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THE UNIVERSITY OF MICHIGAN

COLLEGE OF ENGINEERING

DEPARTMENT OF ELECTRICAL ENGINEERING

Radiation Laboratory

ON THE DESIGN OF A NASA-MSC ANTENNA FACILITY

by

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I. INTRODUCTION

This is the final report under Purchase Order No. T-5282-1800 and covers the period 19 July to 28 August 1963. Under the terms of this contract the Radiation Laboratory is required to furnish design criteria and overall specifications for a four-part facility to be constructed at the NASA Manned Spacecraft Center (NASA-MSC) in Houston, Texas.

The facility is to be located within a designated area of land at the Center and consists of an outdoor range, an anechoic chamber, an associated service building and an optical test range. The purpose for which it is needed is stated in Appendix B of the Scope of Work covering the above purchase order, and additional information was made available at meetings between members of the Laboratory, NASA-MSC and others, held at the offices of the Lummus Company in Houston on 22 July and 15 August 1963. A summary of the information derived from these sources is presented in Chapter II, and in essence the non-optical parts of the facility are required for the testing and evaluation of the antennas and electronic equipment to be mounted on the Apollo vehicle. Over and above this, however, but within the limits imposed by the budgetary appropriation, the facility should have the widest possible capability both for testing future manned spacecraft and as a general research tool. Methods of integrating the individual parts are to be considered, and in the event that the cost of the proposed scheme exceeds the money which is available, possible areas for trade-off are to be suggested.

The sizes, weights and types of antenna configurations to be tested are discussed in Chapter III and from a knowledge of the frequencies of operation, the far field distances are deduced. The possibility of scale model tests which would permit a reduction in all of these factors is examined, and reasons for rejecting this approach as a general test procedure are presented. As a result, the majority of pattern measurements must be performed on an outdoor range, and the pros and cons associated with a ground reflection range as opposed to a free space one are examined. Because of the extremely large dimensions of transmitting antenna and support towers required for the operation of a free space range at the lowest frequencies of interest, the recommendation is for a combination range which would function as a ground reflection system at the lower frequencies and would go over naturally to a free space range at the higher frequencies. For convenience and to minimize the cost of the facility, the transmitter site is fixed and the test object mounted on a movable support which would allow it to be placed at any one of three distances. The third position is within the anechoic chamber whose end doors are open, leading to a partially shielded environment for the test antenna in the event that radio interference proves troublesome.

The anechoic chamber is by far the most costly part of the facility but it is nevertheless an essential feature. Although most of the antenna pattern measurements must be carried out on the outdoor range owing to the severe far field requirements, the anechoic chamber should be used whenever possible in view of its freedom from weather and interference problems and its generally controlled environment. The antenna impedance, RFI and EMI tests will therefore be performed inside the closed chamber, and even some pattern measurements with a single module should be feasible.

The design of a chamber which will function adequately for all of these purposes is described in Chapter IV. Since the largest object which must be accommodated is some 57 feet in length and 20 feet in diameter, a large room is essential, and the recommendation is for a shielded enclosure 70 by 70 feet in cross section and 120 feet in length. Three grades of absorbing material are advocated for mounting on different portions of the walls, and the interior dimensions of the chamber will be decreased by the thickness of the material. The wall at the receiver end should be non-planar and at the other (transmitter) end motorized doors must be provided to permit the opening of a 55 by 55 foot aperture. For use as an integral part of the outdoor range when needed, the chamber should be placed at a distance of 2500 feet approximately from the site of the transmitting tower along the center line of the range, but with the axes of the range and the chamber inclined at (about) 5° to one another so as to reduce the possibility of any specular reflections from the closed doors of the chamber interfering with normal operation of the outdoor range.

A more detailed discussion of the way in which the outdoor range and anechoic chamber are integrated with one another is given in Chapter V, and included here is a description of the support towers for the transmitting and receiving (i.e. test) antennas. It is intended that both the range and the anechoic chamber be capable of remote control from a single location within a service building adjacent to the chamber, and the recorders for pattern measurements, etc, will be placed here. The service building itself is described in Chapter VI.

In comparison with the antenna portions of the facility, the requirements for the optical test range are more definitive and exacting, and leave little scope for inventive design. For this reason, somewhat less attention has been devoted to this part, but in Chapter VII the implications of these requirements are examined in the light of existing optical ranges, and an approximate costing presented.

The cost figures for both the basic facility and the associated equipment are given in Chapters VIII and IX respectively, and the recommendations of the complete study are summarized in Chapter X.

II BACKGROUND INFORMATION

2.1 Budget

A sum of $2.19 million has been appropriated for the construction of the facility and must be committed before the end of FY 64. Originally a vibration and acoustical testing building was regarded as a part, but this has now been separated out. However, an optical range has since been included and must be funded from the available money. The essential requirement is that the overall facility be capable of carrying out the measurements described in Purchase Order No. T-5282-1800, but over and above this it should be designed for maximum utility subject, of course, to the budget limitations.

In addition to the above sum, there is an appropriation for the purchase of electronic equipment, etc., and in consequence the $2.19 million is only for the construction of buildings, ranges, towers and other fixed items. It does not include vehicles and movable objects which are not special items essential to the operation of the facility.

2.2 Site

The site on which the facility is to be constructed is a 425 acre plot within the confines of the MSC on the northwest side of the Campus area. It is roughly rectangular in shape with an additional piece of land at the western end resulting from the bending of the Houston L and P Company canal (see Fig. 1). The east-west dimension is (approx.) 5000 feet and the north-south dimension varies from 3500 feet to 4500 feet. Crossing the area from northeast to southwest is a drainage ditch some 50 feet in width and about 20 feet deep. This has recently been increased in depth to provide

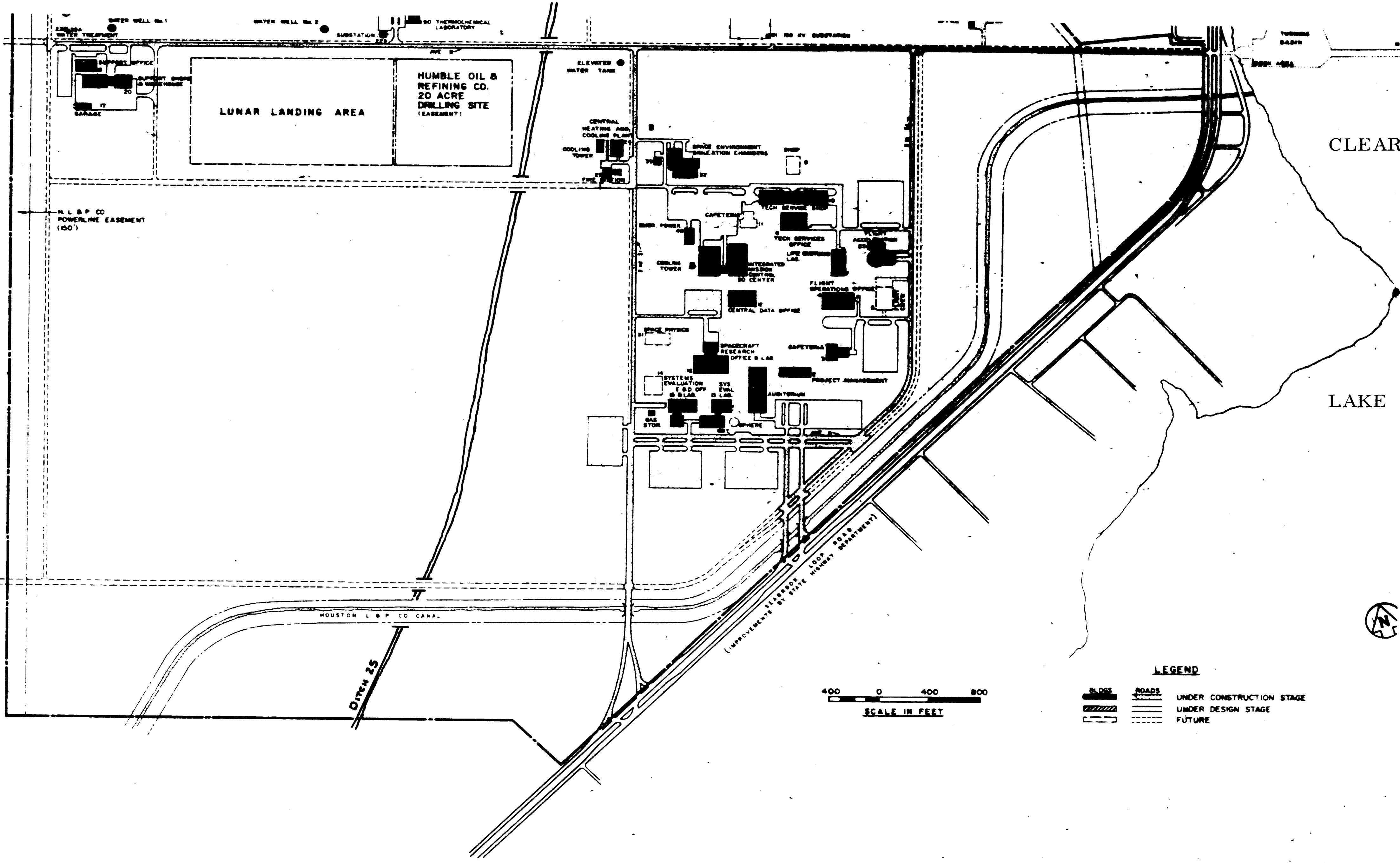
CLEAR
LAKE
TURNING BASIN
DOCK AREA
150 KV SUBSTATION
WATER WELL No. 1
WATER WELL No. 2
WATER TREATMENT
SUBSTATION
50 THERMOCHEMICAL LABORATORY
AVE B
SUPPORT OFFICE
SUPPORT SHOPS & WAREHOUSE
20
17
GARAGE
LUNAR LANDING AREA
HUMBLE OIL & REFINING CO. 20 ACRE DRILLING SITE (EASEMENT)
ELEVATED WATER TANK
CENTRAL HEATING AND COOLING PLANT
COOLING TOWER
FIRE STATION
H. L & P CO POWERLINE EASEMENT (150')
SPACE ENVIRONMENT SIMULATION CHAMBERS
32
SHOP
TECH SERVICE SHOP
CAFETERIA
11
EMER. POWER
TECH SERVICES OFFICE
LIFE SYSTEMS LAB
FLIGHT ACCELERATION FAC.
COOLING TOWER
INTEGRATED MISSION CONTROL 30 CENTER
FLIGHT OPERATIONS OFFICE
CENTRAL DATA OFFICE
12
SPACE PHYSICS
31
SPACECRAFT RESEARCH OFFICE & LAB
16
CAFETERIA
PROJECT MANAGEMENT
2
14
SYSTEMS EVALUATION E & D OFF 15 & LAB.
SYS EVAL 13 LAB.
AUDITORIUM
GAS STOR.
SPHERE
AVE D
HOUSTON L & P CO CANAL
DITCH 25
SEABROOK LOOP ROAD
(IMPROVEMENTS BY STATE HIGHWAY DEPARTMENT)
400
0
400
800
SCALE IN FEET
LEGEND
BLDGS
ROADS
UNDER CONSTRUCTION STAGE
UNDER DESIGN STAGE
FUTURE
N

FIG. 1: SITE

fill dirt for use elsewhere, and it is probably larger now than is required for drainage purposes even in the heaviest storms. It is regarded as feasible (if necessary) to restore the ditch to its original dimensions, or to pipe it, or even to cover it over for some part of its course.

The nature of the land itself can be judged from the photograph in Fig. 2, taken from the edge of the Campus area and looking in a northwest direction down the length of the plot. The ground appears to be relatively virgin and undisturbed over most of the region. It is level and probably flat to within one foot. The soil is compacted, but in various places there are cracks an inch or two in width and as much as a foot in depth resulting from the irregular drying of the ground after rain. The area is covered with a form of coarse scrub grass and apart from a clump of small trees on the south side there are no trees, bushes or obstructions of any kind.

2.3 Climate

The average temperatures in the Houston area very from about 50°F in January to 85°F in July. On occasions the temperature may reach 110°F and can be above 100°F for several days. There are a few killing frosts per year, and though there are cases in which the temperature has fallen to as low as 10°F, a minimum of around 20° to 25° is more typical.

It is the personal experience of the authors that the humidity tends to be high and can remain in the 90's for many days. The rainfall averages 3.5 to 4.0 inches per month, with late Spring being the time of the heaviest rains. No figures are available for the probable maximum rainfall in a 24 hour period (as much as

FIG. 2: NATURE OF THE LAND

10 inches has been suggested), but the general information is that most precipitation in sporadic, with periods of drought followed by heavy rains. There is seldom any snow.

The wind velocity averages some 10 mph but can go up to 90 mph (or greater) under hurricane conditions. Meteorological data also indicates the occasional occurrence of storms called "Northers", which bring a rapid drop in temperature, rain, sleet and high winds up to gale force. The prevailing winds, however, are southerly.

The above information suggests that the proposed facility may be subjected to winds of 35 to 50 mph, though it is not necessary for the range to continue operations during these conditions. It is presumed that sufficient warning will be given if more severe conditions are imminent to permit the movable parts of the outdoor range (tower, dish, etc) to be protected. It also appears that the climate is not such as to rule out the use of grass as an integral part of the range.

2.4 Surroundings

On the southwest side, the site is bounded by a fence bordering on the Houston L and P Company canal, which fence crosses the property line some 1000 feet from the west corner. The canal serves to supply water for airconditioning and no traffic along it is anticipated. Beyond the canal on the south side, however, is Route 528, a main road. This is presently scheduled for improvement by the State Highway Department and considerable traffic is probable now and in the future.

On the northwest side there is a drainage ditch (number 26) similar to Ditch 25 crossing the site. This is just inside the property line. Along the latter, there is a 148 KV power line; and beyond this is a research park which is part of the new Clear Lake City development and which is designated for light industry. The park already contains some buildings (visible in the distance in Fig. 2) and complete development of the area is scheduled for the future. North-northwest of the park is the proposed town center which will contain at least one building 40 stories high.

The northeast boundary of the site is shown in Fig. 1 as a dotted line representing a proposed road. This is not yet in existence even as a dirt road except for a bridge where it crosses Ditch 25. On the other side of the proposed road are miscellaneous buildings on the far left and right (see Fig. 1), and in between the region is designated for a lunar landing area and for oil drilling. We have no definitive information about any buildings which may be constructed in the lunar landing area, but it is thought feasible that one such may be quite large and bubble-shaped. On the oil drilling site, derricks and pumps up to

15 or 20 feet in height may be erected in the future.

The main construction in existence at the moment is in the Campus area, which is separated from the southeast side of the site by 2nd Street. The nature of this construction is apparent from the photograph in Fig. 3, taken from the far side of Ditch 25 and looking in a southeast direction. The buildings are square-on to 2nd Street and the approximate heights of the larger ones are as follows:

Building[+]	Height (feet)
No. 32	120
No. 2	100
No. 45	60
Nos. 13, 15 and 16	35
Auditorium	25

The vibration and acoustical building, which may be as much as 90 feet in height, will probably be located across 2nd Street from the elevated water tank (see Fig. 1).

2.5 Interference

We are informed that a survey of the RF and EM interference levels in the vicinity is presently underway to assist in the evaluation of the site. The survey will also attempt to predict the levels likely to be reached in the future when the whole of the area is developed, but no details of the results are available. Nevertheless, there is one major source of interference existing at the moment which must be borne in mind in orientating the parts of the proposed facility. At Ellington Air Force Base about 5 miles north-northeast of the site are two UHF radars with dishes which are sections of paraboloids some 30 feet in diameter. The antennas radiate at a relatively low angle to the ground, with one producing a fan

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[+] See Fig. 1.

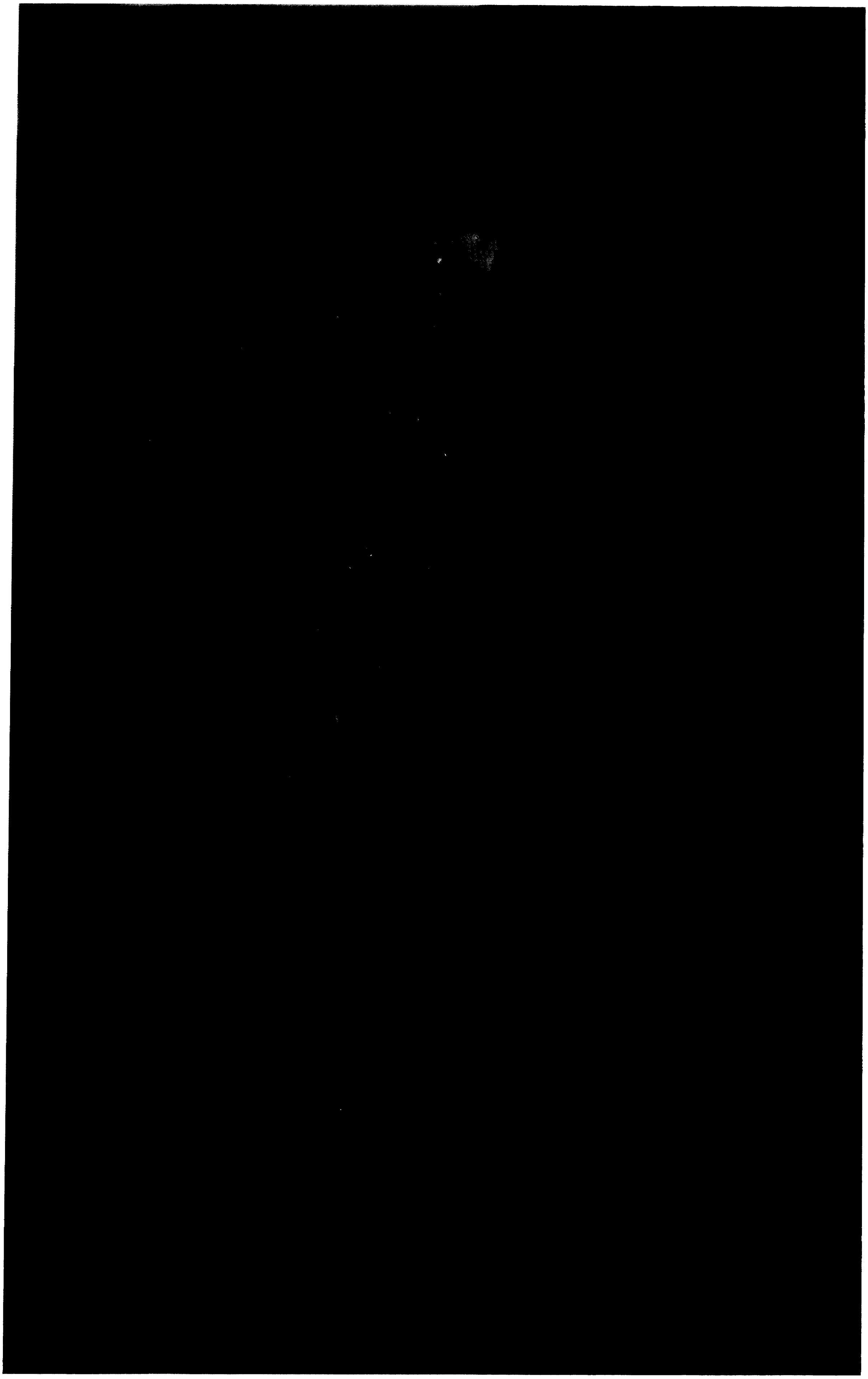

FIG. 3: CONSTRUCTION AREA

beam in the horizontal plane and the other a fan beam vertically, and are in operation most of the time.

Although these radars are regarded as the largest single source of trouble, there is also the possibility of stray signals arising from the navigational radars on ships negotiating the canal into Baytown and Houston. The canal follows a roughly circular arc from northeast to northwest at a distance of about 9 miles from the site. Because of the distance and low power of the radars, the associated interference is not expected to be serious, but it would appear desirable to guard against it if possible.

2.6 Apollo Vehicle

The purpose of the proposed facility is to test the antennas and electronic equipment which are to be carried by the Apollo vehicle, and it is therefore necessary to consider the form which this vehicle will take. The information in this (and the following) section was obtained from a briefing by Mr. E.L. Chicoine and Mr. L. Leopold of NASA-IESD at a preliminary meeting held in the offices of the Lummus Company on 22 July 1963.

The relevant components of the Apollo vehicle are shown in Fig. 4. The escape tower consists of four braced girders 29 feet in length, 6 feet in outside diameter, mounted on top of the command vehicle (CM) wherein the three astronauts will live throughout most of their journey. The CM is 11 feet in length,

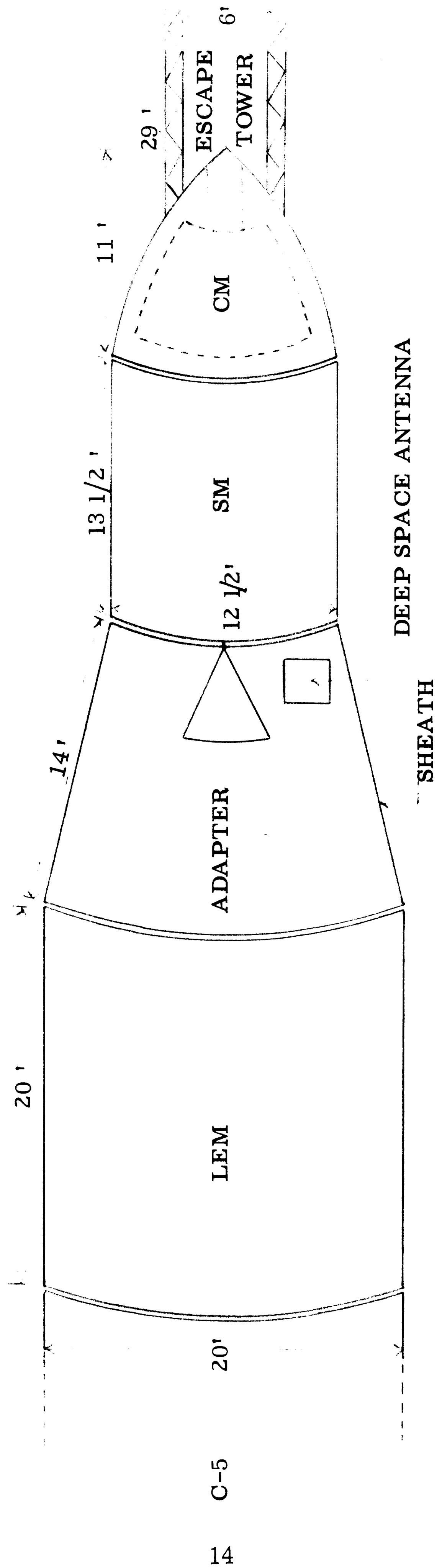

FIG.4: APOLLO CONFIGURATION

12 1/2 feet in maximum diameter, and below this is the service module (SM), 13 1/2 feet in length and 12 1/2 feet in diameter. This in turn is mounted on an adapter of approximately 14 feet in length whose sheath flares out to a diameter of 20 feet. The final component is the Lunar Excursion module (LEM), designed and constructed by the Grumman Aircraft Engineering Corporation, which is 20 feet in length and 20 feet in diameter and rests on top of the Saturn C-5 booster rocket.

The escape tower is blown off about five minutes after successful launch and the whole vehicle then goes into an earth orbit. Whether or not it will describe a complete orbit before taking off on a lunar course is not as yet decided. At an altitude of about 8000 miles the sheath of the adapter is blown off, revealing the deep space antenna formerly concealed beneath, and initiating deep space operation. The LEM is now moved round and attached to the nose of the CM (docking operation), and in this state the vehicle (less the booster, of course) proceeds to the vicinity of the moon and enters a lunar orbit. Two astronauts then transfer to the LEM, leaving one in the CM, and the LEM descends to the lunar surface.

On returning to the lunar orbit, the LEM again attaches itself to the CM enabling the astronauts to transfer back to the CM. The LEM is now detached and remains in orbit. The command and service modules remain temporarily as one unit, but after mid-course correction the SM is also jettisoned, leaving only the CM to return to earth.

It should be noted that all of the components described above are metallic with the exception of the CM, which is covered with an ablating material varying in thickness from 1/4 to 3 inches. The command module has, in fact, a double skin construction with an internal room made of one-inch thick corrugated aluminum. Spaced one to three inches from this is an outer shell of the same material, with trusses or air between. A tunnel traverses the somewhat greater space between the two metal layers at the nose of the vehicle to enable the astronauts to transfer to and from the LEM.

The ablating material external to the outer shell is AVCOAT produced by AVCO Manufacturing Company. The dielectric constant is approximately 2.75, with $\tan \delta \sim 0.02$, and the attenuation after charring is about 24db. Since a scimitar antenna (being designed by McCabe and constructed by the North American Aviation Company at their Downey plant) will probably be located beneath the coating, it is necessary to protect the ablating material from charring on exit through the earth's atmosphere, and for this purpose the AVCOAT is covered with a layer of teflon. When uncharred the attenuation of the ablating material is only about 1db.

The weights which the above components may achieve are as follows:

Escape Tower	6600 lbs
Command Module	8500 lbs
Service Module	7600 lbs
Lunar Excursion Module	8000 lbs

By removing equipment unessential to a given test from a module, it is feasible that most of the antenna measurements could be carried out using stripped-down components with weights a good deal less than those indicated above. An even greater weight reduction could be achieved by going further and constructing mock-ups of the components.

2.7 Frequencies and Antennas

The frequency ranges which the antenna range should be designed to handle were listed in the specifications of the contract as 8-16 Mc, 135 Mc, 220-330 Mc, 400-430 Mc, 2200-2400 Mc, 4-6 Kmc and 8-10 Kmc; and for scaled antenna pattern work, 18 Kmc, 36 Kmc and 70 Kmc. More complete information, however, was provided by Mr. L. Leopold at the previously described meeting and he emphasized the desirability of looking beyond Apollo to future space missions as, for example, to Mars. In consequence, the listing of frequencies and antennas is merely a statement of what is contemplated at the moment, and if possible the facility should have a greater capacity.

As presented by Mr. Leopold, the frequencies of immediate interest are as follows: 8-10 Mc, 125-150 Mc, 220-300 Mc, 400-450 Mc, 1400 Mc, 2100-2300 Mc, 5-6 Kmc and 8-10 Kmc or 12 Kmc. Some model frequency capability (35, 50 and 75 Kmc) would also appear desirable. Typically the antennas will be omnidirectional, although some of the higher frequency ones (e.g. the S-band antennas) may have a gain of 28 to 35 or 40 db. An antenna of the latter type could be a parabolic dish 4 1/2 feet in diameter, but dishes up to 10 feet in diameter with a gain of as much as 45 db are visualized for the Mars mission.

