transmitted and received signal off the same antenna. Although the Goldstone facility will

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*A pseudo-random sequence of ones and minus ones at a 500 kc switching rate. The effective bandwidth of such a code is about 3 mc/s.

possess two 85' systems, for the major part of the planetary flight it will diplex off one antenna. (This mode of operation eliminates many of the operational problems associated with simultaneous coherent tracking from the two Goldstone stations seven miles apart.) Finally, during the terminal phases of the trajectory, the mode of operation will be switched, if necessary, to the two separate non-tracking linear listening feed antennas to provide the gain and sensitivity to accomplish the missions.

The requirement for diplexing both the transmit and received signals on a single antenna dictates an optimum frequency separation. Experience gained at JPL on two previous systems of the same type, one at 960 mc and one at 10,000 mc, verified that if low noise characteristics are required, the frequency separation should be displaced six to ten percent. The 6% minimum is dictated by the diplexer (the closer the separation, the more cavity filters are needed resulting in increased insertion loss) and the 10% maximum by the antenna feed design bandwidth. This 10% maximum becomes extremely important when a circular polarized feed is used as in the DSIF. On the 960/890 system (8% separation), the problem of designing an adequate circular polarized feed at both frequencies proved to be very difficult. Attempts by Rantec Corporation (Contract No. N21454) to achieve circularity on the sum channel at 960 mc/s to within 0.5 db resulted in a considerably poorer circularity both in the difference channels (5-6 db) and in the 890 mc sum channel (2-3 db). It is estimated that this ratio would increase to 8 to 10 db if a 26% separation (2295/1825) were required. A figure this large is totally unacceptable for planetary missions. Calculations on the Mariner A, Venus flight indicate that under these conditions, the ground transmitter power would have to be increased from 100 kw to 1000 kw average power to provide the required command capability to an omnidirectional receiving antenna on the spacecraft in the vicinity of the planet. Commands to a Mars probe would require a still further increase of 10 db over the Venus mission.

Other characteristics which prove to make a high performance feed with greater than 10% bandwidth difficult to design are:

1. Proper matching at both frequencies.
2. Degradation of the aperture illumination function (see Ref.1).
3. Gain degradation due to feed spacing in monopulse systems (see Ref. 2).

Having applied the 6-10% separation requirement, the choice of 2115 ± mc/s for the earth-to-spacecraft frequency was based upon the additional following criteria:

1. The existing 960/890 mc transponder can be readily modified to the 2295/2113 5/16 mc frequency.
2. A simple ground RF system mechanization is employed.
3. The earth to spacecraft frequency should lie below 2400 mc to make use of available commercial equipment and the existing Goldstone, S-band, 10 kw transmitter system.

The exact frequency was selected on the basis of minimum modifications to the existing 960/890 mc transponder. This particular design has proved to be extremely satisfactory. The transponder now being used on the Ranger Spacecraft Series is completely silicon transistorized and has a threshold sensitivity of -139 dbm.

Ref. 1 - Silver, Microwave Antenna Theory and Design, Radiation Laboratory Series, Vol. 12, Pg. 425.

Ref. 2 - Kuecken, John A., Feed Optimization in Multi-feed Antennas, IRE 1957, Wescon Convention Record, Part 1, pg. 164.

Figure 1 is a block diagram of the transponder consisting of an extremely narrow band, double superheterodyne, automatic phase tracking receiver operating at 890 mc and an integrally related transmitter operating at 960 mc.

Figure 2 shows the S-band transponder. The ranging circuitry is shown dashed. It is noted that only the front end mixer, transmitter, and local oscillator multiplier chains have to be redesigned to convert from the low frequency system. All the other modules will only have to be retuned slightly. It is felt that this mechanization not only offers a maximum reliability but also a reduction in development cost of 4 or 5 hundred thousand dollars. In addition, the very tight scheduling on Mariner A (Venus 1962) and Surveyor (lunar 1963) virtually rules out a major design change.

Figure 3 is the proposed ground system to be used in the DSIF station. In a manner similar to the transponder, the ground radio system is designed to utilize many of the existing circuits presently used at 960 mc. This receiver also is a second order phase tracking servo system whose transfer function is similar in form to that of the transponder. It will employ low noise front ends and will have a carrier threshold level of -160 dbm. The Mariner and Surveyor schedules also present a serious problem to the DSIF since the lead time necessary to install a working system in each of the stations calls for a design cutoff date of 12/1/60.

An analysis (equation 1) made at JPL (Ref. 3) on the effects of the ground receiver threshold sensitivity as a function of the noise-to-signal ratio in the airborne receiver when operating

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Ref. 3 - Research Summary 36-2, Vol. I, Part 1, pg. 23.

under a two-way doppler condition indicates that the threshold sensitivity is reduced as G and N/S is increased.

$$\Delta s = \frac{1}{1-G^2 K_R \frac{P_{N_1}}{P_{S_1}}}$$

where Δs = Change in ground receiver threshold sensitivity.