To determine the vehicle components which must be present for adequate testing of the antennas in the Apollo program, a description of the frequencies used at the different stages of the lunar mission is required. The following is believed to be a comprehensive listing.

(1) Launch and Immediately after.

Tracking: C-band

Telemetry: 220-260 Mc

Voice: 300 Mc (approx.)

Data Link: 400-450 Mc (with emphasis on the latter number).

All of the antennas for the above will be near the nose of the CM or around its waist, and as such will be in operation for part of the time with the escape tower in their immediate vicinity. The antennas may be scimitar, or slot.

(2) Deep Space

2100-2300 Mc.

(3) Docking

2100-2300 Mc ,

but depending where the docking takes place, some of the launch frequencies may be used in addition. The 1400 Mc rendezvous radar may be employed and, perhaps, also an X-band frequency.

(4) Lunar Environs

250-300 Mc
2100-2300 Mc
X-band

The first frequency is for communication between the LEM and the CM as the former descends to the surface of the moon, and also for personal communication if an astronaut leaves the LEM to explore the surface. The second frequency is to communicate with the earth, and X-band for rendezvous.

(5) Re-entry

Telemetry and Acquisition: 220-300 Mc

Distress Frequency: 243 Mc

Long Range Recovery: 8-10 Mc.

The question of using the last-named frequency is still unresolved.

The probable powers associated with the various antennas are as follows:

8 - 10 Mc	20 watts peak (single side band)
243 Mc	2 watts CW or pulsed with 100 watts peak
220-260 Mc	(telemetry) 15 watts average
300 Mc	(voice) 10 watts average
400 - 450 Mc	(receiving only) milliwatts
2100-2300 Mc	20 watts average
5-6 Kmc	2500 watts peak (approx. 3 watts average) per antenna
8-10.5 Kmc	approx. 5 watts average (pulsed or intermittent CW).

III OUTDOOR RANGE

This section of the report discusses several aspects of the outdoor range. The subject of modeling is examined first since the size of the components to be tested will seriously affect the range characteristics, i.e. mount sizes, range lengths, test frequencies, heights, etc. After the subject of modeling has been treated it is necessary to both determine and establish the far field requirements for the antenna systems to be tested. As a result of the far field requirements, two types of antenna ranges are considered: free space and ground reflection, and a discussion of their relative merits is presented. Far field criteria as a function of both the transmitting and receiving antennas are established for the above two ranges, along with optimum transmitter and receiver heights.

The outdoor range is designed to operate at frequencies above 100 Mc and is capable of testing full scale space modules comparable to those of the Apollo program.

3.1 Modeling

The problems involved in measuring the radiation patterns of antennas on modules similar to the full scale Apollo modules are extremely severe due to size and weight. The situation is even worse when the tests are made on two or more attached modules, as they must be for certain of the antennas. Modeling has been successfully used in previous tests of antennas on ships, aircraft and missiles and the principles involved have been appropriately described by Sinclair (1948) and others.

If an antenna is scaled down in size by a factor p and the test frequency is scaled up by the same factor, the radiation pattern is essentially unchanged provided that (i) $\sigma' = p\sigma$, (ii) $\mu' = \mu$, and (iii) $\epsilon' = \epsilon$; where σ, μ and ϵ are the conductivity, permeability and dielectric constant respectively of the metallic and non-metallic parts of the full scale antennas, and the primed values are those associated with the scale model.

The conductivity of metals employed in radiating systems is near enough to infinity to avoid any need for scaling and this fact is the basis for the large amount of antenna work that is done by scaling. This is true since most of these antennas and associated "ground planes" have been constructed of metal.

There is, at present, no satisfactory method for handling the "scaling" problems associated with non-metallic parts of antennas. This is the over-riding reason that causes us to recommend the use of the full-sized modules in the major part of the antenna testing. The scaling problem is due to the use of ablating material on the command module. The possibility of using scaled models for the other modules has been considered. However, in testing the low frequency antennas on the adjacent modules it is necessary to have the command module present and therefore it is not feasible to scale these modules and not the command module. Since the antennas on the LEM will be operating when this module is separated from the others, it's antennas could be tested on a scaled-down model. The recommended range will be suitable for such tests but since the range must be able to handle the full scale parts of the other vehicles, it may be more convenient and less costly to test the full scale LEM.

There is another important reason for using full scale rather than scaled down antenna models. A major purpose for the proposed range is to test the performance of the final version of the actual vehicle. Such information is not obtained from model tests. The use of scale models is much more feasible on a research range or for any research to be performed on Apollo antennas on the present range.

There are additional reasons for using full scale models in the impedance and RFI tests that must be made. It is very difficult to properly scale transmission lines and transmission line devices to much higher frequencies. Size alone is one problem and the other is the scaling of dielectric and ferromagnetic materials that may be present. The scaling of a matching network is also difficult particularly if high Q circuits are used, since the location of one component in relation to another may be critical.

In making the RFI or EMI tests it is necessary to have all neighboring devices operating. Economically it is not practical to build a scale model that includes all antennas, motors, generators, receivers and other electrical and electronic devices that would properly simulate the full scale module. Furthermore, it is impractical to make RFI tests on scaled models since one cannot possibly scale the various harmonics that might be present.

Since full scale models must be used in impedance and RFI tests, and since it seems feasible to use test supports that can be wheeled from one test environment to the other, the use of full scale models in the antenna testing does not appear to present any major problems.

In the above discussion one of the reasons for concluding that full scale model measurements would be required was to eliminate the scaling problem of the CM ablating material. However, at the frequency of the long distance recovery system (10 Mc) the physical size of the CM is very small electrically (approximately 0.01λ) in comparison to the operating wavelength (100 feet). In view of the electrically small size of the CM and physically large range length required (approximately 1000 feet both horizontally and vertically) it will be desirable to use antenna modeling techniques for this frequency.

3.2 Far Field Requirements

The antenna range for the NASA-MSC is intended to be used for the final evaluation of antennas installed in flyable spacecraft. As has been pointed out in the previous section, it will be necessary for these antennas to be tested in full scale rather than on scale models for the reasons noted. Since several types of antennas, operating at several different frequencies in the 100 Mc to 10 Gc range, will be employed on present and future spacecraft, the antenna range must be designed for broadband frequency operation.

To achieve the required frequency capability, the range must be designed to satisfy several criteria. In the first place, it should be free of reflecting surfaces to minimize false antenna pattern measurements, and secondly, the range must be such that both the transmitting and test antennas are operating in their respective far fields or Fraunhofer regions. This criterion assists in establishing the range length since it is desirable for the antenna pattern to be independent of distance. It has been shown by Reich et al (1953) that the far field of an antenna exists at ranges greater than $\lambda/2\pi$. To ensure that the antenna patterns are independent of range it has been stated by Hamer (1953), and generally accepted, that the range length should be greater than 10λ long. In addition to the above far zone criterion it is also important for the antennas to be separated far enough to ensure that the phase front across the aperture of the test antenna is flat. Since this condition can only be met when the antennas are an infinite distance apart, a compromised range length has been established (Cutler et al, 1947) which requires the spacing between antennas to satisfy the equation

$$R \geqslant \frac{2D^2}{\lambda}$$

where R is the antenna separation, D is the largest aperture (transmitting or receiving) and λ is the wavelength.

In order to obtain range lengths which will satisfy present and future space programs, it is necessary to determine the effective apertures of the spacecraft antennas to be tested. The majority of this data has been based on the Apollo program since more information is available for this than for any of the future programs.

However, this is not meant to imply that the antenna range will not be of value on other programs. On the contrary, provisions have been made to ensure maximum flexibility of the range so as to be able to handle space programs of the future as well as research studies.

Based on information received from NASA-MSC, most of the present and future manned spacecrafts will consist of a number of individual modules. It will therefore be necessary and desirable to work both with individual and combinations of two or more modules to obtain the needed antenna pattern data.

In the case of the Apollo program (which may be considered typical of future programs), five modules (escape tower, command module, service module, lunar excursion module and adapter) in addition to the launch vehicle must be considered to properly evaluate the system antenna pattern characteristics.

Since the CM and the LEM will function at times as individual modules, some of the antennas on these units must be tested with no other modules present. However, the other three modules (escape tower, service module and adapter) will have no antennas operating when these units are separated from the remainder of the vehicle. There is consequently no requirement for testing these modules individually.

During launch, some of the antennas will operate with all parts of the Apollo vehicle including the rocket stages present. This applies in particular to antennas near the nose of the CM, and since it is not feasible to attempt to test these antennas by manipulating the entire 300-foot vehicle, it is necessary to effect a compromise between an object that is small enough to work with and yet large enough to adequately simulate the complete vehicle.

King (1956) shows that the impedance of a monopole antenna in a ground plane of radius 5 wavelengths is a good approximation (within 3 percent) to the ideal impedance when the ground plane is infinite. The fact that the ground plane is finite causes the currents on the ground plane to take the form of standing waves and this serves to introduce ripples in the far field pattern. Terminating the ground plane in a curve minimizes the standing waves and tends to eliminate the ripples. Dorne and Lazarus (1947) present experimental radiation patterns for slots in a finite ground plane. They show that the size of the ground plane in the plane normal to the plane of polarization (the H-plane) is not critical; however, in the plane of polarization (the E-plane), a ground plane of the order of 5 wavelengths smooths out the ripples characteristic of the finite ground plane such that the pattern is similar in structure to that of a slot in an infinite ground plane.

The exact nature of the telemetry, voice and data link antennas for the CM have not been determined but are expected to be slot or scimitar type. It is believed feasible to assume that the maximum effective length of these antennas is no greater than 10 wavelengths, and in consequence it should be possible to measure both the pattern and impedance properties of the lower frequency and low gain antennas with sufficient accuracy providing enough of the vehicle is retained to place the artificial breaks more than about 5 wavelengths from the antenna under test.

Before starting the discussion of the various configurations to be considered, it should be noted that Table I is a listing of the antennas, frequencies, effective antenna lengths and range lengths required for each of the configurations. In general, the effective length of the low gain antennas has been assumed to be 10λ. In the case of the C-band beacon antenna an effective length equal to the diameter of the CM has been assumed since an omnidirectional pattern is achieved by appropriately placing multiple radiators around the circumference of the module. Since for the high gain antennas surface currents are not expected to contribute to the far field pattern of the antenna the estimated aperture is considered to be the effective aperture. The length of the antenna range (spacing between transmitting and test antennas) is $2D_r^2/\lambda$ where D_r is the effective antenna length and λ is the wavelength.

Configuration 1 (Escape Tower-CM-SM). During the launch phase of the vehicle the telemetry, voice data link and C-band tracking antennas will be operating at frequencies ranging from 220 Mc to 6000 Mc. The above antennas are located on the CM module. The escape tower and service module will be in the vicinity of these antennas and will therefore have surface currents flowing on them from the antennas. To properly simulate the escape tower and SM, and not severely add to the weight of the structure under test, partial mock-ups of the SM and escape tower will be required. Since it has been shown that at least 5 wavelengths of the ground plane, on either side of the antenna under test, is required to simulate an infinite ground plane, this same criterion will be followed for the Configuration 1 antenna tests. Therefore, the overall length of Configuration 1 will be 40 feet, which is approximately ±5 wavelengths from the center of the CM for the lowest frequency antennas to be tested.

Configuration 2 (CM-SM-Adapter - LEM). Although the requirements for this configuration have not been completely defined (at the present time), it has been included in case antenna patterns of the 125 Mc minitrack antenna are required. It is assumed that this antenna is located on the command module and will not be operated until after the escape tower has been jettisoned. The length of the CM - SM - Adapter and LEM configuration is approximately 57 feet or 7 wavelengths at 125 Mc. It is not necessary for this configuration to satisfy the 10 wavelength criterion since only the above units will be in the vicinity of the minitrack antenna when it is operating. Light weight mock-ups of the SM - Adapter - and LEM are advised to limit the weight of the test structure to less than 20,000 lbs.

Configuration 3 (CM-SM-Adapter) This configuration will be required so that antennas operating immediately after the escape tower has been jettisoned, but prior to repositioning of the LEM, may be tested.

Configuration 4 (LEM-CM-SM). Configuration 4 is needed so that antennas operating in deep space, after the LEM has assumed its position in front of the CM, may be evaluated. Tests of the high gain deep space antenna could be made with the antenna detached from the module, but though such pattern measurements would be accurate insofar as the major lobe is concerned, they would not be for the minor and back lobes because of the deep space antenna mounting and attachment to the module.

Configuration 5 (CM-SM). Tests on this configuration may not be necessary if the tests made on Configuration 3 are sufficiently accurate.

Configuration 6 (LEM). Antennas on the LEM which are operating while in separate flight and on the moon should be tested with the LEM separated from the other modules.

Configuration 7 (CM). The antennas on the CM which are used prior to, during and after re-entry, and for recovery, should be tested with the CM alone. A special problem exists[+] for the 10 Mc frequency antenna that is to be used for long distance recovery. Since λ is large and D is small, the 10λ criterion is much greater than the $2D^2/\lambda$ criterion. Therefore the larger distance is given in Table I.

[+] Because of the long wavelength ranges involved for the 10 Mc antenna it is not practical to measure the antenna pattern in the conventional manner. It is therefore necessary to consider modeling the antenna, as suggested in the last paragraph of Section 3.1, or to use a ground level rotator for azimuth patterns and an aircraft or balloons for elevation patterns.

Conf.	Vehicle	Antenna Type	Function	Freq. Mc.	D or Effect. Length (ft)	Est. Wght. (lbs)	Antenna Range Distance (ft)
1	Escape Tower-CM-SM	low gain	telemetry	220	40	<20000	720
			voice	300	33	<20000	660
			data link	400	25	<20000	510
		beacon	C-band Track.	5000	12	<20000	1460
2	CM-SM-Adapter-LEM	low gain	minitrack	125	57	<25000[+]	830
3	CM-SM-Adapter	low gain	communication	250	35	<20000	620
		med. gain	rendezvous	1400	<10(est)		<290
		40db gain	deep space	2100	<20		1710
		med.gain	altimeter	10000	< 4		<330
4	LEM-CM-SM	low gain	communication	250	39	25000	770
		med.gain	rendezvous	1400	<10		< 290
		40db gain	deep space	2100	<20		1710
		med.gain	altimeter	10000	< 4		<330
5	CM-SM	Same as Conf. 3 except for slightly decreased weight and range distance.					
6	LEM	low gain	communication	250	20	8000	200
		low gain	telemetry	220	20	8000	180
		med.gain	altimeter	10000	<4	8000	330
		high gain	comm.w/earth	2100	<20	8000	1710
7	CM	low gain	communication	250	12	8500	70
		low gain	telemetry	220	12	8500	60
		low gain	recovery	243	12	8500	70
		low gain	recovery	10	12	8500	980

[+] Assume mock-up for adapter and LEM.

TABLE I: APOLLO ANTENNA PATTERN TEST CONFIGURATIONS

3.3 Ground Reflection Range

There are two types of outdoor range which may be used for antenna pattern or scattering measurements and these differ according to the manner in which the energy reflected from the ground is treated. The free space range is, perhaps, the more common and in this the attempt is made to suppress any energy which would otherwise be reflected from the ground into the vicinity of the test object. With a ground reflection range, however, the ground is prepared so as to ensure a uniform and predictable reflected signal, and the presence of the latter in the test region is taken into account. Several ranges of this type are now in operation (see, for example, Appendix A) and for reasons which will become obvious later, it appears to be the more attractive scheme for testing most of the Apollo vehicle antennas.

3.3.1 Basic Formulae

Consider a transmitting antenna of diameter D_t situated at a height h_t above a smooth earth whose reflecting properties are sensibly uniform. At a range R which is in the far field of the antenna, i.e.

$$R \geqslant \frac{2D_t^2}{\lambda}, \tag{3.1}$$

but is not so large that the assumption of a flat earth is inappropriate, the total field can be obtained by imaging the antenna in the surface of the earth and is

$$F = \frac{e^{ikR}}{R} P(\theta') + \rho \frac{e^{ikS}}{S} P(\theta) \tag{3.2}$$

(see Fig. 5) where F is a field component, ρ is the corresponding Fresnel reflection coefficient for the ground, and $P(\theta')$, $P(\theta)$ are the polar diagram factors of the transmitting antenna in the directions of the direct and ground reflected rays respectively.

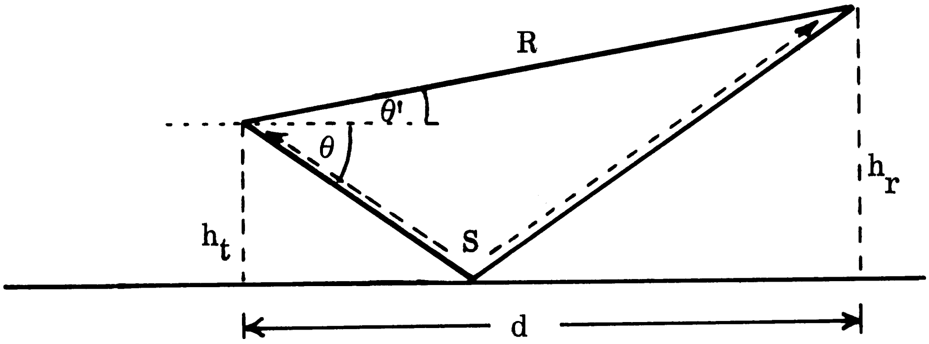

FIG:5: GROUND RANGE CONFIGURATION

If d is much greater than h_t and h_r (as it will be in all cases of practical interest), then

$$R \simeq d + \frac{(h_r - h_t)^2}{2d}$$

$$S \simeq d + \frac{(h_r + h_t)^2}{2d}$$

and hence

$$k(S-R) \simeq \frac{4\pi h_r h_t}{d\lambda} .$$

Moreover,

$$\theta = \tan^{-1} \frac{h_r + h_t}{d}, \qquad \theta' = \tan^{-1} \frac{h_r - h_t}{d} \qquad (3.3)$$

and if the beam width of the transmitting antenna is large compared with these, the expression for the received field reduces to

$$F = \frac{e^{ikR}}{R} P(\theta) \left(1 + \rho \exp \left(i \frac{4\pi h_r h_t}{d\lambda} \right) \right) . \tag{3.4}$$

Equation (3.4) is fundamental to the design of a ground reflection range. It will be noted that the receiver height h_r enters only through the exponential factor, leading to a sinusoidal variation of the field as a function of h_r. The rate of variation decreases with increasing d and/or λ, but to determine the location of the maxima and minima it is necessary to examine the reflection coefficient ρ. This is, in general, a function of the polarization, the electrical properties of the ground and, through the latter, the frequency. It is also a function of the bounce angle θ at which the energy is reflected from the ground. As $\theta \rightarrow 0$, however, $\rho \rightarrow -1$ regardless of the polarization, frequency and ground (providing it is not metallic). It is obvious that this limit is of no practical interest since it requires h_r and h_t to be zero or d infinite, but if θ can be kept small, and in particular, much less than the Brewster angle for the ground material, the polarization dependence of ρ can be made quite small. Thus, for example, incidence at 5° on a material whose dielectric constant is 10 and whose conductivity is [+] $5 \times 10^{-21} f$ leads to a reflection coefficient $0.96 \angle -1.2^\circ$ for horizontal polarization and $0.55 \angle 15.0^\circ$ for vertical polarization (Terman, 1943; pp 698-709), but a reduction of the bounce angle to 2° changes these values to $0.99 \angle 0.0^\circ$ and $0.78 \angle 5.6^\circ$ respectively.

[+] where f is in cycles per second; the resulting values are typical of dry sandy conditions at a frequency of about 5 Mc.

In the following we shall therefore assume that

$$\rho = |\rho| \, e^{i(\pi-\beta)},$$

where β is small and $|\rho| > 0.6$, and the resulting equation for F is now

$$F = \frac{e^{ikR}}{R} P(\theta) \left\{ 1 - |\rho| \exp\left(i \frac{4\pi h_r h_t}{d\lambda} - i\beta \right) \right\} \quad . \tag{3.5}$$

The principle of the ground reflection range is that h_r, h_t, d and λ should be chosen such that the received field is a maximum. This corresponds to the constructive interference of the direct and reflected rays, and from equation (3.5) the locations of the maxima in the interference pattern are given by

$$\frac{4\pi h_r h_t}{d\lambda} = \beta + (2n+1)\pi \ , \qquad n = 0, 1, 2, \ldots \tag{3.6}$$

For economic reasons the first maximum (n=0) is of most interest and the corresponding receiver height is

$$h_r = \frac{d\lambda}{4h_t} (1 + \beta/\pi) \ . \tag{3.7}$$

With this positioning the two rays are in phase at the receiver and the effective source of energy now appears to be somewhere on the line joining the real and image transmitters. For $\rho = -1$ it is where this line intersects the surface of the earth, and the depression of the apparent source below the line of sight must be taken into account in calibrating the pattern of a receiving antenna. Nevertheless, the effective aperture of the transmitting system is in no sense determined by the separation of the real and image transmitters. Equation (3.2) et seq. require only the condition (3.1) and $d \gg h_r, h_t$, and the resulting far field distance is obviously much less in general than would be required by an antenna of diameter $2h_t$. Indeed, any displacement of the receiving antenna above or below the height shown in (3.7) will reveal a field variation which may be quite rapid, and this must be limited in order to allow the accurate testing of a given-sized antenna.

3.3.2 Receiver Height

As the numerical value of h_r increases subject to the condition shown in equation (3.7), the vertical aperture over which the received field is sensibly uniform increases. This is tantamount to 'sliding out' along one of the beams of the interference pattern, and it is therefore clear that any desired amount of uniformity can be achieved by appropriate choice of h_r. In order to specify the degree of uniformity required, we shall first examine the effect of an amplitude taper on the pattern of an antenna.

To do this, consider a rectangular aperture of dimension a which is fed in-phase but with an amplitude distribution

$$f(x) = 1 - (1-\Delta)x^2, \qquad |x| < \frac{a}{2} .$$

The parameter corresponds to the amount of taper, and for five specimen values (equivalent to reductions of 0, -1, -2, -3 and -4db at the edge compared with the center), the pattern characteristics are as shown in Table II.

TABLE II: EFFECT OF AMPLITUDE TAPER

L	Taper (db 1)	Gain	Half-power Beamwidth (deg.)	Position of First Null (deg.)	Sidelobe (db 1)
1	0	1	50.4 λ/a	57.3 λ/a	13.2
0.89	1	0.997	51.7 λ/a	59.2 λ/a	14.6
0.79	2	0.993	52.8 λ/a	60.9 λ/a	15.8
0.71	3	0.987	53.6 λ/a	61.6 λ/a	16.2
0.63	4	0.980	54.3 λ/a	63.6 λ/a	16.5

It will be seen that the gain varies hardly at all. The beamwidth is a little more sensitive to the taper, but the greatest variation is in the first null and in the side-lobe level. Since the ability to accurately locate the null position is a necessary feature of the proposed range, it might appear desirable to specify that the amplitude taper be less than (say) 0.5db. Economically, however, this is impractical, but in view of the above data it is prudent to limit the taper to at most 1db, and this is the figure that will be adopted.

Returning now to equation (3.5), let us put

$$h_r = h_r^o + \frac{1}{2} D_r$$

where h_r^o is given in equation (3.7) and D_r is the diameter of the receiving antenna to be tested. At the edge of the receiving aperture the intensity of illumination is therefore

$$|P(\theta)|^2 \left\{1+|\rho|^2+2|\rho|\cos\left(\frac{\pi+\beta}{2}\cdot\frac{D_r}{h_r^o}\right)\right\}$$

compared with

$$|P(\theta)|^2 \left(1+|\rho|\right)^2$$

at the center, and for the taper to be less than 1db it is necessary that

$$\cos\left(\frac{\pi+\beta}{2}\cdot\frac{D_r}{h_r^o}\right) \geqslant 0.7943 - 0.2057\left(\frac{1+|\rho|^2}{2|\rho|}\right) ,$$

implying

$$\left|\frac{\pi+\beta}{2}\cdot\frac{D_r}{h_r^o}\right| \leqslant \left\{\begin{array}{lcr} 0.9416 & & 1.0 \\ 0.9477 & \text{for} \quad |\rho| = & 0.8 \\ 0.9751 & & 0.6 \end{array}\right. .$$

For a typical module (or combination of modules) to be tested in a horizontal position, the field uniformity must exist over a vertical range of 20 feet centered on the nominal receiver height h_r^o , and with D_r= 20 feet we now have the requirement

$$h_r^o \geqslant \left\{\begin{array}{l} 33.64 \\ 33.15 \\ 32.22 \end{array}\right. (1+\beta/\pi) \text{ feet}, \quad |\rho| = \begin{array}{r} 1.0 \\ 0.8 \\ 0.6 \end{array} .$$

On the other hand, with D_r = 50 feet, corresponding approximately to the testing of two modules in a vertical position, the limitation on receiver height is

$$h_r^o \; \left\{ \begin{array}{l} 83.41 \\ 82.88 \\ 80.55 \end{array} \right. \quad (1+\beta/\pi) \text{ feet}, \qquad \rho \; = \begin{array}{l} 1.0 \\ 0.8 \\ 1.6 \end{array} \quad ,$$

and it would appear economically prohibitive to mount the modules at such a height, even though the base of the modules would, of course, be 25 feet lower than the heights quoted.

The use of a ground reflection system therefore requires that any combination of two or more modules be tested in a horizontal position. The original receiver heights then apply and since the maximum value of β is (about) 15^o under normal operation of a range, the minimum receiver heights which will suffice are 36.44, 35.91 and 34.90 feet corresponding to $|\rho| = 1.0, 0.8$ and 0.6 respectively. However, the largest value of β will in general occur with the smallest value of $|\rho|$, and because it is economically desirable to choose h_r as small as possible, we shall therefore specify that

$$h_r = 35 \text{ feet}. \tag{3.8}$$

Note that this selection is independent of h_t, d and λ. It is the only parameter which can be selected independently of the rest, but the choice of h_r is the factor on which all the other parameters hinge.