G = Phase gain equal to ratio of output frequency to input frequency.

K_R = .6 for bandwidth ratios planned.

$\frac{P_{N_1}}{P_{S_1}}$ = Ratio of noise power to signal power entering the transponder.

In effect, the phase noise entering the transponder receiver is multiplied by the ratio of the outgoing to incoming frequency G. Because of this, it is desirable to select the command frequency close to the received frequency to reduce the value of G. Choosing command frequencies above 2295 mc is essentially precluded by lack of high power transmitting equipments and by gain degradation due to surface irregularities in the antennas. NASA plans for large diameter (250' diameter, approximately) ground antennas are based upon a 2295 mc or lower design operating frequency. If a higher frequency were used, the cost to achieve equivalent effective area would increase roughly as the ratio of frequencies. For the frequencies considered, the cost increase would amount to about $800,000 per antenna (three contemplated in FY 1962 - FY 1966).

Tropospheric-scatter propagation interference is not considered to be a problem since the stations of the Deep Space Instrumentation Facility are located in remote unpopulated areas.

Sites are selected so that the horizon is some 3° to 5° above the antenna elevation, thus giving a bowl shaped contour. For example, Goldstone is some 50 miles from Barstow and 120 miles from Los Angeles. Woomera is 250 miles from Adelaide. The South African site is 40 miles from Johannesburg.

The beamwidth of the large 85 foot reflectors is 0.4° and sidelobes are down by some 20 db; therefore, any illumination will primarily take place when pointing at the horizon. The tracking stations listen to a vehicle when it first rises over the horizon and goes through an acquisition phase. Station transmissions are made later on during any particular tracking mission day. This means that transmissions occur some 10° to 20° above the horizon.

For tropospheric-scatter propagation, the transmitter power of 10 kilowatts, +70 dbm, and the antenna gain of +51 db yield an effective radiated power of +121 dbm. Space loss at 100 miles is -143 db and tropo-scatter an additional -60 db for a total loss of -203 db. The received field strength would be -78 dbm for a 0 db gain antenna sighted along the axis of propagation. This is very low level for most communication systems.

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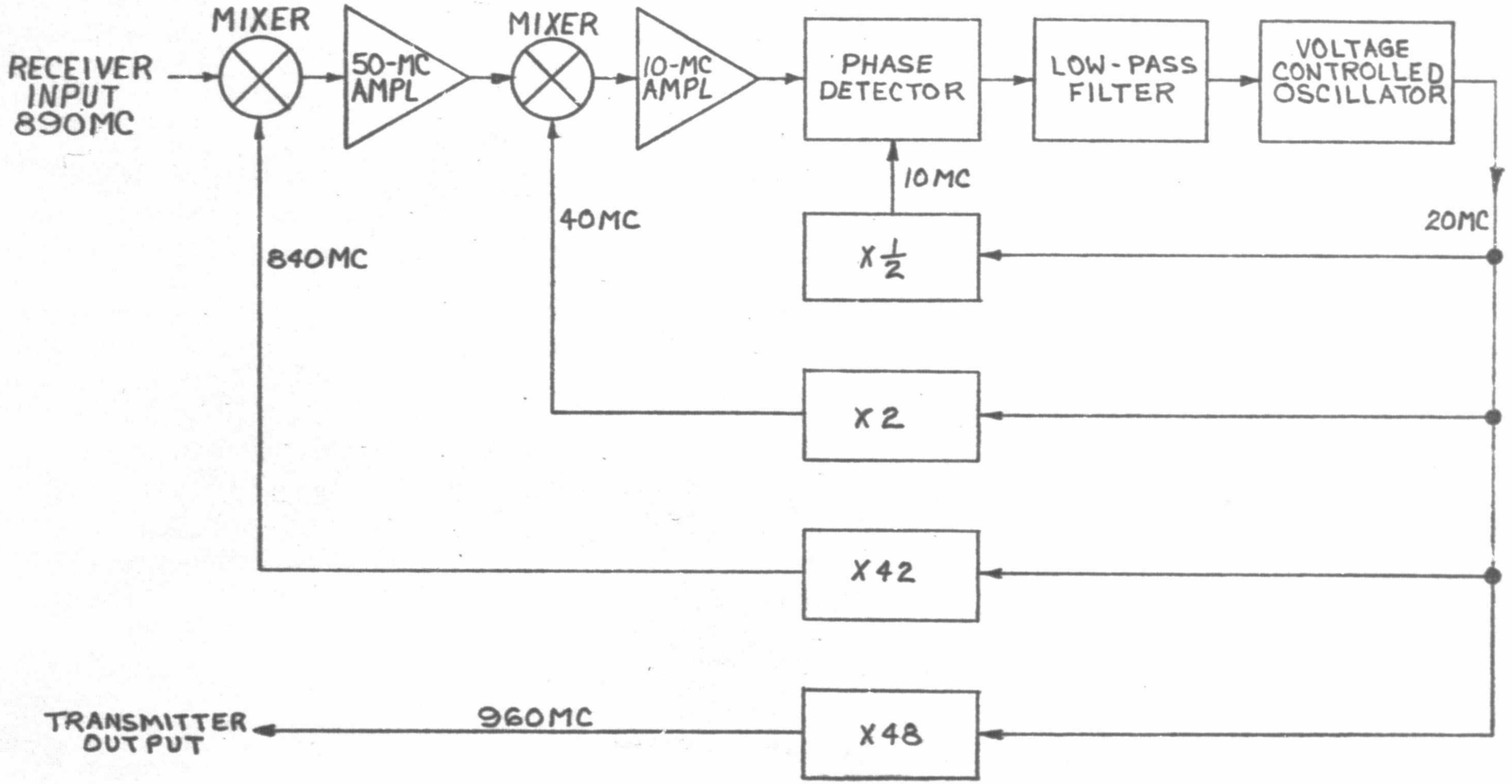