Before confirming this choice, however, it is necessary to consider the implied phase variation of the illuminating signal over the aperture. From equation (3.5) the phase at the edge is

$$\tan^{-1}\left(\frac{\rho\ \sin\left(\frac{\pi+\beta}{2}\cdot\frac{D_r}{h_r^o}\right)}{1+\rho\ \cos\left(\frac{\pi+\beta}{2}\cdot\frac{D_r}{h_r^o}\right)}\right)$$

compared with zero at the center, and with $D_r = 20$ feet, $h_r^o = 35$ feet and $\beta = 0$, the phase taper is therefore 25.7°, 22.7° or 18.8° for $\rho = 1.0$, 0.8 or 0.6 respectively. Tapers of this magnitude are not regarded as intolerable (see Cutler et al, 1947, p.1469).

3.3.3 Remaining Parameters

For a given range length d and the above value of h_r, the height at which the transmitter must be placed to maintain the receiver at the first maximum of the interference pattern decreases with increasing frequency in the manner indicated by equation (3.7). For a practical (non-zero) size of transmitting aperture there is consequently a high frequency cut-off of the range corresponding to the edge of the dish resting on the ground, but depending upon the chosen value for d, this cut-off may or may not be reached before the far field criterion for the receiving (or, indeed, the transmitting) antenna is violated.

From the data in Table I it is seen that the minimum distances required for testing the antennas of the Apollo vehicle vary from about 100 feet at the lower frequencies to 1500 feet or more at 2000 Mc and above. If, for the moment, we exclude these higher frequencies, the smallest value of d which would accommodate the rest is 780 feet, and since the operation of a ground reflection range is simplified by having only one or two distances at which the measurements are carried out, a convenient choice for d is 1000 feet. The higher frequencies could then be covered with a 2000 foot range, and these are the two main cases which will be considered. However, for most efficient integration of these facilities with the anechoic chamber, it is convenient to also examine the implications of a 2500 foot range.

With $h_r = 35$ feet, the variation of h_t as a function of frequency for d = 1000, 2000 and 2500 feet can be obtained directly from (3.7), and the results are shown in Fig. 6 . Since $\beta/\pi = 0.08$ or less, the corresponding term in (3.7) has been omitted in this, and all subsequent, calculations.

At a frequency of 100 Mc, the transmitter elevations of 70.25, 105.38 and 175.63 feet would be necessary for the three ranges, and economically (of course) the smallest of these would be most attractive. If we therefore demand coverage from 100 Mc up, a transmitter elevation of 70 feet would suffice[+] for the smallest d, but would cause the two longer ranges to have low frequency cut-offs of 200 and 250 Mc respectively. In addition, however, there are also high frequency cut-offs. As seen from Fig. 6 , the heights required of the transmitting antenna become infinitesimally small and could not be achieved with dishes of standard practical size. For example, with a dish of diameter 6 feet the cut-off comes when this is resting on the ground (h_t= 3 feet) and the numerical

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[+] Because of the small percentage correction which may be produced by the phase of the ground reflection, the capability for increasing h_t to 73 or 74 feet should be provided.

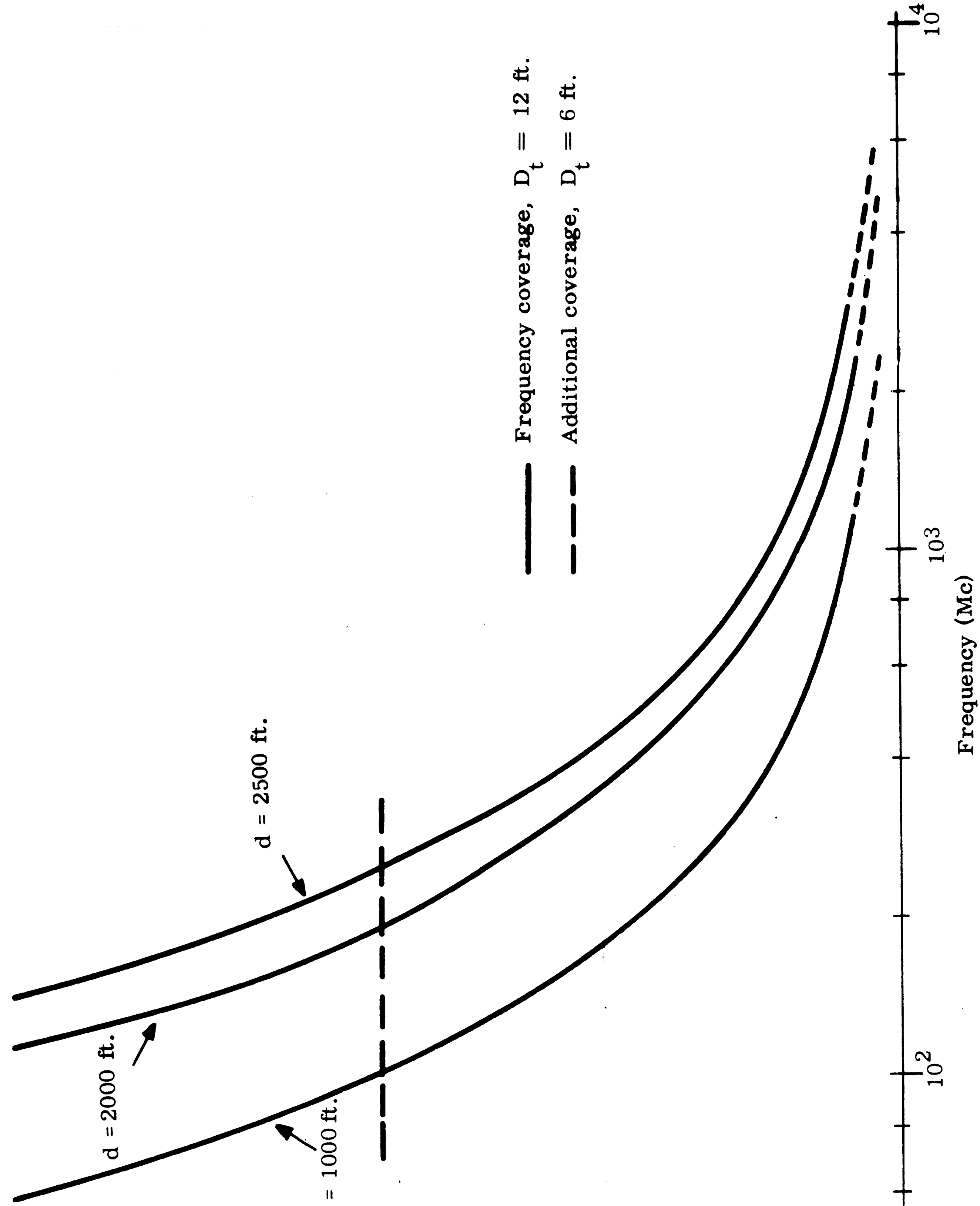

FIG. 6: TRANSMITTER HEIGHT h_t FOR GROUND REFLECTION SYSTEM; h_r = 35 FT.

values for the three ranges are:

d (feet)	f_{max}(Mc)
1000	2342
2000	4683
2500	5855

Similarly, for a dish of diameter 12 feet, we have

1000	1171
2000	2342
2500	2928

Hence, with d = 1000 feet and D_t = 12 feet, the highest usable frequency is 1171 Mc, and to extend the coverage to 2342 Mc it is necessary to go to either a 2000 foot range or a 6 foot diameter dish. At frequencies comparable to and above 2300 Mc the reduction in the ground illumination is generally such that it is feasible to abandon the use of the ground and go over to free space operation. This is a natural transition requiring no overt action on the part of the operator.

With any outdoor range, be it ground reflection or free space, one of the difficulties at the lower frequencies is the illumination of objects off to the side of the range, which may then be the source of stray reflections. To reduce this to a minimum it is desirable to concentrate the transmitted energy to the maximum extent possible consistent with the chosen mode of operation of the range. This in turn implies that the transmitter dish be of relatively large size, but to increase it much beyond 12 feet leads to physical difficulties of handling. Since a dish of diameter 12 feet is standard-sized, we shall therefore adopt this value of D_t for operation at the lower frequencies. Bearing in mind that all of the low gain antennas to be tested have a maximum effective aperture of (about) 57 feet or 10 λ, whichever is the smaller, the horizontal taper at the receiver will then be 0.2db or less.

The final consideration pertinent to the basic specification of a ground reflection system is the relative magnitude of the ground reflected signal. This will depend upon the intensity of illumination of the ground (which is, in turn, a function of the size of the transmitting dish) and on the reflection coefficient (which is a function of the bounce angle, θ). An expression for θ can be obtained immediately from equation (3.3), namely

$$\theta = \frac{h_r+h_t}{d} \quad .$$

This is formally independent of frequency, and in Fig. 7 the numerical relationship between θ and h_t is shown for h_r = 35 feet and d = 1000, 2000 and 2500 feet. If the 1000 foot range is used for all the lower frequencies, the maximum bounce angle involved is 6.0°. The reflected signals for horizontal and vertical polarization may then differ by 2 to 4db depending upon the nature of the ground, but this is regarded as acceptable providing some provision is made for transmitting elliptical polarization in the event that circularly-polarized patterns are to be measured.

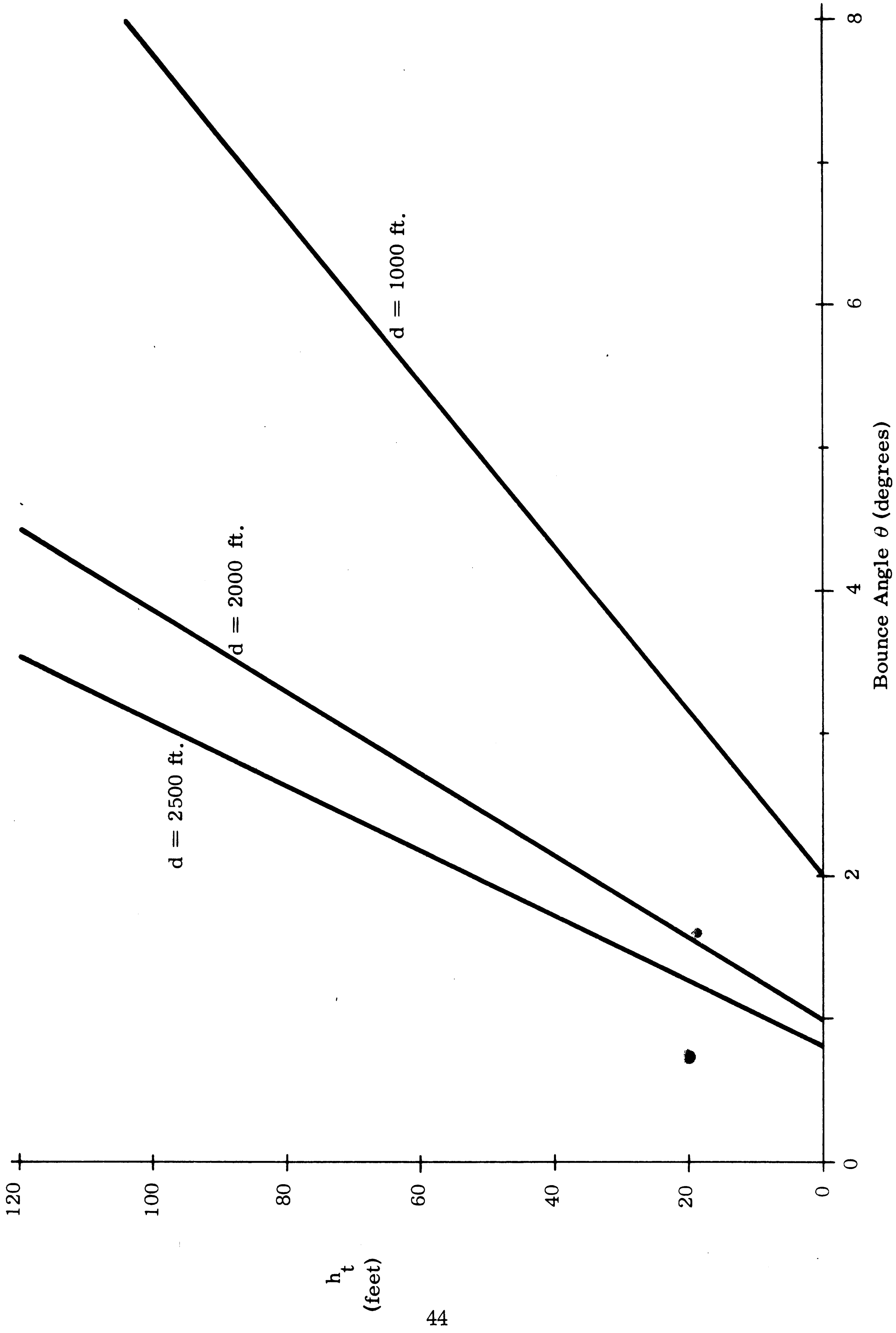

FIG. 7: BOUNCE ANGLE FOR $h_r = 35$ FT.

The remaining factor is the reduction of the ground illumination due to the polar diagram of the transmitter dish. For a circular radiating aperture, the normalized power pattern is

$$P(\phi) = \left(\frac{2}{x} J_1(x) \right)^2$$

where $x = \frac{\pi D}{\lambda} \sin \phi$ and ϕ is measured from the peak of the pattern. If the dish is directed at the receiving antenna, the value of ϕ appropriate to the ground reflected ray is (see Fig. 5)

$$\phi = \theta + \theta' \simeq \frac{2h_r}{d}$$

and hence

$$x = \frac{2\pi D_t h_r}{d\lambda} \quad .$$

Clearly x (and therefore the power reduction) increases with increasing frequency and at the high frequency cut-off for any of the three ranges with $D_r = 12$ feet, the reduction in the intensity of the ground reflected wave due to this effect is 2.85db. This is an added reason for care in any measurement using circular polarization, but does not represent a major obstacle to a ground reflection system.

In the light of the preceding discussion, the following specifications for a ground reflection range are recommended:

h_r = 35 feet,

h_t variable up to 70+ feet

D_r = 12 feet (an additional dish of diameter 6 feet would be desirable at the higher frequencies),

d = 1000, 2000 and 2500 feet.

The first two ranges would be sufficient for all of the proposed pattern measurements at frequencies of 100 Mc and above, but the third range is necessary for integration with the anechoic chamber. In effect, therefore, the third range enables the tests to be carried out with the receiving antenna in a shielded environment. At the higher frequencies the two longer ranges go over automatically to a free space method of operation.

3.3.4 Ground Preparation

To ensure uniformity of the ground reflected signal, preparation of the ground in an area which embraces all points of the main reflection is strongly recommended. There are two aspects to this preparation. In the first place the ground must be made level on at least a scale of the smallest wavelength to be employed, and a more desirable criterion is that the irregularities shall not exceed $\lambda/4$. The highest frequency at which the ground plane method would be used would be about 3000 Mc (with d = 2500 feet), and since the wavelength is then 4 inches, it is recommended that the central strip be level to within ± 1 inch. This tolerance is closer than might be considered necessary based on Lincoln's and ESSC's experience (Appendix A). However, the incidence angles involved in this range are much greater and some allowance is being made for possible deteriation with time.

In theory the only basis for selecting a material for this region is the magnitude of the associated reflection coefficient, and its uniformity as a function of frequency. There are several possibilities which are theoretically acceptable and economically feasible. Grass is very good, but maintenance (e.g. mowing, watering and filling-in of water run-off channels) could be a problem. Just about equally good, however, are asphalt and crushed stone. The latter could be oiled so as to stabilize it and cut down dust. Concrete is yet another possibility but this appears to be fractionally inferior to the others.

The location, shape and area of the prepared strip can be obtained from a consideration of the projection of the Fresnel zones of the transmitter on the surface of the ground. If ℓ is the distance from the center of the zones to the base of the transmitter tower, ℓ is a maximum at the low frequency cut-off of each range (corresponding to the transmitting antenna at its greatest height) and decreases with increasing frequency. From Fig. 5 we have

$$\ell = h_t \cot\theta = \frac{d}{1 + h_r/h_t} \qquad (3.9)$$

giving rise to the following values for ℓ_{max}:

d = 1000 feet,	ℓ_{max} = 667 feet
2000	1333
2500	1667

Since the radius of the first Fresnel zone is approximately $\lambda/4$, which is less than 2.5 feet for $f > 100$ Mc, the preparation of the central strip need only be carried 1670 feet forward from the transmitting site.

The radius of the projection of the first Fresnel zone on the ground is

$$r = \sqrt{\frac{\ell\lambda}{2}} .$$

But

$$\lambda = \frac{4h_r h_t}{d}$$

and from equation (3.9)

$$h_t = h_r \frac{\ell}{d-\ell} .$$

Hence

$$r = h_r \frac{\ell}{d} \sqrt{\frac{2}{1-\ell/d}} \tag{3.10}$$

and it is now trivial to compute r for each of the ranges under discussion. In practice, however, it is desirable to prepare somewhat more than the first Fresnel zone only. To include n zones increases r by a factor $\sqrt{n}$, and the proposed region pictured in Fig. 8 is based upon the inclusion of approximately three Fresnel zones. The maximum value of r, which occurs at the low frequency cut-off of each range, is then[+] 100 feet, giving a strip of total width 200 feet.

The percentages shown in Fig. 8 indicate the amount of preparation left in each segment by 'pinking'. Thus, for example, the area of the arrow head extending out to a distance of 670 feet is only 40 percent of a uniform strip of width 200 feet extending out to this same distance. Similarly, the prepared area between 670 and 1335 feet is 64 percent of the area of a uniform segment,

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[+] To produce a simple value for r, n was actually taken to be 3.0612

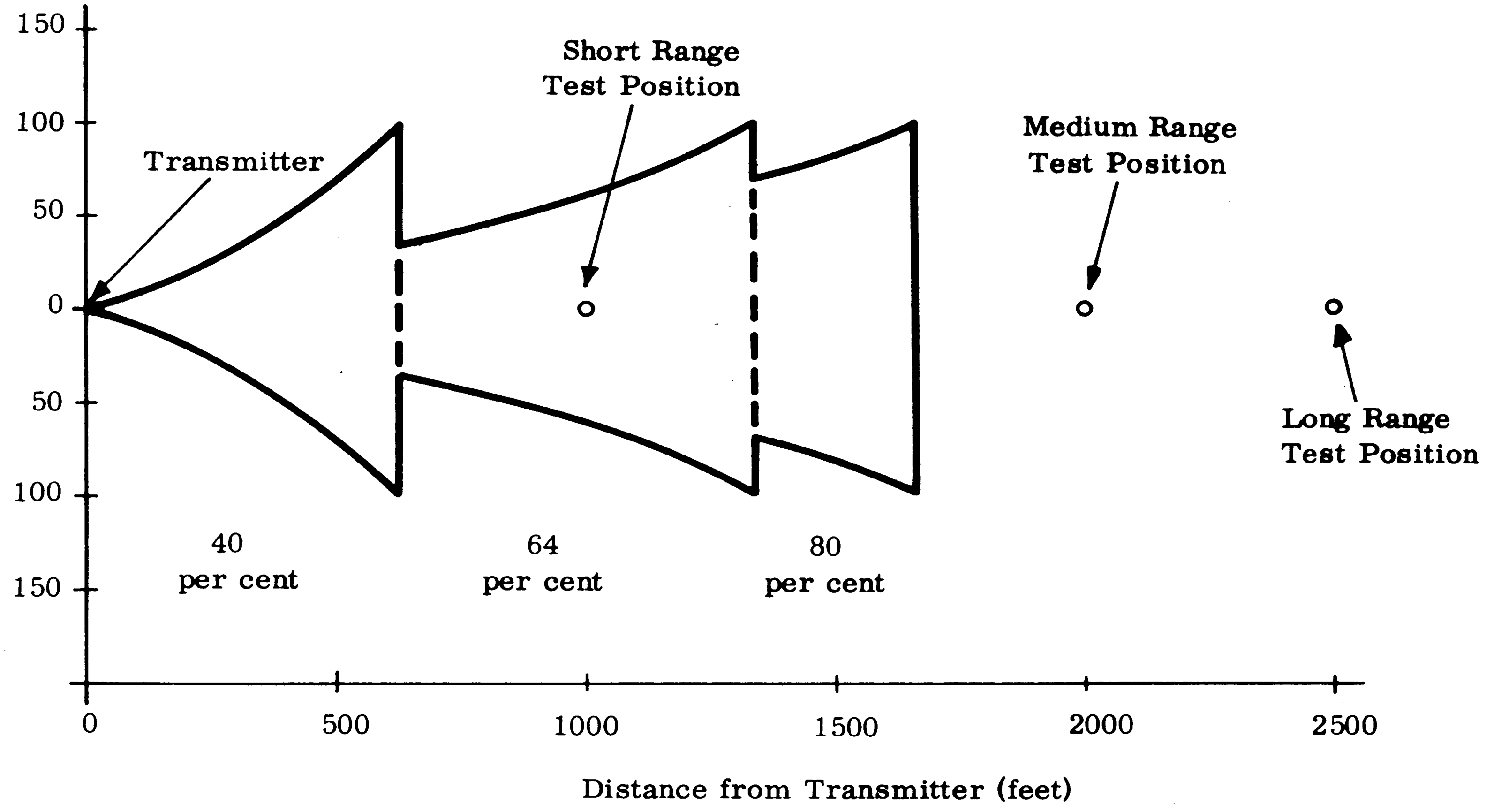

FIG. 8: 'PAVED' REGION FOR PROPOSED GROUND REFLECTION SYSTEM

and so on. The total prepared area is approximately 194,000 square feet, compared with an area of 334,000 square feet for the uniform strip. This represents a net saving of 42 percent.

In the area adjacent to the central 'paved' strip some preparation of the ground is desirable, but this need not be as elaborate. The aim should be to avoid any marked discontinuity in electrical properties at the edge of the paved region, and to have a sufficiently uniform and level ground to take care of the energy which is reflected out of the plane containing the normal to the ground and the direction of radiation. It should be enough to merely level the natural terrain to within (about) ± 2 inches, and possibly stabilize it with coarse grass, leading to a region comparable to a golf course fairway (non-championship variety). Since there are no ranges in existence whose frequencies of operation are comparable to the one proposed, the only basis for estimating the width of this outer strip is the set of measured data on the azimuthal behavior of the reflection coefficient obtained by Cosgriff et al (1960) . The data is quite sparse, but suggests that a region of 500 feet in width on either side of the paved strip will suffice.

Beyond this, the site would appear such that no levelling of the ground will be necessary, but it should be cleared of all brush, bushes, trees, etc., and no buildings of any sort should be permitted within 1000 feet of the center line of the range.

3.4 Free Space Range

A free space range implies that the antenna under test is placed so that the effects of terrain and surrounding objects will not introduce errors into the antenna pattern measurements. Ideally the transmitted wave should arrive at the test aperture as a true plane wave, i.e. uniform in amplitude with a flat phase front over the aperture, but in practice there will be some departure from uniformity. This may be caused by reflection from the earth and nearby structures, an antenna range of insufficient length or a transmitting antenna which is too large, and depending on the magnitude of the phase and amplitude variations, the errors in the pattern measurements may or may not be significant.

3.4.1 Free Space versus Ground Reflection

As noted in Section 3.3 the essential difference between a free space and a ground reflection range is in the way that the energy reflected from the ground is treated. With a free space range an attempt is made to prevent any such energy from entering the region of the test antenna, and this is done by placing the first null of the transmitted polar diagram at the specular point. If the transmitting antenna is a circular dish with its axis directed at the test antenna, the condition for zero reflection is

$$\frac{2\pi D_t h_r}{d\lambda} = j_{11} ,$$

where $j_{11} = 3.8317\ldots$ is the first zero of the Bessel function $J_1(x)$, and the notation is as in Section 3.3. This gives

$$D_t = 0.6098\frac{d\lambda}{h_r} . \tag{3.11}$$

We remark in passing that an alternative condition which is sometimes imposed is to place the 3 db point of the transmitted polar diagram at the base of the support tower for the receiving antenna. This is a somewhat less severe requirement and implies that

$$D_t = 0.5140\,\frac{d\lambda}{h_r} \tag{3.12}$$

Note that (3.11) and (3.12) are independent of the height h_t of the transmitter.

To complete the specification of a free space range it is necessary to consider the uniformity of the transmitted field over the receiving aperture, and the conditions which result are similar to those imposed on the ground reflection scheme. The usual criterion for phase is that this shall not vary by more than $\lambda/16$ over the aperture, and from this we obtain immediately that

$$R \geqslant \frac{2D_r^2}{\lambda} , \tag{3.13}$$

which is the standard far field condition. Under most circumstances met with in practice, (3.13) is sufficient to ensure uniformity in amplitude as well, but the exceptional cases are those in which the transmitting aperture is larger than the receiving one. Thus, for example, to achieve an amplitude taper which is not more than 1 db requires that

$$\frac{\pi D_t}{\lambda} \cdot \frac{D_r}{2d} \leqslant 0.9504 ,$$

and since $d \sim R$, this implies

$$R > 1.6528 \frac{D_t D_r}{\lambda} . \tag{3.14}$$

This is more restrictive than (3.13) for all $D_t > 1.2101\ D_r$.

The conditions[+] (3.12), (3.13) and (3.14) are fundamental to the design of any free space range. If it is assumed that D_r and λ are specified in advance, a lower bound for R is given immediately by (3.13), and (3.14) then provides an upper limit for D_t in accordance with the chosen R. On the other hand, as the frequency is decreased, (3.12) forces us to an ever larger D_t (or h_r) in order to maintain a transmitted beam whose effective width is sufficiently narrow. This is the direct opposite of the situation met with in the design of a ground reflection range, and it is the practical conflict between (3.12) and (3.13) or (3.14) which makes almost impossible the design of a free space range at the lower frequencies. To illustrate this fact, it is only necessary to consider the case in which (3.14) dominates (3.13). From (3.12) and (3.14) we then have

$$h_r \geqslant 0.8495\ D_r \tag{3.15}$$

and the resulting receiver height could be intolerable. This is certainly the case if we attempt to specify a free space range which would be sufficient for testing all of the antennas present in the Apollo program. If we exclude the 10 Mc

---

[+] Note the interesting, but not too surprising, fact that the transmitter height h_t does not appear in any of these equations.

frequency, the lowest frequency of prime interest is 125 Mc, and the effective aperture dimensions of the minitrack antenna are given in Table 1. With $\lambda = 7.87$ feet and $D_r = 57$ feet, the condition (3.13) demands that $R > 825.7$ feet, and when this is fed into (3.12), we have

$$D_t h_r \geqslant 3340 \text{ ft}^2 . \tag{3.16}$$

The maximum D_t such that (3.13) will still apply is 68.98 feet, and consequently (3.16) requires that

$$h_r \geqslant 48.62 \text{ feet} . \tag{3.17}$$

Any increase in D_t above 68.98 feet forces us to use (3.14) in place of (3.13), but does not affect the condition on h_r as can be seen by putting $D_r = 57$ feet in equation (3.15).