FIGURE 1. 960/890 MC TRANSPONDER MULTIPLICATION SYSTEM

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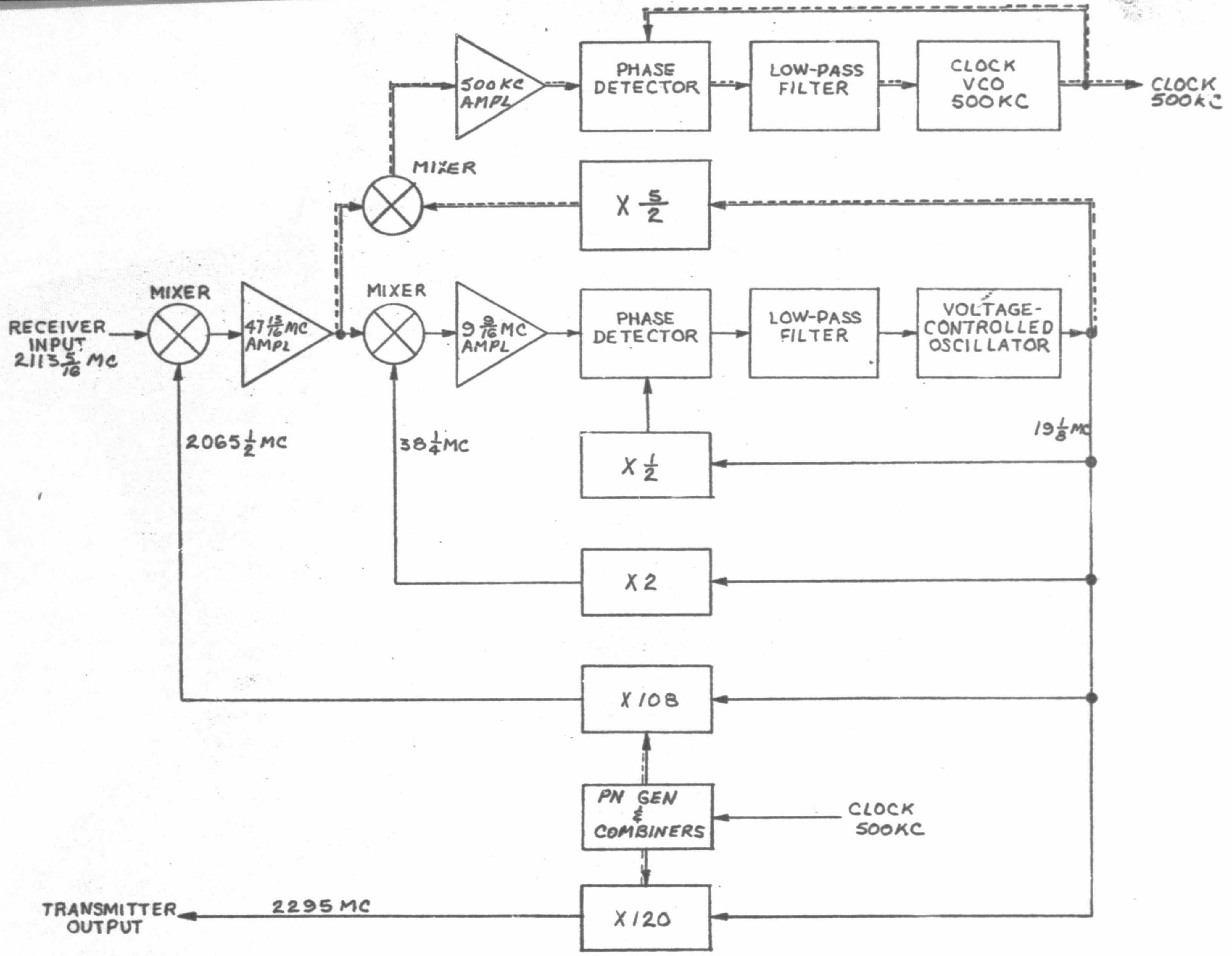

FIGURE 2. 2295/2113 5/16 MC RANGING TRANSPONDER

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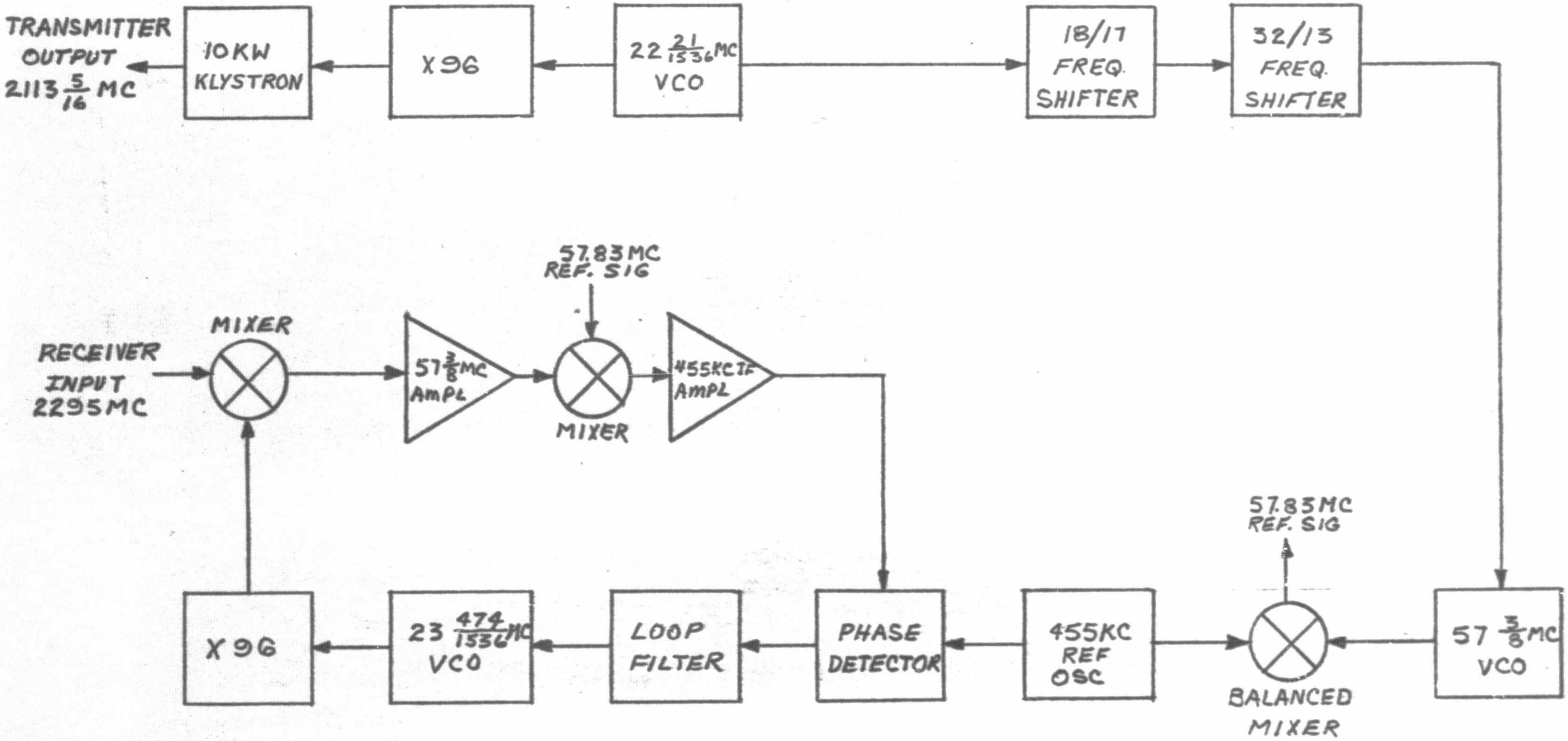

FIGURE 3. DSIF RF MULTIPLICATION SYSTEM