Because of the large size and weight of the vehicle components which are to be tested on the proposed facility, a receiver height of almost 50 feet is undesirable, and to increase the distance beyond the minimum demanded by (3.13) in no way affects this result. Moreover, a transmitting antenna of 70 foot diameter is also an unpleasant thought, and this could only be reduced in size at the expense of an increase in h_r. In comparison we recall that for the gound reflection range the corresponding results were $D = 12$ feet and $h_r = 35$ feet, and these were sufficient for a frequency coverage down to 100 Mc.

Even if we ignore the minitrack antenna and attempt to design a free space range with a capability for testing at all frequencies above 220 Mc, the system is still not competitive with the ground reflection scheme. From Table 1 the effective aperture of the 220 Mc telemetry antenna under launch conditions is 40 feet. Equation (3.13) then gives $R \geq 715.80$ feet, and hence $D_r h_r \geqslant 1645$ ft^2 The minimum receiver height is therefore 33.98 feet for a transmitter dish of diameter 48.40 feet, and though we have succeeded in reducing h_r to approximately the value used for the ground reflection range, the size of the transmitting antenna is highly undesirable.

In view of the above facts, it would appear that a ground reflection range is superior to a free space range for all of the required testing at the lower frequencies, and it is our opinion that the free space method is not competitive either economically or as regards convenience of operation. We therefore recommend the provision of a ground reflection range with the specifications outlined in Section 3.3.3.

3.4.2 High Frequency Coverage

It will be recalled that the ground range proposed in Section 3.3.3 has a fixed transmitter site with transmitter elevation up to some 70 feet, a constant receiver elevation of 35 feet, and three lengths of range: 1000, 2000 and 2500 feet. The restriction on the maximum value of h_t produces low frequency cut-offs for the three ranges of 100, 200 and 250 Mc respectively, but in addition there are also high frequency cut-offs which are reached when the transmitting dish is resting on the ground. With a dish of diameter 12 feet, for example, the m.u.f.'s are 1171, 2342 and 2928 Mc respectively, and these limits are doubled if D_t is decreased by a factor 2.

From a consideration of the types of antennas which have to be tested, the most economical means of operation would seem to be to use the 1000 foot range with a 12 foot diameter dish at frequencies up to about 1000 Mc. Above 1 Kmc some of the antennas at least demand a range length greater than 1000 feet, so it would appear logical to change over at 1 Kmc to the 2000 foot range, but retaining the same transmitting dish, and this would extend the frequency coverage to beyond 2 Kmc. In the event that outside interference proves troublesome, the 2500 foot range incorporating the anechoic chamber could be employed instead, but since this would prevent the use of the chamber for independent measurements, the 2500 foot range is regarded as an additional feature of the proposed design to be activated only when necessary.

It is therefore assumed that coverage from 1 to 2 Kmc would (in general) be provided by the 2000 foot range with the 12 foot diameter dish, but at frequencies above 2342 Mc, a smaller dish is required. On the other hand, at any one frequency the largest possible dish has advantages from the point of view of reducing stray reflections by decreasing side illumination, and to avoid the proliferation of dishes which would result from an attempt to cover frequencies up to 10 Kmc with a ground reflection system, the possibility of allowing the 2000 foot range to go over naturally to a free space mode of operation at such frequencies appears attractive. It is therefore appropriate to examine the requirements which this operation would impose in the 2 to 10 Kmc band when d = 2000 feet and h_r = 35 feet. However, this should not be construed as a recommendation for a transfer to free space operation at 2 Kmc; although the free space method is clearly more convenient at the very highest frequencies, the point at which the transfer is made is largely at the discretion of the user.

For free space operation, there is first of all the condition on the size of the transmitting dish required in order to place the first null of the beam at the point of specular reflection on the ground. From equation (3.11) with d = 2000 feet and h_r = 35 feet, we have

$$D_t = \frac{3.4271 \times 10^{10}}{f} \tag{3.18}$$

where D_t is in feet and f in cycles per second, and this equation is plotted in Fig. 9.

To ensure a phase variation not exceeding $\lambda/16$ over the receiving aperture, the range length R must satisfy the far field criterion (3.13), and if R is specified the equation can be used to give an upper bound on the transmitting apertures which can be considered. From (3.13) we have

$$D_r \leqslant (R\lambda/2)^{1/2} \tag{3.19}$$

and in Fig. 10 the maximum value of D_r is plotted as a function of frequency. A comparison of this Figure with the data in Table 1 shows that the range would be adequate for testing the antennas on the Apollo vehicle at frequencies above 2 Kmc.

The final criterion to be satisfied by the free space range is that of a uniform amplitude distribution across the receiving aperture. The consequences of a 1 db amplitude taper were discussed in connection with the ground reflection

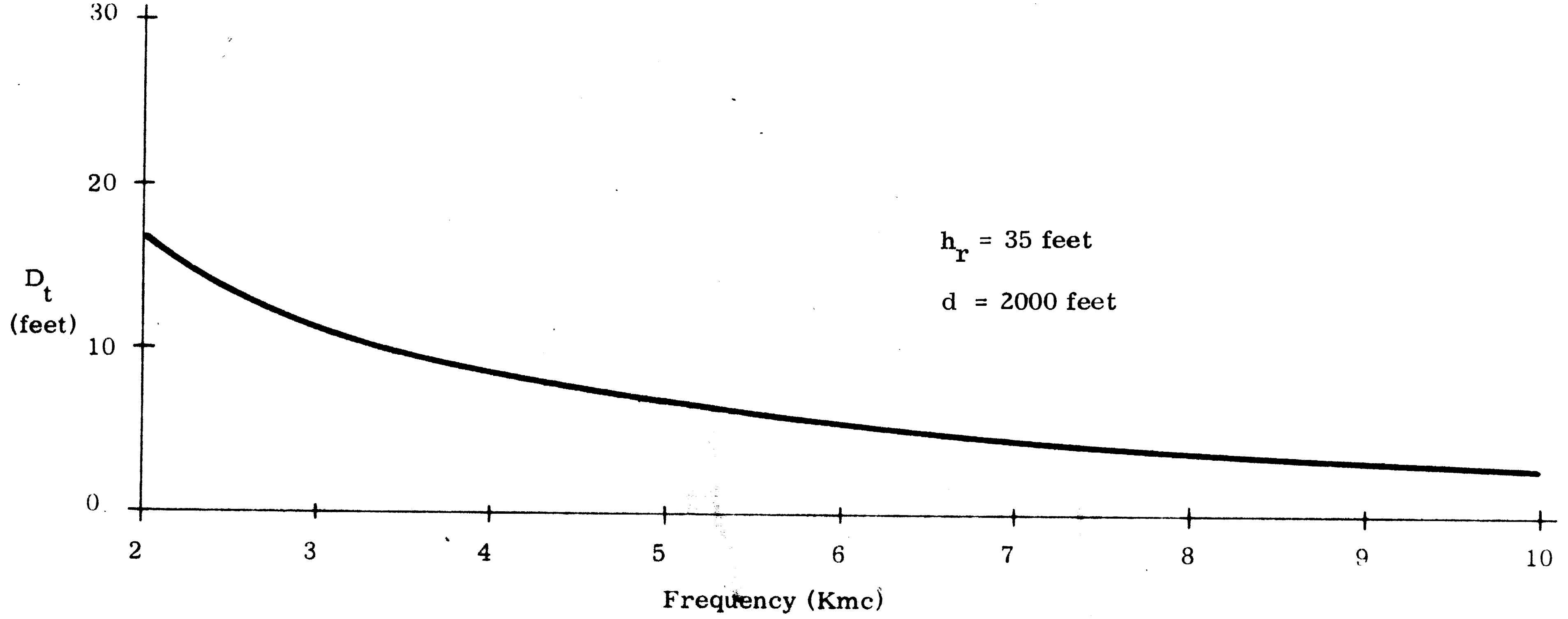

FIG. 9: TRANSMITTING APERTURE FOR MINIMUM SPECULAR REFLECTION

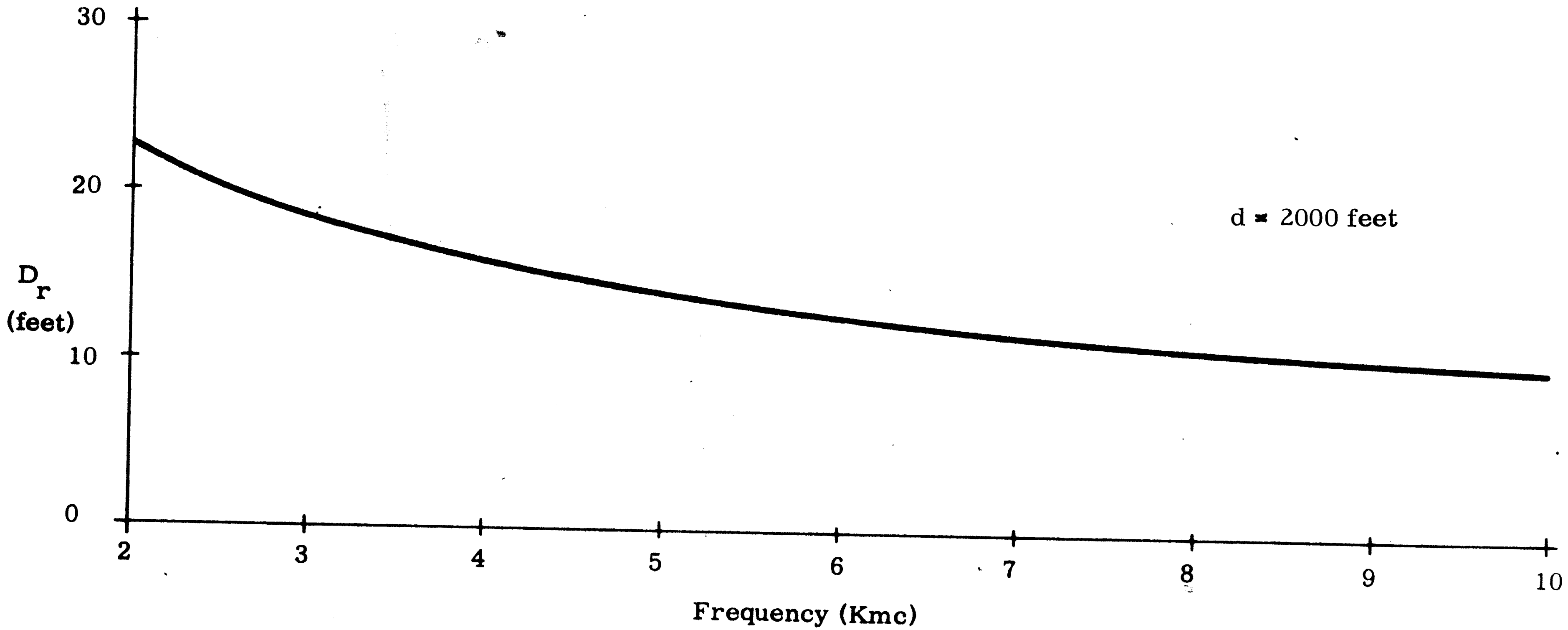

FIG. 10: **MAXIMUM RECEIVING APERTURE FOR PHASE UNIFORMITY**

mode, and though it was shown that such a taper is not serious, it is not necessary to use it as the criterion for the free space range at high frequencies since it is both feasible and practical to hold the taper to about 1/4 db. This is a somewhat more standard amount (see Cutler et al, 1947), and will therefore be adopted.

The equation analogous to (3.14), but for a taper of 1/4 db, can be rearranged to give

$$D_r \leqslant 0.3056 \frac{\lambda R}{D_t} \tag{3.20}$$

and in Fig. 11 the maximum value of D_r is plotted as a function of frequency for transmitting apertures of 12 and 6 foot diameter. When this is examined in conjunction with Table 1 it is seen that the allowed taper is sufficient for the testing of all of the higher frequency Apollo antennas providing a 12 foot diameter dish is employed.

Let us now examine the foregoing results on the basis of a receiving aperture of 40 wavelengths, which is typical of 35-40 db antennas operating at 2 Kmc and above. It is recalled that the 2000 foot ground reflection range has a high frequency cut-off of 2342 or 4683 Mc for a 12 or 6 foot diameter transmitting antenna respectively, and inasmuch as a range of this length is required for testing several of the Apollo antennas, it is advisable to use it for most of the basic testing at frequencies above 1 Kmc. However, to annul any ground reflection as required for the free space range, a transmitting antenna of diameter 17.14 feet is demanded at 2 Kmc, and the diameter does not reduce to 12 feet until a frequency of 2857 Mc is reached (see Fig. 9). There is therefore a gap of 515 Mc between the cut-off of the ground range and the onset of free space conditions with a 12 foot dish, and this must be bridged by a continuation of the ground reflection mode with a 6 foot diameter dish. Since it is sufficient[+] to interpret equation (3.11) as a specification of the minimum value of D_t, a 12 foot dish provides coverage at frequencies above 2857 Mc on the free space range. On the other hand, there is also the requirement for amplitude uniformity over the receiving aperture, which provides an upper bound on the magnitude of D_t, and reference to Fig. 11 indicates that for $D_r = 40\lambda$ it is necessary to use a transmitter dish of diameter less than 12 feet at frequencies above 6 Kmc.

The fact is brought out more clearly in Fig. 12 in which the two solid curves are taken directly from Figs. 9 and 11, and the dashed curve is for a receiving aperture of 40 wavelengths. Ideally this should lie below the solid curves if the postulated uniformity in phase and amplitude is to be achieved, and though Fig. 12 shows that the amplitude variation will be fractionally greater than 1/4 db, this is not regarded as serious in view of the analysis in Section 3.3.2.

From this discussion it is concluded that the mating of the ground reflection and free space modes of operation is quite straightforward. Two transmitting dishes of diameters 12 and 6 feet are required, and for typical antennas the ground reflection range will be used at frequencies up to 2342 Mc with a

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[+] A value of D_t greater than the minimum forces the bounce point into the side lobes of the transmitter pattern.

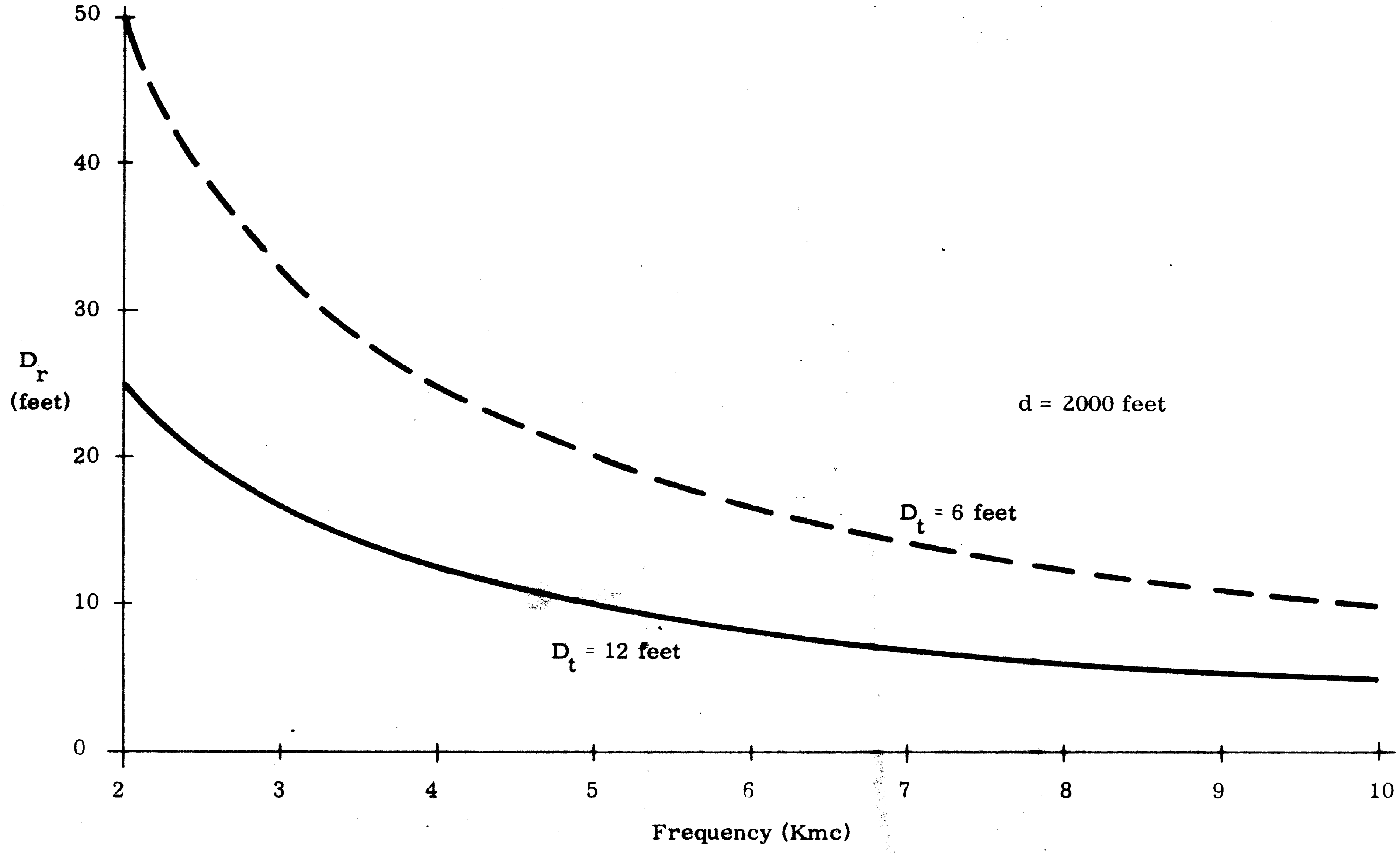


FIG: 11: MAXIMUM RECEIVING APERTURE FOR AN AMPLITUDE TAPER LESS THAN 1/4 db

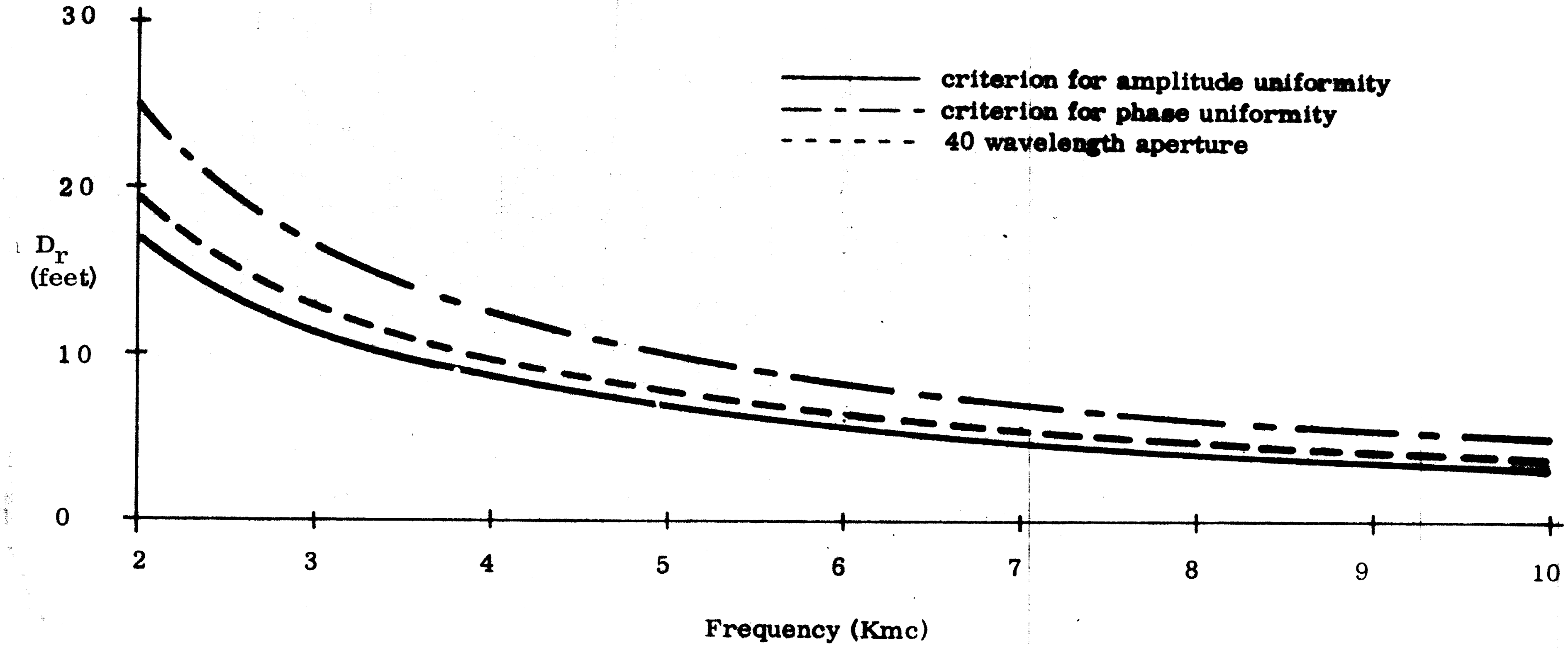


FIG. 12: LIMITATIONS OF A 2000 FT. FREE SPACE RANGE

12 foot dish, with an increase in coverage up to 4683 Mc if a 6 foot dish is employed. At 2857 Mc, however, the free space mode becomes applicable with a 12 foot dish, and this has no practical upper limit of operation providing dishes of smaller diameter are also available. Although the criteria for the free space range produce no restriction on the height of the transmitting antenna, the convenience of having the beam directed horizontally may be sufficient reason for advocating a choice of 35 feet for h_t.

3.5 Sensitivity

A few remarks about the sensitivity of the antenna range system would appear to be in order. For this purpose, a criterion must be established to ensure that sufficient antenna pattern detail (minor lobes and nulls) can be satisfactorily investigated and analyzed. Since most commercial pattern recorders have a standard 40 db dynamic range and typical high gain antennas (40 db or greater) have sidelobes of about -20 db, a 40 db signal to noise ratio is considered to be an acceptable minimum sensitivity requirement.

The sensitivity of the antenna range can be calculated from the equation:

$$S/N = \frac{G_r G_t W_t L T_\ell}{R_s} \tag{3.21}$$

where S/N is the signal to noise ratio, G_r is the gain of the receiving antenna, W_t the transmitter power level, R_s the receiver sensitivity, $T_\ell = \lambda^2/16\pi^2 d^2$ is the path attenuation and L the system losses.

The following sensitivity table has been prepared assuming a 200 mw transmitting source, an isotropic receiving antenna and no system losses for frequencies in the 0.1 - 10.0 Kmc range.

The calculation for the frequency range of 0.1 - 2.0 Kmc (first four frequencies of Table III) have been made for a ground reflection antenna range. Since the range is designed to operate as a free space range in the frequency range of 2.0 - 10.0 Kmc, the last three frequencies of Table III have been calculated for this configuration. It is to be noted that the difference between the two ranges is in the effective gain of the transmitting antenna. If one assumes the same frequency and antenna size for both ranges, it can be shown theoretically that the gain of the antenna in the ground reflector system can be as much as 6 db greater than when the same antenna is used on a free space range. However, in practice the ground reflection gain will be somewhat less than this due mainly to the imperfect reflection of the ground, but also to a reduction in the intensity of the ground ray (see Section 3.3.3), and a figure of 4 db for the excess gain over a free space antenna will therefore be assumed.

TABLE III

ANTENNA RANGE SENSITIVITY

Freq. (Kmc)	G_t (D_t = 12 ft.)	T_L (d = 1000 ft.)	S/N	Antenna Range
0.1	13 db	-62.5 db	63.5 db	GR*
0.5	27 db	-76.5 db	63.5 db	GR
1.0	33 db	-82.5 db	63.5 db	GR
2.0	39 db	-88.5 db	63.5 db	GR
2.0	35 db	-88.5 db	59.5 db	FS*
5.0	43 db	-96.6 db	59.5 db	FS
10.0	49 db	-102.6 db	59.5 db	FS

*GR is Ground Reflection *FS is Free Space

For a 2000 foot range, 12 foot transmitting antenna: S/N = 57.5db(GR) and 53.5 db(FS)

For a 1000 foot range, 6 foot transmitting antenna: S/N = 57.5 db(GR) and 53.5 db(FS)

For a 2000 foot range, 6 foot transmitting antenna: S/N = 51.5 db(GR) and 47.5 db(FS)

It has been assumed that the transmitted power is +23 dbm, the receiver sensitivity is -90 dbm and the gain of the receiving antenna is 0db with respect to an isotropic radiator.

From the above table it is concluded that the criterion of 40db sensitivity is adequately met provided the system losses do not exceed 7.5db for a 2000 foot range employing a 6 foot transmitting antenna. The S/N margin is greater for all other range conditions shown in Table III

IV. ANECHOIC CHAMBER

4.1 Introduction

Almost all modern antenna test facilities now include an anechoic chamber. The antenna studies may be such that all the work can be performed in the anechoic chambers but in most cases, as in the range being planned here, the chamber is needed to supplement the outdoor antenna measurement capabilities.

Three types of antenna tests must be performed on the Apollo antennas. They are radiation pattern measurements, impedance measurements and interference measurements including both radio (RFI) and electromagnetic (EMI) frequencies. As discussed in the previous chapter, in order to make radiation pattern measurements the antenna under test is illuminated by a plane wave transmitted from a distant source. In a free space range the plane wave is produced by locating the receiver site away from objects that would reflect energy into the area of the test antenna. Within a building, reflecting surfaces are present in the vicinity of the receiver but their influence is minimized by the use of radar absorbing materials over these surfaces. The uniformity of the plane wave in an anechoic chamber depends upon three factors: (i) the elimination of reflected contributions through the use of high performance absorbing materials, (ii) space attenuation, which is particularly significant in a large room, and (iii) shaping the room, or the use of baffles to cause multiple reflection and absorption of signals prior to their entry into the test region. The first two of these factors are of unquestioned importance; differing opinions on the use of baffles are held by leading designers of anechoic chambers. Their effectiveness depends upon the amount of specular versus diffuse scattering as the energy strikes the reflecting surfaces. It is our opinion that this technique will improve room performance when the baffles are large in terms of the wavelength. This introduces difficulties when the rooms are to be used at low frequencies since the size of the required baffles decreases the usable floor space in the chamber.

The ability to produce large uniform plane waves in the proposed anechoic chamber is the most important requirement in the design. As stated, this is a requirement imposed when radiation patterns are to be measured. Any room designed to meet this condition will almost certainly be adequate for impedance and interference measurements. In impedance investigations a signal propagates through a transmission line to the antenna under test, from which it is radiated into space. The impedance of the antenna as measured in the transmission line is in error if any of the radiated energy re-enters the antenna due to external reflections. This, however, should not be a serious problem in measuring the impedance of the Apollo antennas in the anechoic room.

The chamber design should provide for the use of absorbers in the receiver end whose power reflection coefficient is at least less than one percent (-20db) at 200 Mc and higher. As the frequency increases the reflection coefficient decreases; typical values would be -35db at 300 Mc, -45db at 600 Mc, and lower at higher frequencies. If all the radiated energy re-entered the antenna in phase after being reflected by a -20db absorber, and if there was zero space attenuation, a room VSWR of 1.22 would be added to that of the antennas.

The corresponding figures for -35db and -45db are VSWRs of 1.03 and 1.01. The amount of the energy re-entering the antenna will be much less than this due to space attenuation and multiple reflections and since it will be returned with random phase, the above-mentioned values will almost certainly be lower by 10db or more. In their preliminary proposal for a chamber for the NASA-MSC, Emerson and Cuming(1962, 1963) stated that the ratio of received power to transmitted power would be -40db for VSWR measurements with typical antenna locations for frequencies above 150 Mc. This corresponds to a possible error of 1.02 in the VSWR and should be tolerable.

In measuring the effect of interference, the impedance and coupling behavior of one antenna is studied with and without other antennas and electrical devices operating. If the radiation from antennas not under test is reflected into the test antenna, the results of the interference measurements will differ from measurements made under ideal conditions in free space. Since any such reflected energy will be down by at least 30db and more probably by 40 to 50db due to the absorber properties, multiple reflections and space attenuation, the conditions for interference measurements should be satisfactory. It is always possible to identify the influence of room reflections in impedance or interference measurements by changing the position of the test antenna with respect to reflecting surfaces.

Another desired condition in an anechoic chamber for any of the above measurements is isolation from outside radiation or noise and the avoidance of radiation from the chamber that may disturb work in progress on the outside. At the higher frequencies this is largely accomplished by the absorbing material. To add to the attenuation due to the absorbing material and to provide attenuation for frequencies down to 100 Kc, the room should be completely shielded. This is discussed in more detail in later sections.

4.2 Anechoic Chamber Requirements for Apollo Measurements.

In making recommendations for an anechoic chamber for Apollo measurements we have followed the principle that tests should be made indoors rather than outdoors if at all possible. Our justification for this is as follows:

(i) Working time is not limited by weather conditions. Equally, or possibly more, important, workers' efficiency is considerably improved when working in an airconditioned room.

(ii) Success of outdoor measurements may be handicapped by interference from radiation and noise from external sources.

It is our opinion that impedance and interference measurements should ordinarily be made in the anechoic chamber. The consideration of the required test distances for the Apollo antenna made in the previous chapter shows that it will not be practical to run many of the radiation pattern tests within the anechoic room. However, the room should be designed to accommodate the measurement of Apollo antenna patterns to the extent possible.

For maximum convenience and compatibility between the antenna range and the anechoic room, it should be possible to wheel the Apollo vehicle from the antenna pattern range into the anechoic room. Once inside the room, it should be possible to proceed with impedance, interference or pattern tests with no further changes in the mounting. This provision helps to determine the room dimensions. Outside pattern test requirements appear to be best met with a receiving antenna height of 35 feet. Since the center of the antenna is 35 feet above the ground it is most logical for this point to be the center of the building both vertically and laterally. We thus have a building 70 feet wide by 70 feet high. This gives a clearance of 25 feet between the vehicle and the wall for that part of the Apollo that is 20 feet in diameter, though note that the clearance will be decreased by the thickness of the absorbing material.

A further justification for a room 70x70 feet in cross section is seen in the Emerson and Cuming (1962, 1963) room design for an anechoic chamber for the Apollo vehicle. It is the policy of the above organization to design a chamber to produce a "quiet zone" along the axis of the room. The quiet zone is created by the use of longitudinal baffles which prevent reflected rays from entering the quiet zone before having been reflected two or more times. After two or more reflections the energy is so low that it has little effect on the plane wave in the quiet zone. This design is based upon ray tracing procedures and assumes that the specular reflections are of major importance in comparison with diffuse reflections. Emerson and Cuming find it desirable to have a ratio of from 3 1/2 to 5 between the diameter of the quiet zone and the room cross section dimensions. For larger ratios the number of bounces can be greater resulting in an improved quiet zone performance. In their preliminary design for the NASA-MSC anechoic chamber, Emerson and Cuming specified a room with a width and height of 71 feet and 9 inches (inside dimensions without absorber) to create a quiet zone 21 feet in diameter. This is a logical choice for the quiet zone diameter since the LEM is 20 feet in diameter.

It is difficult to arrive at a strict theoretical justification for recommending that the chamber have dimensions of 70x70 feet rather than, say, 65x65 feet or possible 60x60 feet. It is obvious,however,that room performance increases with size. This is shown by ray tracing studies. It is also apparent that with a larger room the incidence angles will be larger and the deterioration in absorber performance due to low incidence angles will be less. A further consideration should mentioned. Space attenuation is an important factor in a 70x70 foot room but it will contribute little in the lateral direction in a 40x40 foot room. The radar return from a wall or any other target is inversely proportional to the fourth power of the distance (assuming far field distances are involved)and thus a reflecting surface 20 feet distant (as in a 70 foot room) will have a return 12db less than when the distance is 10 feet (as in a 40 foot room).

In our effort to obtain maximum performance for the NASA-MSC antenna test facility we are proposing an additional use of the anechoic chamber that greatly adds to its utility and at the same time significantly extends the capability of the outdoor antenna range. For this application, we would have doors on one end of the anechoic chamber that open to form an aperture 55x55 feet. The room is oriented so that its axis is at an angle of 5^o with respect to the direction of the antenna range. This makes it possible to wheel the receiver mount and test vehicle several feet into the anechoic chamber and at the same time maintain a 50 foot test vehicle in full view of the transmitter.

The ability to take antenna patterns with a major part of the Apollo vehicle inside the anechoic room is very desirable. It provides the opportunity to continue measurements during inclement weather and more important it produces a shielded environment where outside radio and microwave interference can be almost completely avoided.

The ability to take antenna patterns within the open doors of the anechoic chamber is a further major reason for the recommended 70x70 foot dimensions .

The next question is to determine the proper length of the anechoic chamber. If we provide the same 25 foot clearance at each end as is provided on the sides, and if we consider the Apollo vehicle, less the escape tower, to be 57 feet long, one would have a room 107 feet in length. The length of an anechoic room is ordinarily determined by the tests that are to be performed in it. A room 70x70x107 feet is adequate for the impedance and RFI tests on the Apollo vehicle. It was shown in Chapter III that most of the antenna pattern tests will require a range of 500 or 600 feet or more. Some of the ranges required for the CM alone are of the order of 50 or 60 feet, and the corresponding patterns could be taken in the anechoic room. It does not seem feasible to make the room large enough to make any of the other full scale pattern tests required on the Apollo. A room 200 feet long would still be too short for much additional work on the full scale modules.

Since the anechoic room is to be designed for maximum utility and since future tests other than those for the Apollo may become important, it seems unwise to recommend a 70x70x107 foot room. The optimum ratio of room length to width is 2 or 3. In practice, the length is usually determined first and is based on the antenna pattern range requirements. The width is then 1/2 or 1/3 the length and this is a function of the absorber performance for off-normal incidence. For normal research tests, we would recommend that the room be at least 140 feet long were it not for cost considerations. With the latter in mind, our recommendations for room dimensions are 70x70x120 feet (less absorber thickness).

Apart from size, the second most important cost consideration in an anechoic room is the minimum operating frequency. The required thickness of the broadband absorbing material commonly used in anechoic rooms is of the order of 1/3 to 2/3 of the maximum wavelength to be used. The cost of the material increases rapidly as the minimum frequency is decreased.

The minimum frequency to be used on the Apollo may be of the order of 10Mc, but since this involves a wavelength of approximately 100 feet, it is out of the question to attempt to cover this frequency. The next Apollo frequency is 125 Mc if the minitrack antenna is to be included. Since the wavelength is still quite long (8 feet) and since all the more important antennas are to operate above 200 Mc it seems logical to set the minimum frequency at 200 Mc. A room that performs well at 200 Mc will be adequate for impedance and interference tests at 125 Mc.

4.3 Use of Anechoic Chamber for Radar Cross Section Measurements

The formal description of the intended use of anechoic chamber did not mention radar cross section measurements. It is well to note, however, that the recommended room would be highly satisfactory for such measurements. In radar cross section work the model under test is located in the receiver half of the room and would be illuminated by a directive antenna located in the opposite end. The illuminated target scatters in all directions but in most studies only the backscatter or near backscatter radiation is measured. Since the back wall and near lateral areas are covered with superior absorber material and since the room cross section is large the chamber should make an excellent cross section measurement facility. The 70 foot width of the room makes it feasible to do good bistatic cross section work. This is not possible in most anechoic rooms. There should be no problem in operating at frequencies as low as 1000 Mc. This laboratory has been making such measurements in a 100 foot long anechoic room for several years. Although problems occur in measuring targets at aspects for which the back scattering cross section is very low whilst the forward scattering cross section is simultaneously large, this condition is not likely to be of particular interest to NASA-MSC.

Either conventional CW or short pulse back scatter equipment could be employed in the room. It would be necessary, of course, to provide a target support that had a radar cross section much lower than the values to be measured.

4.4 Anechoic Chamber Specifications

4.4.1 Absorber Considerations

No attempt will be made to give detailed design information on the anechoic room. Preliminary room designs may be obtained from Emerson and Cuming, Inc., of Canton, Massachusetts or from the B. F. Goodrich Company Sponge Products Division, Shelton, Connecticut. After room specifications and performance figures are fixed, quotations should be obtained from interested suppliers (including the above two companies) to provide the detailed design of the room, supply and install the material and complete room performance tests.

Recommended specifications on the anechoic room are as follows:

1. Room dimensions are 70x70x120 feet and the room will be shielded according to specifications given in Section 4.4.2 of this report.

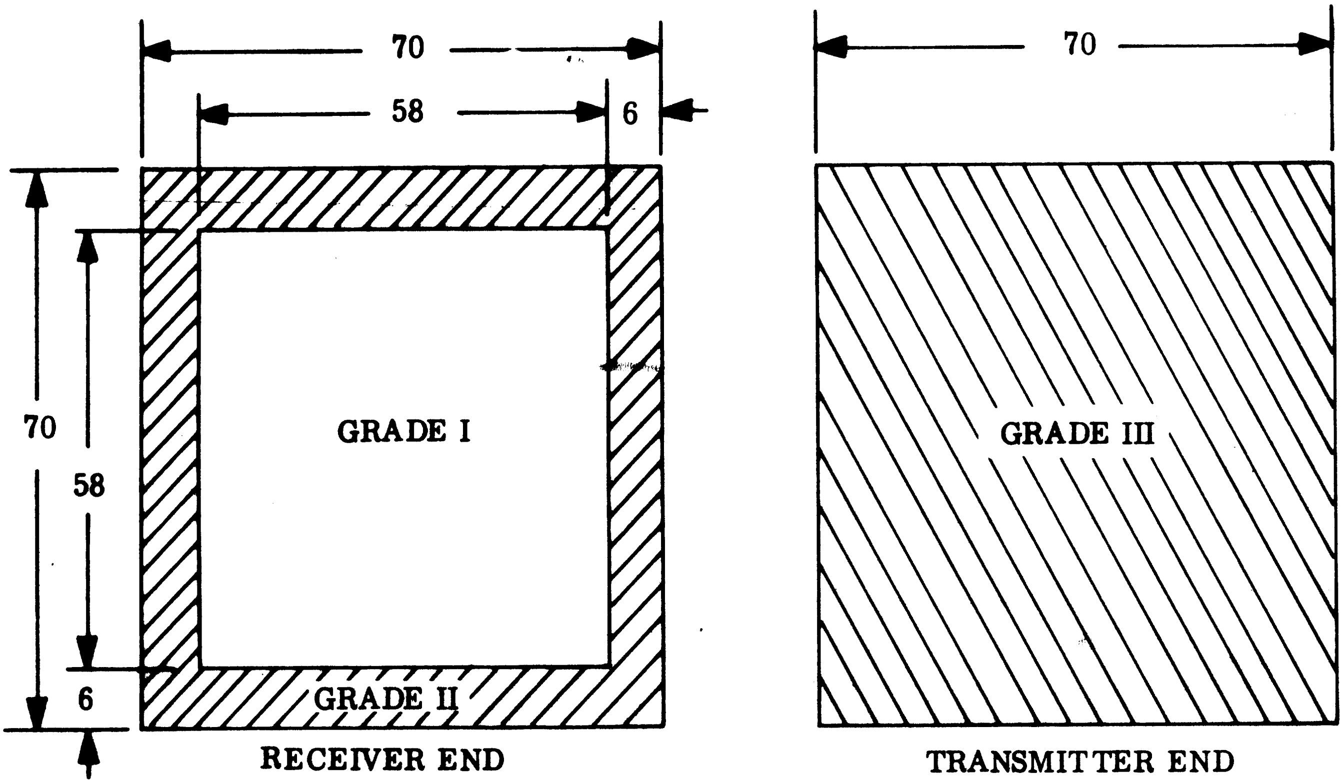
2. Personnel access doors will be provided for entry into the service building. Motorized doors providing a 55x55 foot opening will be built into the

transmitter end of the chamber. It will be necessary to design the transmitter cubicle with a powered arrangement for positioning it on axis or for removing it in order to clear the large doorway. A method of rotating the test vehicle from the control room in the service building should be provided.

3. The use of baffles are at the discretion of the supplier except that the receiver end wall should be non-planar. This wall may be in the form of a smooth curve forming a section of a vertical cylinder or it may be wedge-shaped with the vee of the wedge in the vertical direction and having a radius of curvature of a few feet. The cylinder or wedge should extend about 5 feet into the room.

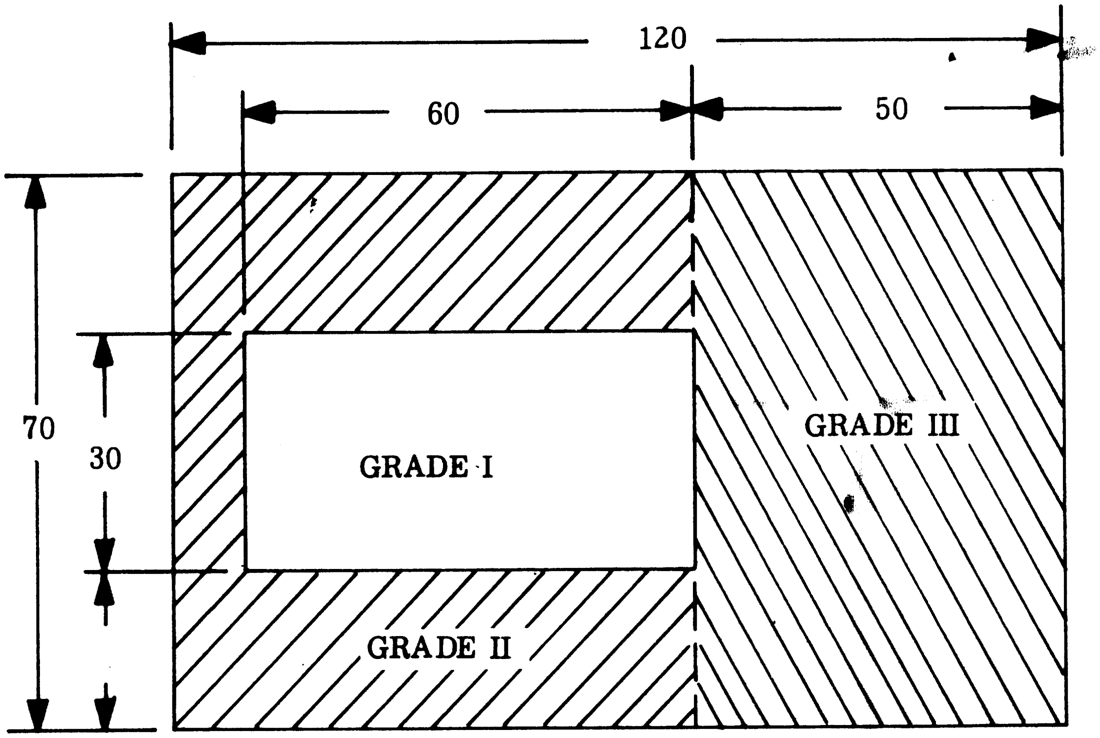
4. Three grades of absorbing material should be used. The highest performance material, grade one, is used in the most critical areas. The second and third grade materials may be located in less critical areas and their use will decrease costs. The exact extent and placement of the three grades of material should be compatible with the detailed design of the supplier. A tentative arrangement is as follows: (see Fig. 13)

(a) Install first grade material over the receiver end in all areas except for a 6 foot border. Install first grade material as a central strip on walls, floors and ceiling extending from a line 10 feet from the receiver end to a line 50 feet from the opposite end. The width of this central strip on the walls, floors and ceiling should be 30 feet.



RECEIVER END

TRANSMITTER END



SIDES, FLOOR AND CEILING

FIG. 13 : PLACEMENT OF ABSORBER IN ANECHOIC CHAMBER

(b) Install grade two material on all other areas on walls, floor, ceiling and receiver end up to a line 50 feet from the transmitter end.

(c) Install grade three material onremaining areas.

Special floor material of equivalent performance should be substituted as needed.

The performance of these materials for normal incidence should equal or exceed the following:

Grade One	-30db at 200 Mc and -40db or better for frequencies above 500 Mc.
Grade Two	-30db at 350 Mc and -40db or better for frequencies above 800 Mc.
Grade Three	-30db at 500 Mc and -40db or better for frequencies above 1000 Mc.

It is expected that performance as a function of angle of incidence will be equal to currently advertized claims for superior material.

NASA or their representatives will want to observe spot performance checks on these materials at the supplier's plant or in a laboratory of their choice.

5. The design of the room should be such that a quiet zone or test area 20 feet in diameter is established along the axis of the chamber extending over most of the length of the receiver half of the room. For chamber illumination by a transmitting antenna having a gain of approximately 10db or less located near the transmitter end on the chamber axis,the reflectivity level will be down from the direct ray as follows:

30 to 35db	from 200 Mc to 300 Mc
35 to 45db	from 300 Mc to 600 Mc
45 to 55db	from 600 Mc to 40 Kmc.

If specifications (4) or (5) are incompatible, the tighter requirement will be followed.

6. The method of attaching the absorber should be left to the supplier, but he should guarantee that it will stay in place for a reasonable length of time. Floor panels should be removable to allow entry of test vehicle and support.

7. All other conventional room refinements will be provided.

8. Various methods of evaluating room performance have been proposed. These are reviewed by Hiatt et al (1963). The methods of evaluating room performance advocated by leading builders of anechoic chambers may differ and still be satisfactory. Those proposing to design the room and supply the absorbing material should also indicate their intended method of evaluation. If,upon review, the method proposed by the successful bidder appears to be satisfactory, this testing procedure should be accepted.

4.4.2. Shielding Considerations

The requirement for shielding the anechoic room should next be considered. The specifications in the contract call for a 100db minimum attenuation of any electromagnetic signals passing into or out of the anechoic chamber. It is suggested that the specifications for the shielding material require 100db minimum attenuation for both electric and magnetic fields from 100 Kc to 10 Kmc, and 40db minimum attenuation for magnetic fields between 14 Kc and 100 Kc. These levels of attenuation are within the state of the art of manufacturers of shielded rooms.

The size of the facility requires that the shielding materials be attached to the framework of the building rather than be free standing. Standard panel widths of shielded material are either 40 or 48 inches. Panel lengths are normally 8 feet. Attachment to the framework of the building can be made at the joints between the panels, and the requirement for the building framework is therefore that it accommodate one of these two standard widths and the standard length. Drawings of typical shielded room constructions are available from the Shielding Division of Shieldtron, Inc., Ace Engineering and Machine Company, and Emerson and Cuming, Inc. These drawings outline the detail at the joints between panels where attachment to the building framework can be made. They also show details on access doors, electrical wiring, lighting, and ventilation that are typical for these types of rooms.

The large access door required for this chamber is not a standard accessory with any shielding manufacturer but can be built by any one of the three companies mentioned above. The problem of maintaining attenuation around this large access door is, however, severe. Normally, shielded doors have beryllium-copper fingers mounted around the door edge to contact the metal door jamb along the entire periphery of the door. These fingers generally have a travel of not more than one-half inch, so that the door will have to be hung true within this tolerance. The spring action of the fingers also imposes a problem on closing the door.

This type of door has been constructed by each of the shielded room manufacturers for several different facilities. If they are simply given the problem of meeting the attenuation specification, the design of this door can be entrusted to them. The air vent and lighting techniques used in the anechoic chamber will differ somewhat from those used in the standard shielded room, inasmuch as the interior surface will be covered with several feet of absorbing material. The drawings from the Shielding Division of Shieldtron, Inc., and from Emerson and Cuming, Inc., both show their recommendations for lighting the anechoic room.

Filters for the electrical power lines entering the chamber should provide for handling 24 volts dc (300 amps), 115 volts ac (200 amps) and probably a 440 volt, three-phase filter capable of handling the power for the Apollo mount. Provision should also be made for entry of needed control cables for the mount, the doors and the transmitter cubicle.

The shielded room manufacturer should be required to furnish the room filters and the ventilation inputs to the room, to supervise its installation by the general contractor and to test the room to assure its conformance to the attenuation specifications by the testing methods outlined in Military Specifications MIL-I-4767.

4.5 Trade-offs in the Anechoic Chamber Design

4.5.1 Background Information

Since the cost of the anechoic room is the largest single item in the NASA-MSC antenna facilities budget, it is in order to consider methods of decreasing its cost. We have estimated that the cost of a 70x70x120 foot anechoic room would be $1,080,000. This figure is arrived at as follows:

Building shell (based on $50/sq.ft. of floor space		$420,000
Shielding (based on $3.50/sq.ft. of interior surface)		152,000
Absorber material		
10,564 sq.ft. based on $16/sq.ft.	$ 169,024	
13,936 sq.ft. based on $11.70/sq.ft.	163,051	
18,900 sq.ft. based on $6.40/sq.ft.	120,960	
		453,000
Door (55x55 feet)		45,000
Provision for removable transmitter cubicle		10,000

Possible savings on the first four items will now be considered.

Room Size. The building size is of most concern since this affects the cost of the shell and also the amount of shielding and absorber required. One must be particularly careful in considering a reduction in size since this tends to be a non-reversible decision. That is, you cannot decide to build a 40x40x120 foot building now and then decide to change it to a 70x70x120 foot building later. It is physically feasible to add to the length of a building after one or two years but government policy and procedures make this an unattractive plan. It is important therefore to select building dimensions that will be adequate for several years in the future. We strongly recommend that the building dimensions be approximately 70x70x120 feet. The reasons for this and the advantages have already been discussed,but some of them bear repeating. A prime reason is that the 35 foot center height is compatible with the outdoor range activities. It makes possible antenna pattern work in the open end of the chamber and obviates the need for re-mounting the large test vehicles at every change from outdoor to indoor operation. It is not possible to create a large test zone or quiet zone without having a room cross section much larger. This is supported by ray tracing studies and by space attenuation considerations. Moreover the large room makes possible an unusually good chamber for radar cross section measurements.

One of the most important reasons for recommending a large size anechoic chamber has hardly been mentioned. The facility is to be designed with considerations of the future in mind. It is quite likely that future spacecraft, such as those required in a Mars mission would be too large to fit into a 40x40x120 foot room - much less to be tested therein. Since this chamber is to be built for the manned spacecraft program it should be built with future craft in mind. There are several chambers in the country with cross section dimensions on the order of 35 or 40 feet. It is important for this building to be a significant step in advance of existing facilities. If NASA-MSC built a conventional-sized room now, another government agency or contractor might be spending government funds to build a 70x70 foot room a year or so later. We are, therefore, reluctant to recommend any trade-offs or back-offs with respect to the anechoic chamber size.

Shielding. There is a firm specification for 100db shielding in the anechoic room. Shielding is required to properly perform interference and receiver tests and it may become an important requirement in pattern and other tests. If shielding is to be included, it is not practical to consider adding it at a later time since there would be a very high take-down and installation cost with the absorber. It may be possible to save a little money by using inferior shielding but this seems inadvisable since there is not that much difference between the cost of the two, and since it would not be practical to improve the poor shielding at a later date. It is necessary to provide some surface over the building interior in order to have something to which the absorber material may be attached. The shielding serves this purpose very well, so part of its cost is justified in this manner.

We therefore recommend no back-off in regards to shielding.

Quality of Absorber Material. If there must be a back-off in the cost of the anechoic room, it seems as if the most feasible way to decrease the cost would be in the quality of the absorber material used. It was noted above that the estimated costs of Grade 1, Grade 2 and Grade 3 material are $16.00, $11.70 and $6.40 per square foot, respectively, and the placement of these materials in the anechoic room was described in Section 4.4.1. It is possible to achieve savings by using lower grade materials on all locations. For example, $100,000 would be saved if the cost per square foot was uniformly less by $2.50. It is possible that competitive bidding on this amount of material will result in a substantially lower price but it seems inadvisable to degrade the entire room performance by using inferior material throughout. If money must be saved now it should be possible to upgrade the room at a later time by replacing the inferior material with a better grade. Rather than taking off all the material at that time to be discarded or moved to a less sensitive position, it would seem best to use material of the recommended quality throughout the receiver end of the room. The area upon which the Grade 3 material was to be placed included the transmitter end wall and the sides, floor and ceiling to a distance of 50 feet, a total area of 18,900 square feet. If the third grade material, which has a 30db reflectivity at 500 Mc, is replaced with a thinner material with a 20db reflectivity at 900 Mc, a savings of $2.40 per square foot, or $45,360 can be realized. This change would have some effect on the room performance in the far end of the room, particularly if the design depends on longitudinal baffles in the transmitter end to help achieve the quiet zone in the receiver end. The change should not appreciably decrease the effectiveness of the room for impedance and interference measurements in the receiver end, but it could have a serious effect on the accuracy of antenna patterns taken in the transmitter end of the room when used in conjunction with the outdoor range. The possible errors in the antenna pattern depends on the antenna pattern level involved, E_1 and the level of the room reflectivity, E_2 that causes the error. These are related as follows (Hiatt et al, 1963, p. 37):

$$\delta = \frac{E_1 + E_2}{E_1 - E_2} \quad .$$

Buckley (1963) uses a similar relation in discussing methods of evaluating anechoic chambers and presents a chart in his Figure 7 which relates these factors when expressed in db. Table IV is presented to illustrate the penalties involved in using lower performance material. The values in Table IV are taken from Buckley's chart.

To some extent it may be possible to offset the poorer performance in taking patterns in the transmitter end by moving the pedestal well back into the receiver end of the anechoic room. This would appear to be satisfactory for smaller aperture antennas.

TABLE IV
POSSIBLE PATTERN ERROR (DB) AS A FUNCTION OF ABSORBER REFLECTIVITY AND PATTERN LEVEL

Pattern Level (db) \ Room Reflectivity (db)	20	30	40
0	1.7	.55	.17
5	3.2	1.0	.32
10	5.5	1.7	.55
15	10.0	3.2	1.0
20	--	5.5	1.7

The second step in the back-off in absorber quality would be the replacement of the Grade 1 material on the walls, ceiling and floor in the receiver area with Grade 2 material. The area involved is 7200 square feet and the price difference is $4.30 per square foot making a possible saving of $30,960. This would have the effect of replacing the material in these critical areas with an absorber that was about 10db poorer in performance for frequencies below 350 Mc. The effect on impedance and interference measurements would be in direct proportion to the 10db change in reflectivity. This may still be tolerable. The effect on the quiet zone performance would probably be less than 10db.

Further savings could be achieved by using less costly materials in other areas or by using still cheaper materials in the above two areas but estimates of this kind are hardly appropriate until more firm figures are available to show the relation between the total expected cost and the available funds.

There is a possibility of making a significant saving in the amount of absorber required by using a novel idea advanced by Emerson (1963). In some preliminary studies, Emerson has replaced the usual rectangular transmitter end with an absorber covered tapered section reaching from the transmitter antenna to the test area. This resembles a tapered horn leading to a large untapered horn section, all of which is absorber covered. Emerson reports a significant improvement in performance by using this design and some results are included in the above reference. If further and more elaborate tests substantiate Emerson's findings, his idea would deserve careful consideration in finalizing the NASA-MSC anechoic room design. We have not attempted to include it in our consideration since we would first want to conduct an experimental study of the configuration and there has not been sufficient time to do this. To use it in the present design would require a 180° rotation of the anechoic chamber. This puts the 55x55 foot doors on the receiver end and the thickness of the absorber used there seriously complicates the door problem.

The 55x55 Foot Door. The final item to be considered in possible back-offs to reduce the cost of the anechoic chamber is the large door area. The minimum door size that could be considered (assuming the Apollo is to enter the chamber) would be on the order of 30x30 feet. This provides a small amount of clearance and would require the removal of the vehicle from the receiver pedestal before taking it into the chamber. If this is to be avoided, the door must be 50 or more feet high. The requirement for the 55x55 foot aperture results from plans to use the chamber for pattern work in connection with the outside range. Although the cost of the larger door is probably more than double the cost of a 30x30 foot door, it seems to be well justified by these two major advantages.

V. SPECIFICATION, INTEGRATION AND SITING OF STRUCTURAL COMPONENTS

The proposed antenna range facility has five basic components: (1) transmitter tower, (2) transmitter building, (3) receiver tower, (4) anechoic chamber and (5) service building. Operation of the range centers around a stationary transmitter tower which is located 2500 feet from, and transmitting towards, the anechoic chamber - service building complex, and a brief comment about this recommendation is desirable.

Because of the large size and weight of the Apollo modules and the height at which they have to be mounted, the support pedestal is a major structural item and if it is possible to achieve a fully operational facility using only a single pedestal, so much the better. Clearly more than one fixed pedestal would be necessary to cope with both the outdoor range and the anechoic chamber, and since at least two antenna range lengths are required for outdoor pattern measurements, we are therefore faced with the following choice: (i) a movable transmitter tower and at least two fixed receiver (i.e. vehicle) pedestals, or (ii) a fixed transmitter site and a minimum of three fixed receiver pedestals, or (iii) a fixed transmitter site and a single movable receiver mount. The first alternative and, to a lesser extent, the second, would involve the transfer of the modules from one support to another in the course of a series of tests covering more than one frequency band, and this should be avoided if at all possible. Only the third alternative minimizes the set-up and take-down time. Finally, a desirable feature of our proposal is that the anechoic chamber should be capable of being used as a test cubicle in conjunction with the outdoor range should electromagnetic interference and weather conditions warrant it, and such an operation is most easily performed if the test vehicle is mounted on a pedestal which can be wheeled into the chamber. In view of all these factors, it is recommended that the test antenna positioner should be mounted on wheels so as to act as a movable receiver pedestal. It is conceivable that the transmitter could also be movable, but there is no apparent advantage to demanding this capability.

5.1 Transmitter Tower

The transmitter tower is a steel structure approximately 75 feet tall, capable of supporting a 12 foot parabolic reflector at the 73 foot level, and a 6 foot parabolic reflector at the 35 foot level for operation in winds up to 35 mph. The tower should be capable of withstanding 135 mph winds under non-operating conditions (reflectors at ground level).

Each of the reflectors will be mounted so as to have three axes of movements: azimuth, elevation and polarization, with remote control possible from either the transmitter building or the central control room. Polarization indicators will be required at both control points, and though indicators may be provided for the other axes of movement, they are not mandatory. The antennas, along with their three axis mounts, are attached to separate elevator carriages which can be independently raised and lowered by remote control. Controls for this function along with height indicators will be located in both the transmitter building and the central control room.

Since it may be desirable to operate both the 12 foot and 6 foot reflectors simultaneously, two independent elevator systems are necessary with the dishes mounted side by side on the front face of the tower. To allow the 6 foot reflector to be operated at the 73 foot level, it should be possible to interchange the dishes, but a somewhat more versatile arrangement would be to give the second elevator system a 50 (rather than 35) foot capability. In the event of a power failure or similar breakdown, it will be necessary to be able to raise or lower the elevator carriages manually, and a hand ladder should be provided on the back of the tower to allow a man to make preventative maintenance checks.

To reduce transmission line losses, the transmitting antennas are fed by low-loss Styroflex cable which is attached to a self-winding drum to avoid entanglement with the elevator systems.

5.2 Transmitter Building

The transmitter building is located at the base of the transmitter tower, and a suggested floor plan is shown in Fig. 14.

The building will house the transmitters necessary to cover the frequency range 100 Mc to 10 Kmc, and their associated power supplies. The transmitters should be electronically tunable both from here and the central control room, and the nominal RF power level available from them is 250 milliwatts. Space will be

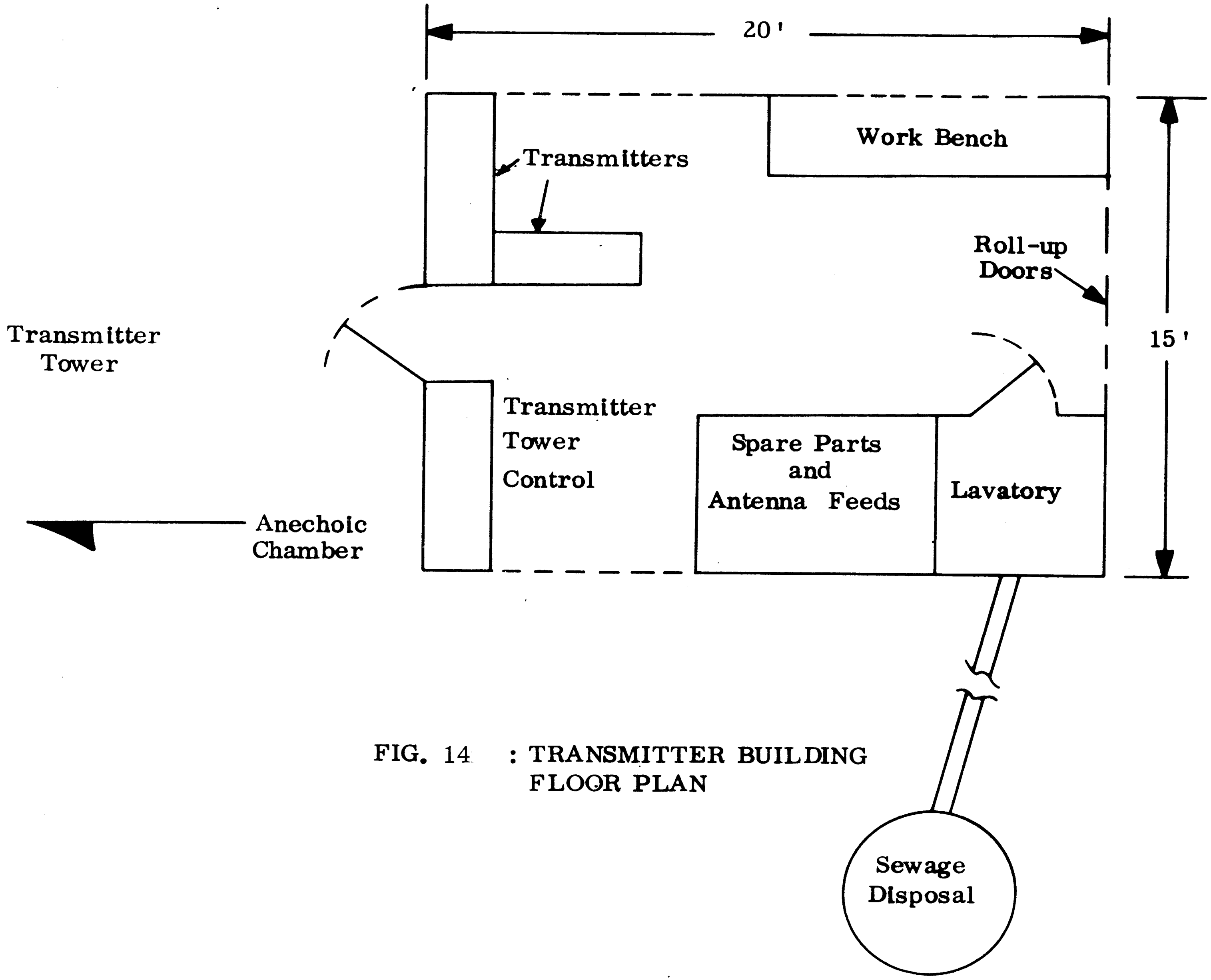


FIG. 14 : TRANSMITTER BUILDING FLOOR PLAN

provided for spare transmitting antennas, transmission lines, reflector feeds, etc. A small work area is necessary for repairing transmission lines and troubleshooting the transmitters. The electrical service required for the building is 115 volt, 60 cycle, single phase, 100 ampere and 220 volt, 60 cycle, three phase, 200 ampere.

Power and control cables between the transmitter building and the central control room will be underground to minimize stray pick-up and to eliminate the possibility of RF scattering.

5.3 Receiver Tower

The receiver tower is mounted on a dolly whose wheels run on a railroad track 9 or more feet wide to provide the needed stability. Tracks have been recommended to facilitate the movement and placement of the tall (35 - 45 feet) massive (weight > 20,000 lbs) structure, but there are no fundamental objections to the use of rubber tires on the mount if this is practical and less expensive. A small airport-type tractor is envisaged as the prime mover, and support jacks (possibly on extension beams) will be necessary to ensure the stability of the tower after it has been positioned.

The mechanical construction of the tower should be similar to that suggested by Scientific Atlanta, Inc. (1962). This is shown in Figs. 15, 16 and 17 (taken directly from their proposal). The tower must be sufficiently versatile to permit the mounting of up to 4 connected Apollo modules in a horizontal position.

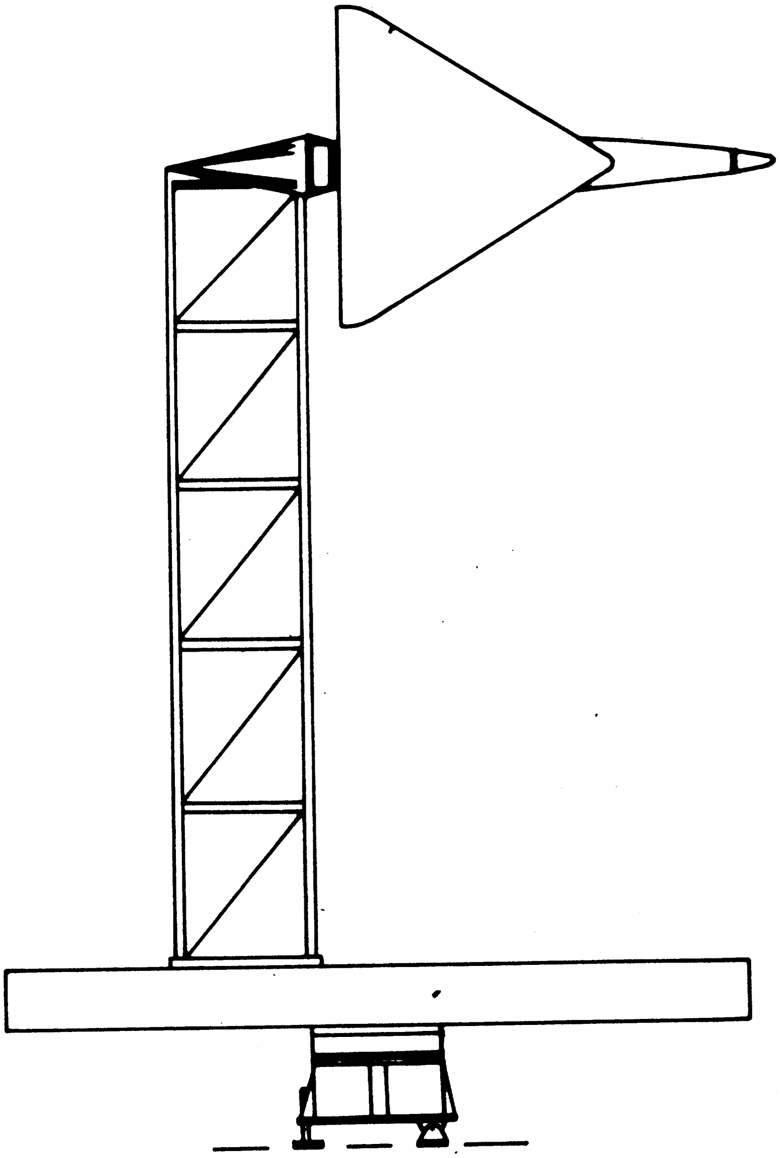


FIG. 15: RECEIVER SUPPORT TOWER (Scientific Atlanta, Inc., 1962)

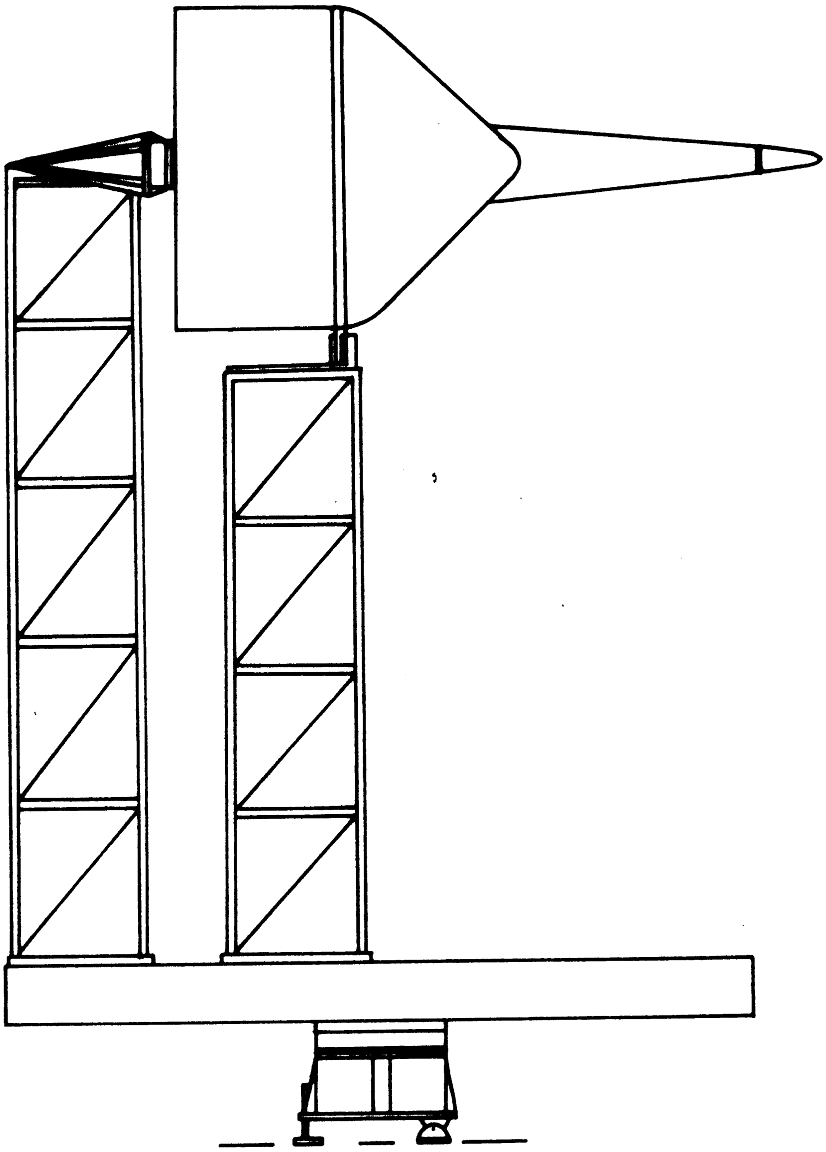


FIG. 16: RECEIVER SUPPORT TOWER (Scientific Atlanta, Inc., 1962)

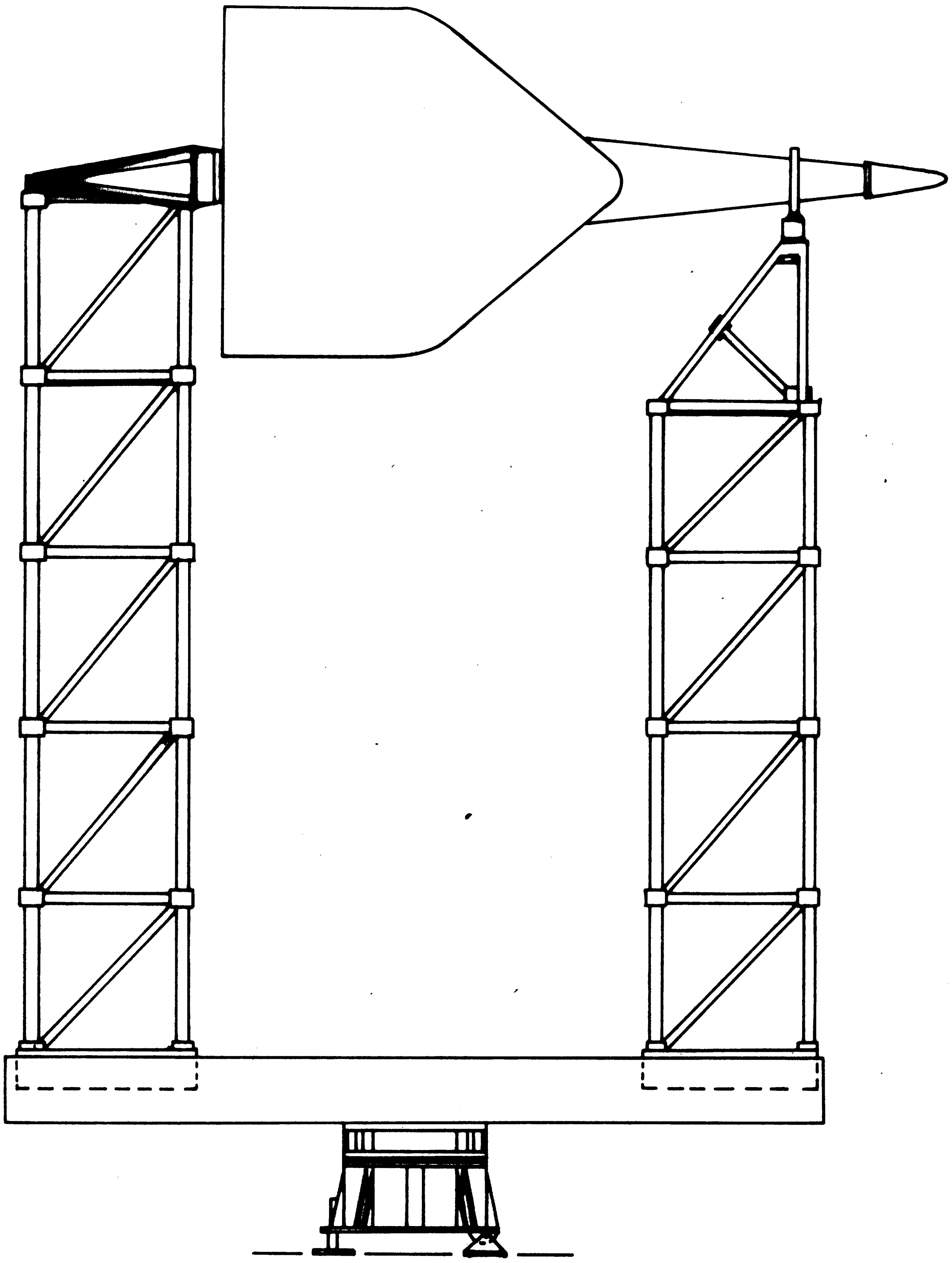


FIG. 17: RECEIVER SUPPORT TOWER (Scientific Atlanta, Inc., 1962)

Two axes of movement (azimuth and elevation) are required, with the elevation axis located 35 feet above ground level, and the method of attachment of the modules should allow rotation about their axis. Having set the elevation of the modules in accordance with the propagation mode employed, the antenna patterns for complete spherical coverage can now be taken by rotating the modules about their own axis for a series of different azimuthal values. Alternatively, the modules can be moved through 360° in azimuth for a series of different roll angles, and the fact that complete coverage is so easily obtainable in either of these ways is a major reason for advocating the horizontal mounting of the modules. Any attempt to achieve the same coverage with the modules placed on end involves their ultimate displacement out of the vertical, and leads, to stability problems.

Since the local oscillator signal from the mixer on the antenna is fed to the receiver via coaxial cable, there is an upper limit to the allowable separation of the mixer and the receiver. This distance is commonly set at about 75 feet, but in recent conversations with representatives of Scientific Atlanta, Inc., we have been informed that the distance can be increased to about 500 feet by using low loss cable. It may therefore be possible to operate the receiver tower at the 2000 foot site with both the receiver and the recorder in the central control room some 550 feet distant from the mixer. If this does not prove feasible, it will be necessary to operate both the 1000 and 2000 foot ranges with a receiver mounted in a weatherproof cubicle at the base of the tower, and an amplified audio signal fed through a cable to the recorder in the control room. In such cases an operator should be available to monitor crystal current at the receiver and to make needed tuning modifications, and it is probably advisable for him to be there at all times for routine observation of equipment and vehicle behavior.

Power, signal and control cables between the central control room and the receiver tower will be buried along the railroad track with outlets located 1000 and 2000 feet from the transmitter tower. This will involve connecting and disconnecting cabling to the receiver tower when the latter is moved, but this is not considered to be a serious problem since it will also be necessary to raise and lower jacks every time the tower is relocated.

5.4 Anechoic Chamber

The antenna range is essentially an outdoor facility, but because of the radar station at Ellington Air Force Base and the research and development activities that are to be located in close proximity to the range (see Fig. 18), some provision for additional shielding may well be desirable now and in the future. It is felt that the anechoic chamber can play a major role in this, and it is therefore recommended that the chamber be oriented in such a way as to permit the placing of test modules within it as part of the outdoor facility. It is well to note that representatives of both organizations contacted in connection with ground reflection ranges (see Appendix A) indicated the importance of housing the test antenna within a cubicle to minimize external RF and weather disturbances.

The above recommendation will not degrade the performance of the anechoic chamber as a self-contained facility providing it is incorporated into the initial design. To allow the receiver tower with the test module(s) in place to be moved into the chamber, a large door opening 55x55 feet at the transmitter end of the room is necessary. Such doors must maintain the required 100db shielding of the interior when closed, and since it is conceivable that they could be opened and closed an average of once a day over a six-month period, it is recommended that the doors be motorized. Their exterior surface must be plane and mounted nearly flush with the face of the anechoic chamber to minimize non-specular scattering which might otherwise interfere with pattern measurements on the outdoor range.

When using the outside range in its normal operating configuration the doors of the anechoic chamber will be closed and will present a large flat surface to the transmitted field. If the surface is flat the scattering will be primarily specular, and to prevent this return from reaching the vicinity of the test antenna it is desirable to tilt the axis of the chamber relative to the axis of the range. From a consideration of the beam width of this specular lobe, it is felt that a tilting of 5^o should reduce the interference to a tolerable level, and though a greater angle would be beneficial, it would limit the depth to which a test object could be placed inside the chamber and still remain visible to the outside transmitter. An inclination of 5^o is therefore recommended and with a door opening 55 feet in dimension, a 50 foot object could be placed 28 feet back from the aperture without any shadowing occurring.

This angle also applies to the service building, which should be placed on the far side of the anechoic chamber (see Fig. 19) to reduce the possibility of corner reflector effects.

5.5 Service Building

A full description of the service building is given in Chapter VI, and the only feature requiring mention here is the central control room. This is the nerve center of the entire antenna range facility, and from this location it should be possible to adjust and control the positions of the transmitting and receiving antennas both on the outside range and in the anechoic chamber, tune the transmitters and receivers, and record all data. To maximize the effectiveness of the room, it must be convenient to the chamber, the microwave laboratory, and any place where maintenance work on the modules is to take place. It must also provide a wide angle of visibility of the entire facility, particularly along the full length of the range, and it has therefore been located at the range end of the third story of the service building.

5.6 Siting

In Section 5.4 it was recommended that the anechoic chamber be incorporated as part of the outdoor range facility and the orientation of the axis of the chamber relative to the center line of the range was also specified. However, no mention has yet been made as to how the range should be sited on the plot of land available.

The factors which affect the siting are the present and future sources of RF interference, the availability of general service facilities and the character of the land. The principal source of interference at the moment is probably the radar system at Ellington Air Force Base, but the research and development which is to take place at Clear Lake City may be a factor in the future. In addition there is the possibilityof some interference from the Houston Ship Canal. The position of this is shown in Fig. 18, and since it is approximately 9 miles from the facility with a water level approximately 15 feet below ground level, the effect is not expected to be serious.

Finally, there is the possibility of interference due to reflection of the transmitted energy from structures in the general vicinity of the facility. Most of the major buildings are presently located in the Campus area and in the Clear Lake City development. A diagonal orientation of the range on the plot would therefore seem desirable, and from a consideration of all of the electromagnetic factors which may influence the performance of the facility, the position shown in Fig. 19 has been selected. The axes of the range and the anechoic chamber-service building complex are tilted at angles of 40 and 45 degrees respectively with regard to Second Street, though we remark in passing that the chamber could be tilted 5° on the <u>other</u> side of the range axis if desired, provided that the service building is then placed on the other side of the anechoic chamber (i.e. always on the side of the obtuse angle). With the location shown in Fig. 19

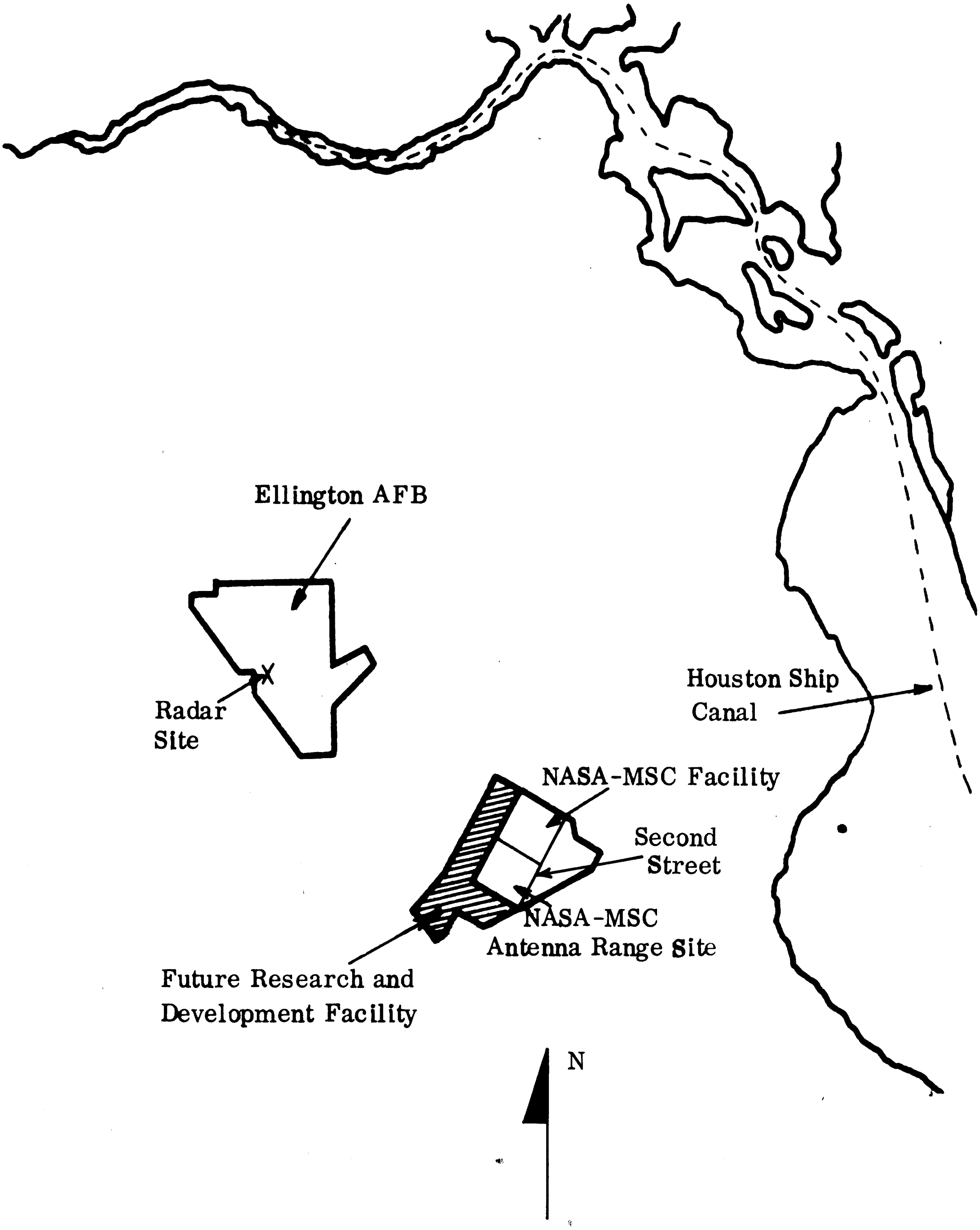


FIG. 18 : NASA-MSC AND IMMEDIATE VICINITY

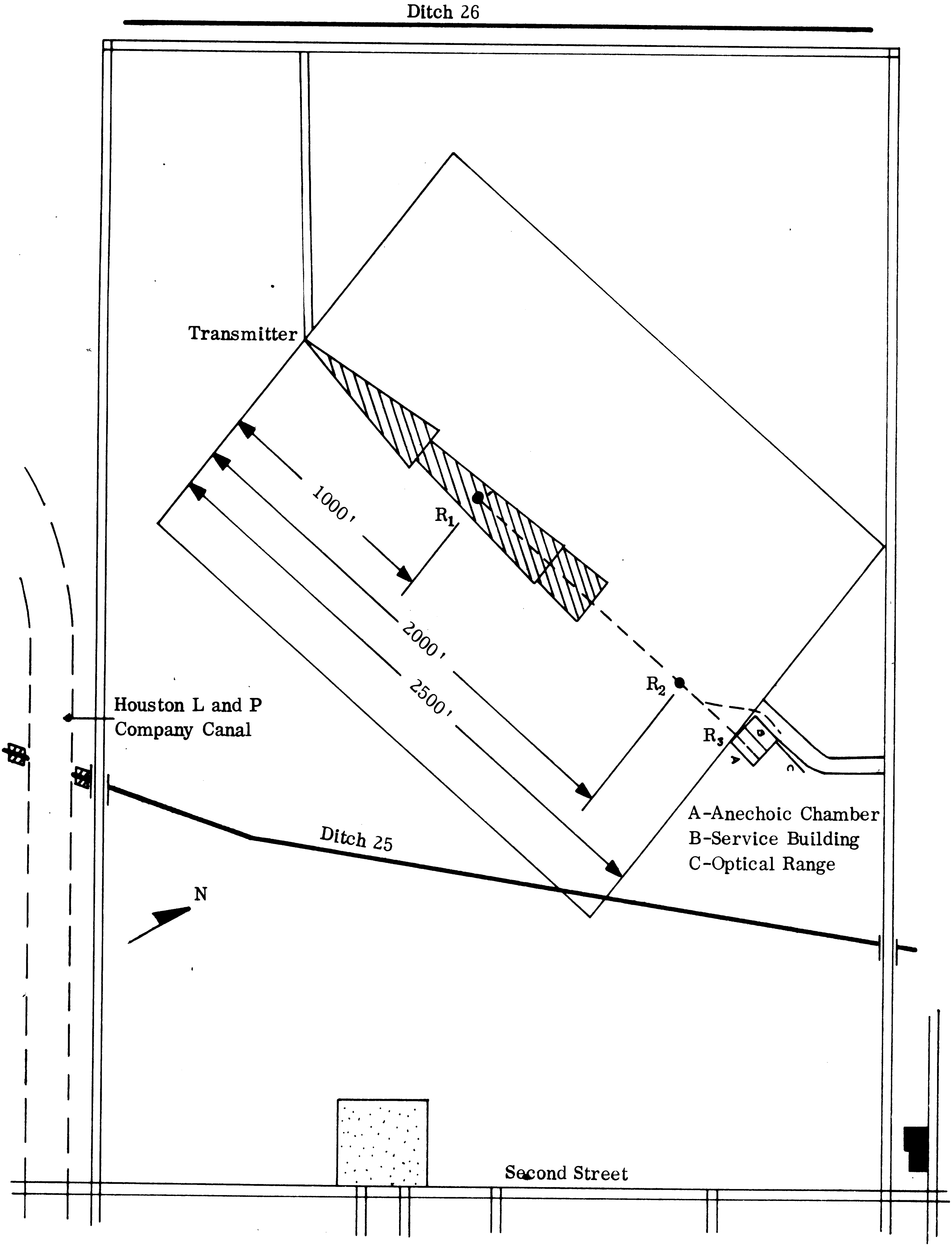


FIG. 19 : NASA MANNED SPACECRAFT CENTER ANTENNA RANGE

the center of the anechoic chamber doors is 1900 feet northwest of Second Street and 1850 feet southwest of Avenue B, and for availability of water, electric and sewage facilities it may be desirable to reduce these distances somewhat. On the other hand, any large reduction will mean that Ditch 25 will encroach on the cleared (or even the prepared) area of the range, and could lead to interference through reflection of the transmitted energy from the sides of the ditch into the region of the test antenna.

The railroad tracks indicated by the broken line in Fig. 19 are for the movement of the receiver support tower. The main track extends from the receiver end of the anechoic chamber to within 1000 feet of the transmitter site. A manual rail switch is located (about) midway between the 2000 foot receiver position and the entrance to the chamber, giving access to a sidetrack which is curved so as to bring it parallel to the service building. It will extend approximaterly half way along the building, and be equally spaced about a line some 10 feet away from (and parallel to) the service building.

5.7 Future Expansion of the Antenna Range Facility

The antenna range that has been recommended in this report has been designed primarily for making full scale Apollo module (and future space program) antenna measurements, and all of the Apollo antennas can be tested full scale with the exception of the 10 Mc antenna. It was pointed out in Section 3.2 that to test this antenna it would be advisable to use a ground level azimuth rotator to obtain azimuth patterns and balloons or airplanes to obtain elevation patterns (Terman and Pettit, 1952). Since this capability is not provided by the present range, it should be considered as a future extension of the present facility. A suggested location for the ground level rotator is shown in Fig. 20 and denoted by the symbol GLR.

At the first opportunity, attention should be given to the purchase of a second receiver support tower identical to that described in Section 5.2. To further enhance the research capability of the facility in the future, plans should be made to install two short ranges having a maximum length of 1000 feet. These could be directed at right angles to the present range, extending from the transmitter tower to points such as those marked 'RR No. 1' and 'RR No. 2' in Fig. 20. Transmitting antennas for the ranges could be placed on the side of the existing tower.

It is also probable that a range whose length is even greater than 2500 feet will ultimately be desired, and a possible 3500 foot range is shown in Fig. 20. The location of these future ranges should be re-examined before final siting to take advantage of new information on interference sources.

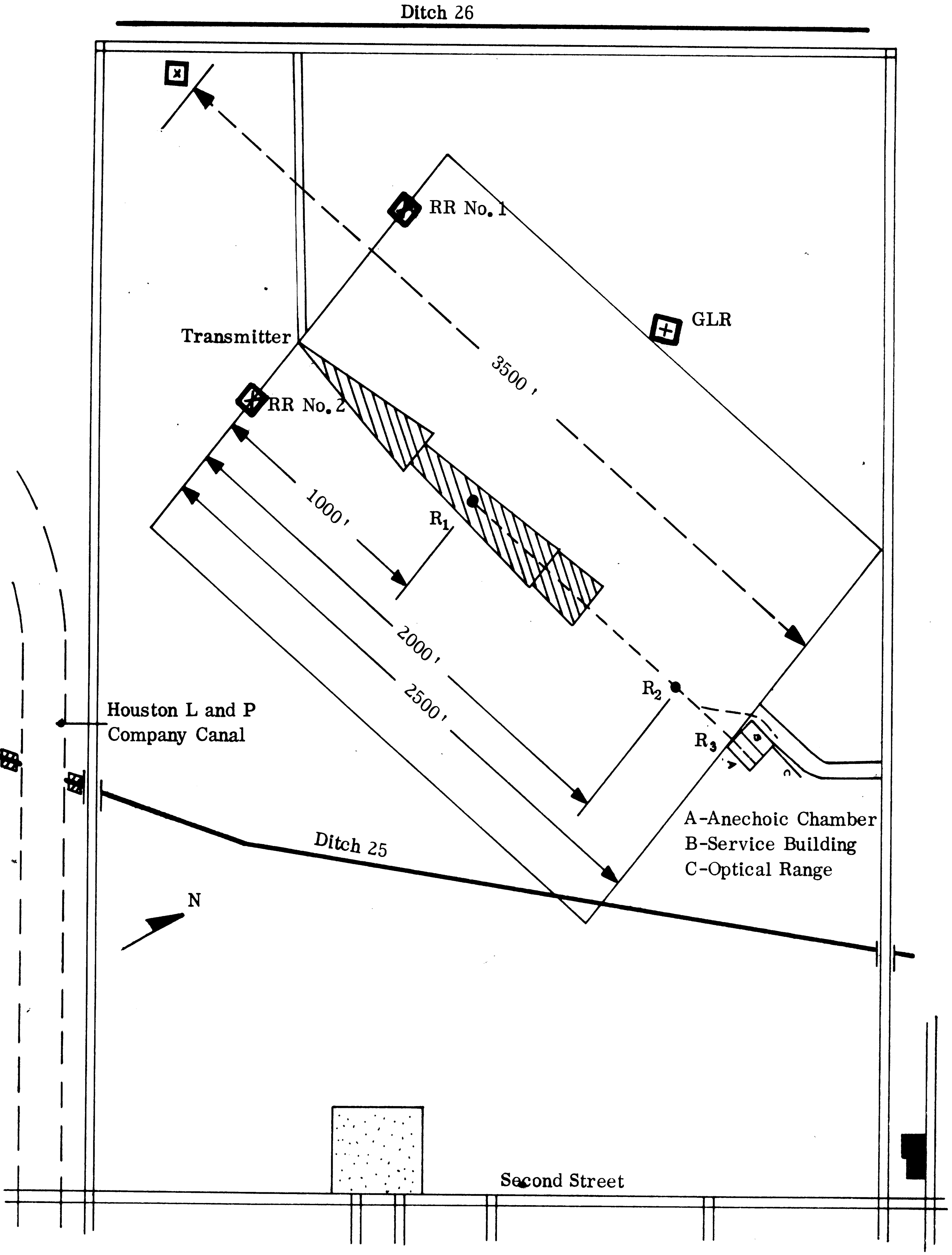


FIG. 20 : NASA MANNED SPACECRAFT CENTER ANTENNA RANGE SHOWING FUTURE RANGE CAPABILITIES

VI SERVICE BUILDING

The service building is a three-story 40 by 120 foot structure in which the optical laboratory, light weight shop facility, staging area, office space (including conference room), microwave laboratory, anechoic chamber shield room and antenna range central control room will be housed. A suggested floor plane for the service building is given in Fig. 21 . This is not intended as an architectural drawing, but there are nevertheless definite reasons for locating the major portions of the building relative to one another (and to the anechoic chamber and outdoor range) in the manner shown.

The building itself is placed alongside the anechoic chamber (see Section V). The front of the first floor serves as the receptionist area, visitors' lounge and optical laboratory central office, and in the rear there is a small machine shop and large staging area. The machine shop should include a small mill, large and small lathes, metal shear, roll and brake, welding booth, and associated equipment, lumber, storage racks, etc. This is a basic assortment of machinery for a light weight machine shop, and the list should not be regarded as complete in itself. The staging area serves as a place for assembling modules prior to antenna tests, and as a general purpose laboratory facility to enable prolonged modifications, trouble-shooting, etc. to be performed within the confines of the airconditioned building. The latter aspect is important in view of the climatic conditions in the Houston region, and in the event of a severe storm or hurricane the modules can be removed from the antenna test support and sheltered in the staging area. For these reasons, the area has been located in the

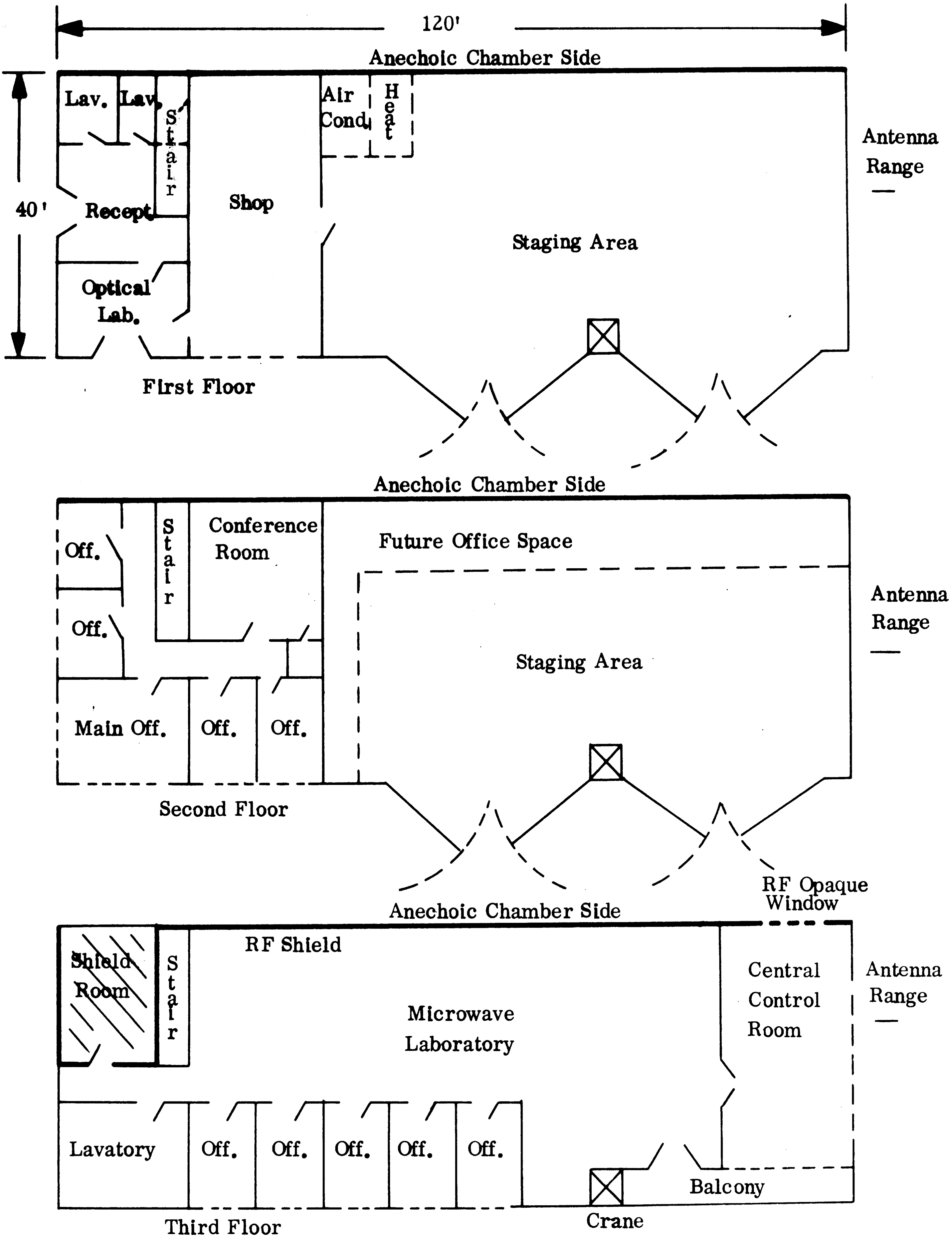


FIG. 21: SERVICE BUILDING FLOOR PLAN

rear of the building to give easy access to both the outdoor range and the anechoic chamber. Since it is desirable to have the surface of the building facing the range as smooth as possible to minimize non-specular reflections, the large doors of the staging area have been placed on the side. This is also convenient since it enables modules, etc. arriving at the facility to be unloaded from trucks and taken into the staging area without disturbing the operation of the outdoor range. Between the double doors is the pedestal for a fixed crane. It can be argued that this is an unnecessary feature of the facility. However, it is obvious that a crane will be needed to transfer modules to and from the flat bed trucks, dollys (for movement of modules in the staging area), and the antenna test support, and it is our experience that the only way to assure the constant availability of a crane is to have it fixed. All of the transfer operations will be carried out within reach of a crane placed as shown.

To satisfy the work requirements of the staging area, the following electrical service is recommended:

220 volt, 60-cycle, three phase, 200 ampere
115 volt, 60-cycle, single phase, 200 ampere
115 volt, 400-cycle, single phase, 100 ampere

24 volt d.c., 300 ampere.

The front of the second floor of the building houses the central offices of the facility and a conference room. For the latter, visual aid equipment may be necessary, and sound proofing materials should be used here and in those offices where it is deemed desirable. Because of the two story staging area, the second floor extends back only 40 feet, but provision could be made for adding some office space above part of the staging area if the additional offices may be required at a later date.

The third floor accommodates the antenna range central control room, microwave laboratory, engineering offices and anechoic chamber shield room. The shield room is a required adjunct of the anechoic chamber and will be used in carrying out RFI and EMI measurements. Being at the front of the building, and therefore adjacent to the receiver end of the anechoic chamber, some recording equipment will be placed here. The room should be lined in the same manner and with the same material as the anechoic chamber. A section of anechoic chamber microwave absorber will be removable from inside the shield room to allow the setting up of equipment for special tests that must be conducted within the anechoic chamber.

The following electrical service will be required in the shield room:

220 volt, 60-cycle, three phase, 100 ampere
115 volt, 60-cycle, single phase, 100 ampere
115 volt, 400-cycle, single phase, 100 ampere
24 volt d.c., 300 ampere.

The electrical inputs will be filtered to prevent outside interference from entering the anechoic chamber. When using the chamber for making antenna pattern measurements in the conventional manner, it should be possible to control the antenna positioner from the shield room. An additional control panel for the heavy duty antenna pedestal should be installed in the room to permit the positioning and control of the pedestal from this area.

Central control of all operations is, however, provided by the room at the back of the building on the third floor. To maximize the effectiveness of this room it is necessary for it to have a wide angle of visibility to allow the operating personnel to see the full length of the outdoor range. The windows at the back should therefore be of the airport control tower configuration, tinted and slanted. The antenna pattern consoles and control facilities for the transmitter building and receiver tower must be placed so that personnel can operate them and view the antenna under test simultaneously. In addition, the central control room has windows overlooking part of the balcony area where modules may be undergoing test or trivial modifications whilst on the antenna support, so that operations here can also be observed, and finally there is a one foot high by two feet long RF-opaque window in the common side of this room and the anechoic chamber to permit visual observation of test operations there. From the central control room, personnel should be able to adjust the transmitting antenna to the proper position and tune the transmitter and receiver, all by remote control. Antenna patterns of modules under test either on the outdoor range or in the anechoic chamber will be recorded here. 115 volt, 60-cycle, 300 ampere electrical service is required, with outlets to facilitate the use of special equipment as the need arises.

To give the control room personnel voice communication to the transmitter building, receiver tower, anechoic chamber and to the operator of the receiving tower prime mover, a communications network is essential. This can take the form of a low frequency (less than 1 Mc) radio net to ensure nearly full time voice capability, but if this method is deemed inappropriate, a public address system could be set up so that personnel not in the vicinity of a telephone can be contacted.

The adjacent microwave laboratory will require the following electrical service to operate various microwave instruments, controls, hand tools, etc.:

220 volt, 60-cycle, three phase, 300 ampere
115 volt, 60-cycle, single phase, 300 ampere
115 volt, 400-cycle, single phase, 100 ampere
24 volt d.c., 300 ampere.

Next to the laboratory are the engineering offices. These are designed to provide some degree of privacy, along with an area suitable for the study of future space antenna problems. The offices should be well lighted, both with natural light and commercial illumination, and, as in the case of the rest of the building, there is the possibility of tinting the windows to minimize heat transfer to the interior.

The balcony on the third floor is an important feature of the building. Below it, and extending the length of the building, is a concrete pad some 40 feet wide connecting to a service road leading to the Campus area. Tracks are embedded in the pad so that modules can be wheeled on their support tower from the antenna range and anechoic chamber to the side of the service building. The essential purpose of the balcony is to provide a work platform convenient to the laboratory from which to make adjustments to the modules without removing them from their support. For major work on the modules, however, it may be desirable to remove them from the antenna support and take them into the staging area; or, alternatively, to merely wheel the support into the anechoic chamber. On the other hand, for relatively minor adjustments to the module components, the provision of such a balcony could be highly desirable. In order to adapt the balcony area to future as well as present space systems, it would be convenient to have the floor capable of variable extension 5 to 10 feet from the side of the building, with a railing at the outside edge to ensure safety of personnel working in the area. Electrical service similar to that in the microwave laboratory is required.

VII OPTICAL FREQUENCY RANGE

7.1 NASA Requirements

The design requirements for the topical frequency range are as follows:

1. Range length: 80 meters.

2. Range diameter: 4 meters, tubular construction (3^o beam divergence).

3. The range should be buried 1 1/2 to 2 meters below the surface of the earth with foundation boxes (concrete) at both ends and a small building constructed over each box.

4. The range should be evacuable to 10^{-4} torr (modification to original specifications made at August 15th meeting).

5. The range should have door openings at both ends.

6. The range should have a double-way track running the full length of the tube with two carriages.

7. For maniupulation of systems to be tested, a Nike-Ajax precision tracking pedestal should be mounted inside the tube at both ends.

8. To supply the internal equipment with power, high voltage low current and low voltage high current, vacuum electrical feeds through the connections should be provided.

9. The range should have port windows (optical flats) and shutters at ends only, for observation and introduction of external sources of radiation.

10. The inner wall of the facility should be light absorbing.

11. The pumpdown time is not critical, but should not exceed four to six hours.

12. The tunnel will be used over the spectrum of 15μ to 2000 Å.

7.2 Desirability of Meeting These Requirements

Optical and infrared equipment that will be tested in the Apollo and future NASA programs will be used in space. The performance of these systems may differ appreciably depending upon whether they are in a normal atmosphere or in space. Testing in a normal atmosphere would subject the energy to diffraction and scattering and to absorption in certain spectral ranges. The size of this range is dictated by the desirability of testing long focal length systems, highly divergent beams (up to almost 3^{o}), and the ability to fold the range many times for low divergent beams such as lasers, without experiencing interference.

Originally NASA had asked that the range be evacuated to 10^{-1} torr.[+] This level would have simulated free space as far as scattering and diffraction of the atmosphere is concerned. It would not, however, have prevented absorption by atmospheric gases and this tends to be a problem for certain portions of the spectral range of interest. At a level of about 10^{-4} torr, a sharp decrease in absorption is experienced, and achievement of this level of evacuation will make the optical range much more useful.

7.3 Siting

It would be desirable to have the optical frequency range as close as possible to other optical laboratory facilities. Many problems, however, preclude the placement of this optical range in the Campus area. It is therefore

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[+] 1 torr = 1 mm of Hg

recommended that one terminus of the range be placed in the service building adjacent to the anechoic chamber, and that the range extend outward from this building towards the road. This places the other terminal point close enough to the road to allow easy personnel and equipment easy access.

Isolation from vibration is one of the most important factors in considering the siting of this range. The large acoustical facility being constructed in the Campus area will probably disturb the optical range wherever it is placed. The vibration caused by movement of the large Apollo mounting towers on the antenna range and in the anechoic chamber may also have an adverse effect on the operation of the optical range. This disturbance, however, should be periodic, so that the use of the optical range can be scheduled to avoid this problem.

The recommended siting of the range in conjunction with the service building substantially reduces the cost of additional service facilities which would otherwise be required if it were in a more remote part of the area. The vibration problem would undoubtedly be present for any location in this area, and the assumption is therefore made that this problem will have to be solved by some means other than distance from the vibration sources.

7.4 Construction

The optical frequency range should be maintained at a constant temperature throughout its length and periphery. Placing it underground at a depth of at least six feet is recommended. The large variation in surface heating of the ground in the Houston area will, however, cause considerable variation in the temperature of the fill above the tunnel. It is therefore recommended that the surface above the tunnel be paved and painted with a light reflecting paint and that at least four inches of foam glass be placed between the paving and the tunnel to reduce the temperature variation.

The tunnel should be built of steel of sufficient thickness to provide the wall strength necessary for an evacuated chamber of this size. Sections of the vessel should be welded together and the welds checked for leaks. The walls on the inside of the tunnel should be ground smooth with the surface to prevent discontinuities. The interior of the tunnel should be painted with Minnesota Mining Optical Black Paint or other flat black paints that remain black over the spectral region 15 μ to 2000 Å.

While less expensive materials, such as concrete, could be used for the walls, most of these would provide out-gassing problems. To avoid the vibration problem it is recommended that the tunnel be mounted on piers and that it be isolated from these piers by a vibration damping material. Where the tunnel enters the building at either end, it should also be isolated from the building structure by vibration dampers.

The terminus for the tunnel in the service building should be a room at least 15x20 feet in lateral dimension and it should have access from the ground level for equipment weighing at least one ton and 6x6 feet in cross sectional area. The room at the end of the tunnel should be shielded electromagnetically and should have an airconditioning system capable of providing the same temperature as that at which the tunnel is maintained by the ground temperature. This airconditioning system should have a dust filtering system and should maintain a positive pressure on the room. This will effectively prevent airborne dust particles from entering the area.

7.5 Associated Equipment

The Nike-Ajax Precision Tracking Pedestals that are to be placed inside the tube at both ends should be mounted on vibration isolation pads to isolate them from vibrations of the tunnel wall. The track running the length of the tunnel should be isolated in a similar fashion with some consideration given to the use of an air mounting system similar to that used for the optical benches.

The length of this tunnel, and the possibility of folding the range effectively, magnifies the problems of vibration in the tunnel. Optical systems in calibration laboratories are capable of working to one second of arc. A vibration with an excursion of approximately 1/10 inch would cause an inaccuracy of one second of arc if the range were operated in folded fashion with ten excursions throughout the length of the range.

Lights in the tunnel should be of the incandescent type to reduce electromagnetic interference. Some means should be provided for personnel to traverse the tunnel. The evacuation equipment to achieve 10^{-4} torr must include both a fore pump and a diffusion pump. Pumps of the type, such as Beach-Ross, 1000 CFM, 50 HP with a Roots-Connersville 100 HP booster, and a Consolidated Vacuum Corporation TMC 4100 diffusion pump would evacuate this chamber within six hours. Faster evacuation would require such large pumping systems that it is not considered feasible.

The air inlet to this chamber should include an arrangement for attaching supplies of other gases than air. The large fore pumps should be located as far from the tunnel as possible and the pumping system should be isolated, vibration-wise, from the tunnel itself. The building at the far terminus of the tunnel need only provide access to the tunnel end. The room need not be more than 15x15 feet in lateral dimension, and should provide access for one-ton equipment 6x6 feet in cross sectional dimension. It should be airconditioned in the same manner as the service building terminus and be shielded electromagnetically. In addition, the building should be isolated from the tunnel by vibration dampers.

7.6 Cost

The optical frequency range is estimated to cost $425,000. This figure is broken down as follows:

Tunnel fabrication and installation	$ 225,000
Evacuation equipment	40,000
Building	50,000
Site preparation; excavation and installation of mounting piers	60,000
Equipment, including modification of Nike-Ajax pedestals, tracks, optical flats, etc.	50,000
TOTAL	$ 425,000

VIII. ESTIMATED COST OF NASA-MSC ANTENNA FACILITY

8.1 Introduction

As explained in Chapter I of this report, it was required that the cost of the proposed antenna facility be within the limits of the FY 64 funds available. The proposed design should result in an operable facility at a cost not exceeding $2.19 million. Recommendations are to be made for future needs beyond this dollar value that will help to make a more complete and versatile installation. An additional budget is available for special equipment required for the facility, and the equipment is discussed in the next chapter.

In estimating the facility costs, seven major items were considered. These have been discussed in some detail in previous chapters and their estimated costs are as follows:

1. Antenna range site work	$ 113,000
2. Transmitter tower and building	50,000
3. 2000 feet of wide gauge railtracks with appropriate foundation	40,000
4. Receiver support pedestal	180,000
5. Anechoic chamber 70x70x120 feet	1,080,000
6. Service facility	250,000
7. Optical range	425,000
TOTAL	$2,138,000

In the following paragraphs, the factors considered in arriving at these figures are briefly discussed.

8.2 Basis of Cost Estimates

8.2.1 Antenna Range Site Work

Surveys, grading and other preparations for paving and drainage	$40,000
Paved antenna range area	38,000

The area amounts to approximately 190,000 square feet and the estimate is for asphalt over a compacted local material base. The surface should be level to within ±1 inch with sloping to the sides to provide for drainage. The paved region will have the dimensions shown in Fig. 8.

The prepared area will be comparable to a golf course fairway and level to within about ±2 inches and have a total width of 1200 feet. The cleared area will be free of brush, trees and buildings but will require no leveling and will have a total width (including above areas) of 2000 feet.

Roads, power, fencing, sewage and paving for transmitter building and transmitter tower.	25,000
Duct or tunnel for power, control and signal cables extending from transmitter building to service building with outlets at the two receiver sites.	10,000

It may be possible to use waterproof type cables and eliminate the need for the tunnel.

TOTAL	$113,000

NOTE: The above figures are based on estimates made by Scientific Atlanta, Inc., (1962) and on information provided by the Lummus Company.

8.2.2 Transmitter Tower and Building

Transmitter tower	\$ 40,000

This is to be a steel tower approximately 75 feet tall capable of supporting both a 12 foot and 6 foot parabolic antenna at a height of 73 feet. The antennas will face the anechoic room and vertical tracks will be provided to allow attachment and positioning of conventional antenna mounts at the desired height. The structure should be sufficiently rigid to operate in winds up to about 35 mph with the antenna axis stable to within $\pm 1/4^{\circ}$, and it should be capable of withstanding winds up to 135 mph in non-operating conditions.

Transmitter building, 15x20 feet.	10,000

This building is to be used for housing transmitter equipment with some place for maintenance work and storage of antennas and spare parts. Equipment, to a large extent, will be controlled remotely and it is not envisioned that personnel will ordinarily occupy the building. A typical floor plan is shown in Fig. 14 . Power required will be 110 V 1 ϕ and 220 V 3 ϕ with 100 ampere capacity, plus any required for heating and airconditioning.

TOTAL	\$ 50,000

8.2.3 Tracks (including foundation)

Wide gauge tracks (9 feet or more)	\$ 40,000

The tracks should be about flush with the prepared foundation, and the latter should be suitable for use as a road for rubber tired vehicles. The cost estimate is based on \$20.per foot and an estimated 2000 feet. The possibility of using rubber tired vehicles for supporting the receiver tower should be considered if safety and stability requirements can be met at a lower cost.

	TOTAL	$40,000

8.2.4 Receiver support tower.

Receiver support tower	$180,000

The tower will be essentially as described by Scientific Atlanta, Inc., (1962) and as sketched in Figs. 15, 16 and 17 except that it will be mounted on a dolly with steel wheels for track, or rubber wheels for a concrete roadway. The dolly will be positioned by an auxiliary tractor. The height of the center of the test vehicle is to be 35 feet. The receiver tower should include provisions for housing a superheterodyne receiver whose size is approximately 2x2x3 feet. The mounting arrangement for supporting test objects on the tower must be sufficiently versatile to hold and rotate any single Apollo module, and any multiple group of modules as indicated in Table I.

	TOTAL	$180,000

8.2.5 Anechoic room (70x70x120 feet)

Building shell, 8400 square feet at $50/sq.ft.		$ 420,000
Shielding, 43400 square feet of interior surface at $3.50/sq.ft.		152,000
Absorber Material		
10564 sq.ft at $16/sq.ft.	$ 169,024	
13936 sq.ft at $11.70/sq.ft	163,051	
18900 sq.ft at $6.40/sq.ft.	120,960	453,000
Doors, 55x55 feet		45,000
Provision for a removable transmitter cubicle		10,000
TOTAL		$1,080,000

NOTE: The shielding and absorber cost estimates should be sufficient to include, in addition to the material, any needed design information, installation and appropriate performance tests after installation.

8.2.6 Service facility (40x120 feet, three floors)

Service facility	$ 250,000

The proposed floor plans for this building are as shown in Fig. 21 and additional details on its construction are contained in Chapter VI.

TOTAL $ 250,000

8.2.7 Optical range (4x80 meters)

Tunnel fabrication and installation	$ 225,000
Evacuation equipment	40,000
Building (at far end)	50,000
Site preparation; excavation and installation of equipment	60,000
Equipment including modification of Nike-Ajax pedestals, tracks, optical flats, etc.	50,000
TOTAL	$ 425,000

The optical range specifications are discussed in Chapter VII.

8.3 Remarks

In some preliminary consideration of the cost of the antenna facility, four additional items had been considered. These were: (i) a 15-ton crane, (ii) a compact airport-type tractor for moving the receiver pedestal or other supports carrying the Apollo modules, (iii) a cherry picker for servicing antennas on the Apollo when on the range or at the service building balcony, and (iv) extra dollys for moving the Apollo into the staging area or elsewhere. These items have been removed from the above budget since it is now understood that they are obtainable from the NASA-MSC central facilities pool.

No high accuracy can be claimed for the cost estimates but the figures are thought to be reasonably close in all cases. We are gratified to find that our estimated total is within the allocation, and no major cutback has been made to arrive at this figure. By removing the four standard equipment items mentioned above and by eliminating one of the two identical receiver pedestals, the cost estimate has been reduced to below the level of available funding.

One of our first recommendations for improving the facility would be the addition of a second receiver pedestal. The second pedestal should be obtainable for perhaps half or two-thirds the cost of the first.

IX. EQUIPMENT

9.1 Introduction

No attempt will be made to present a detailed discussion of the equipment required for the antenna test facility. This was not a formal requirement of the study, but in the first meeting (July 22) with Lummus, NASA and Army Corps of Engineers personnel, it was suggested that equipment should also be considered. An added reason for doing so is that it might be possible to transfer money from one fund to the other if this seemed necessary due to budgetary limitations. However, our cost estimates indicate that an operable facility can be built with available funds and since our brief examination of equipment needs indicate that equipment funds are adequate for initial operation, no recommendation for transfer of funds will be made. It is our understanding that approximately $390, 000 is available for equipment for the antenna facility.

The equipment is grouped into six categories and the rough estimates of cost are as follows:

Special Range Equipment	$32, 000
Receiving equipment for two ranges	85, 520
Transmitting equipment for two ranges	62, 850
Range equipment for 10 Mc and mm freqs.	60, 000
Standard Test Equipment	100, 000
Machine Shop Equipment	50, 000
	$390, 370

Although the NASA-MSC antenna facility is unique in the type of measurement problems expected, the equipment requirements are, for the most part, the same as for any other large range.

9.2 Special Range Equipment

There are, however, a few special items. These will now be described and a rough estimate of their cost given. In previous chapters, the specially designed receiver tower or pedestal has been described. There should be an alternate receiver pedestal available which would be more versatile and more appropriate for testing research devices or single Apollo antennas removed from the module. This pedestal would be special only in that it should be on wheels and should have a 35-foot working height. In addition, it should have a weatherproof cubicle for the superheterodyne receiver. For versatility, an azimuth over elevation over azimuth mount is suggested and one having a capacity of 5000 lbs should be more than adequate. The estimated cost for the pedestal and modifications, with indicators and servo control system, is $ 18,000 .

A second special piece of needed equipment is a mobile field measuring device which should provide a means for sampling the amplitude (and phase, if desired) of the field at any of the three receiving sites. It should be possible to sample the field at heights varying from 25 feet to 45 feet for any of the range frequencies. It should also be possible to take horizontal samples, and it may be feasible to do this by moving the equipment laterally on its own wheels. The vertically moving antenna should be motorized and able to record automatically the antenna position and its signal level on one of the standard recorders. The unit should also have provision for housing a superheterodyne receiver.

The sampling gear is a relatively simple device, and the sampling antennas will be small and lightweight, but the requirement for heights up to 45 feet and sufficient stability for phase measurements will add significantly to the cost. To our knowledge, no equipment is manufactured to accomplish this type of measurement, but a modification of the Antlab, Inc. source positioner and elevator may be used for the purpose. Their model 3714 is designed to move an antenna over a 20-foot vertical aperture. Scientific Atlanta, Inc. also have a source positioner that may be suitable if modified. Their SP 217 transmitter tower and associated positioners provide for a vertical excursion of from 17 inches to 35 feet which, if raised 10 feet or so and put on a movable platform, should be more than adequate. Estimated cost, with positioners, control and modification, is $14,000.

9.3 Standard Range Equipment

In addition to special equipment, it is necessary to have transmitting, receiving and recording equipment for two complete ranges to operate at frequencies extending from 100 Mc to 10 Gc. One set of equipment would be assigned to the outdoor range and the second would be available for pattern work within the anechoic chamber. For use on either range, a contour plotter and an antenna pattern integrator are required, and it is also desirable to have at least one set of pattern test equipment for the frequency bands at 18, 36 and 70 Gc.

RECEIVING AND RECORDING EQUIPMENT

2	Receivers, superheterodyne 20 Mc to 100 Gc with sensitivity ⩾ -95 dbm to 12 Gc and ⩾ -70 dbm to 100 Gc, $8500 each	17,000
2	Sets of mixers for above receiver, 10 Mc to 12 Gc	2,000
2	Recorders, combination polar and rectangular, with optional plots and angle ratios, $7,000 each	14,000
1	Antenna pattern integrator for use with above receiver and recorder	2,400
1	Antenna contour plotter, automatic with digital printout and with choice of the angle and db increments. Includes positioner programmer ($1200) and has provision for punch tape output ($2800) with supplies and accessories	13,000
2	Consoles for mounting receivers, recorders, indicators, positioners, etc. $700 each	1,400
3	Control Systems for positioning special Apollo pedestal (one on pedestal, one in central control room and one in anechoic chamber shield room), $7,200 each	21,600
3	Position indicators for above, $1,400 each	4,200
2	Remote signal source tuning units. Price included in signal source listed later	
2	Positioner control (polarization, height, azimuth elevation) units for transmitter sources, $475 each	950

2	Indicator unit for height and polarization of transmitter, $900 each	1,800
2	Adapter sets - waveguide to coaxial for 600 Mc to 12.4 Gc, $1290 each	2,580
2	Sets of Gain Standard horns, 600 Mc to 12.4 Gc, $2,295 each	4,590
		$85,520

TRANSMITTING EQUIPMENT

1	Polarization positioner* and remote controlled height positioner modified for 12 foot dish and 70 foot height	$8,000
1	Polarization positioner* and remote controlled height positioner for 6 foot dish and 70 foot height	6,000
1	Polarization positioner* for anechoic room	1,860
3	Rotary joints for above, $150 each	450
2	Sets remote-tuned signal sources with outputs of 20 dbm from 50 Mc to 11 Gc, $11,095 each	22,190
1	Antenna reflector, 12 feet in diameter with compatible mounting brackets	2,400
2	Antenna reflector, 6 feet in diameter with compatible mounting brackets (one for outdoor range, one for anechoic room), $1,050 each	2,100
3	Sets log periodic feeds with required modifications — 1 set for 12 foot reflector, 2 sets for 6 foot reflector. The feeds for the 12 foot reflector start from 100 Mc	6,200

*NOTE: The possibility of using variable polarization feeds should be considered as an alternative to a rotating dish.

1	Log periodic array for 100 to 400 Mc for use in anechoic room.	650
	Cables and junction boxes as required	12,000
	Dehydrator and pressurizing equipment for rf cables	1,000
	TOTAL	$62,850

9.4 Range Equipment for 10 Mc and mm Frequencies

Signal generator, antenna and receiver for 10 Mc band	10,000
Antennas, oscillators, and waveguide components for 18, 36 and 70 Gc frequency bands.	50,000
TOTAL	$60,000

9.5 Standard Test Equipment

Some of the major items in this list include:

Complete line of signal generators (2)
Standing wave measuring equipment for all frequency bands (2)
Oscilloscopes
Spectrum analysers
Sweep frequency oscillators
Noise generators
Interference measuring equipment

Cost estimate (minimum)	$100,000

9.6 Machine Shop Equipment

To include small and large lathe, mill, metal shear, roll, brake, saws, welding and soldering equipment

$50,000

9.7 Remarks

It is believed that $390,000 will prove adequate for instrumentation and equipment for initial operation of the antenna facility. It is recommended that acquisition of equipment for the 10 Mc and mm frequency operation be delayed until additional funds are available. These funds ($60,000) should then be added to the standard test equipment fund, since $100,000 seems inadequate for this equipment.

X. SUMMARY RECOMMENDATIONS

To provide an overall picture of the complete facility, the main recommendations about the range, anechoic building, service building and optical range will now be summarized.

(i) The basic decision from which all others follow naturally is that most of the testing will be on full scale modules.

(ii) Pattern measuring capability should extend from 100 Mc to 10 Gc, with single or multiple Apollo modules as test vehicles.

(iii) From field uniformity and vehicle support considerations, all antenna tests should be made with the vehicle in a horizontal position.

(iv) The range will be a combination ground reflection and free space facility, with the first mode covering the lower frequencies, and the second mode the higher.

(v) The separation distances are 1000, 2000 and 2500 feet.

(vi) The variable range separation is provided by a movable receiver (i.e. test vehicle) support tower, with a fixed transmitter tower and building.

(vii) The height of the axis of the test vehicle remains constant at 35 feet. The transmitting antenna is either a 12 or 6 foot diameter reflector, whose height is variable up to 73 feet.

(viii) Certain areas of the ground (see Fig. 8) out to a maximum width of ± 100 feet and a maximum distance of 1670 feet from the transmitter are to be levelled and paved. Lesser restrictions apply to the ground out to a distance of 1000 feet from the range center line, including the region between the end of the paved strip and the 2500 foot receiver position.

(ix) Normal operating conditions of the range are:

(a) 100 to 250 Mc or higher: 1000 foot ground reflection range

(b) 200 to 3000 Mc or higher: 2000 or 2500 foot ground reflection range

(c) 2.9 to 75 Kmc: 2000 or 2500 foot free space range.

See Section 3.3.3 for considerations of the upper frequency limits of the ground reflection ranges.

(x) The receiver support tower will be on wheels and will carry with it a superheterodyne receiver (when necessary) for relaying signals to a distant recorder at audio frequencies.

(xi) The anechoic chamber will provide a 55x55 foot test cubicle for the 2500 foot range to permit pattern measurements with the test antenna in a partially shielded environment free of electromagnetic interference and weather disturbances.

(xii) With the test vehicle on the support tower it will be possible to take antenna patterns at either of the two outdoor sites, or within the anechoic chamber where interference and impedance measurements can also be made, all without any changes in mounting.

(xiii) The anechoic chamber will be 70x70x120 feet with 100db shielding, and designed to have a 30db or better reflectivity at 200 Mc with improving performance above 200 Mc.

(xiv) All RFI, EMI and impedance measurements will usually be carried out in the anechoic chamber. Within the limits imposed by far field restrictions, the chamber should also be excellent for antenna pattern and radar cross section measurements.

(xv) The axis of the chamber is inclined at an angle of about 5^{o} to the axis of the range.

(xvi) The service building is adjacent to the chamber and is a three-story 40x120 foot structure. It accommodates some 9 offices, an optical laboratory, microwave laboratory, machine shop, large staging area for the Apollo vehicle, work balcony, and control rooms for operations on the range and in the anechoic chamber, plus the usual amenities.

(xvii) The optical range is 80 meters long and 4 meters in diameter, capable of being evacuated, and designed to have temperature and vibration-free characteristics which equal or exceed the original specifications.

(xviii) One end of the range will be served from the optical laboratory in the service building and the other by a special building to be constructed nearer the Campus road.

The estimated costs of the facility are given and the total is within the allocated budget. Equipment and instrumentation requirements are also examined. Major items are listed and here again the estimated costs are in line with available funds.

Recommendations for improving and extending the future capability of the antenna test facility are presented in Section 5.7.

XI ACKNOWLEDGEMENTS

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Visits and conversations with representatives of organizations operating ranges which are in some regard comparable to the ones proposed here have helped considerably in solidifying our ideas. On the radar side we are grateful to Messrs. L. Riccardi and L. Niro of Lincoln Laboratory and Mr. A. Cohen of the Electronic Space Structures Corporation for details of their respective ground reflection ranges; and in connection with the optical test range our thanks are due to Mr. F. Hall of ITT Laboratories, Mr. C. Evans of the Naval Ordnance Test Station at Inyokern, Calif., Mr. W. Blackmon of the 2802nd Inertial Guidance and Calibration Group, Newark, Ohio, and Messrs. I. Goodner, J. Casey and S. Hallamore of Aerojet-General Corporation, Azusa, California.

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APPENDIX A

GROUND REFLECTION RANGES IN OPERATION

At the present time there are at least three ground reflection ranges in operation. These are located at the Bell Telephone Laboratories (Christie, 1958), Whippany, New Jersey; Lincoln Laboratory (Cohen and Maltese, 1961), Lexington, Massachusetts; and at the Electronic Space Structures Corporation, Concord, Massachusetts.

Lincoln Laboratory Antenna Range

During a recent visit to the Lincoln Laboratory Antenna Range it was learned that the range has been in operation for approximately three years, with no deteriorating effects noted. The range is electrically checked daily to ensure that it is operating satisfactorily. These electrical checks are made in the form of height-gain measurements obtained by erecting, at the receiver site, a vertical pole to which is attached a receiving antenna. The height of this antenna is varied and the power level received is plotted as a function of height. The results of the height-gain measurements made during the past three years have indicated that there has been no electrical degradation to the range. It was also learned that these measurements have been recorded under various operating conditions, i.e. both with and without water or snow on the ground plane as well as for long and short grass conditions, and all of the measurements have indicated little or no variations in the electrical characteristics of the antenna range.

The Lincoln antenna facility has two basic ranges, a short range (740 feet long by 200 feet wide) which operates from 250 to 2000 Mc, and a long range (2000 feet long by 200 feet wide) which operates from 2 to 16 Gc. No height gain measurement have been recorded for the short range; however, patterns that have been recorded on this range have indicated that it is electrically satisfactory.

It was learned that although the long range is designed to operate at frequencies up to 16 Gc it has been used at frequencies up to 100 Gc with satisfactory results. It was pointed out that when the range is operated at frequencies in the Ka band and above, the ground plane is no longer used, but instead the range is used as a free space range. This is done because the transmitting antenna beam width is too narrow to obtain the required specular reflections from the ground plane surface for operation as a ground reflection range.

A pattern comparison has been made of antennas whose patterns have been recorded both on free space and ground reflection ranges. The comparison shows no change in the major lobe characteristics. However, in the side lobe structure minor variations were noted, but were not considered critical.

The effects of varying polarization have also been investigated on the Lincoln range. This investigation was carried out at X-band by obtaining height-gain measurements for vertical, 45°, and horizontal polarizations. The maximum deviation between these three curves was 0.3db, which was regarded as acceptable.

The two ground reflection ranges are oriented at right angles to each other with the short range receiving site located on top of the receiver building and the long range receiver sites located on the ground level inside microwave absorber cubicles. Through the use of the test cubicles it is found that specular reflection and external RF interference is minimized, thus improving the accuracy of the antenna measurements made in the cubicles. However, it was pointed out that originally specular reflections from metallic rails located at the front of the cubicles caused unwanted reflections in the test cubicles. Through the use of microwave absorber shields it was possible to reduce these reflections from a reference -27db level before, to -42db after the absorber shields were installed.

The original ground plane surface had been prepared to be level to within ± 1 inch. During the past three years there has been some settling of the range which was apparent to the eye. However, this settling has not caused any serious change in the electrical characteristics of the antenna range.

It was noted that the ground 150 feet on either side of the ground plane surface had been cleared of brush and trees. Lincoln personnel pointed out that the clearing had been done to reduce sources of reflection to a minimum. The receiver building has been canted 3^o to the straight line path from the transmitter to receiver to minimize the back wall reflections.

Electronic Space Structures Corporation

During a recent discussion with Mr. Albert Cohen of the Electronic Space Structures Corporation (ESSC) it was learned that they are operating a ground reflection range in the S- through Ka-bands. Mr. Cohen pointed out that the ground tolerance of their range was ± 4 inches as compared to the ± 1 inch for the Lincoln range. This relaxation in tolerance was found to be acceptable because of the small grazing angles (less than 1^{o}) which the incident and reflected wave make with the ground. Their lower frequency limit is dictated by the maximum height to which they are able to raise their transmitting antenna. However, if the transmitting antenna could be raised further, Mr. Cohen could see no reason for not using the range at lower frequencies. A further point of interest is the fact that ESSC advocates the use of ground reflection ranges at all frequencies since in this configuration (of an antenna range) the ground reflection is under the control of the antenna range user. He further stressed the fact that they have been able to achieve much flatter phase fronts across their test apertures than they were able to on normal free space ranges.

ESSC uses their range for making both boresight and backscattering measurements as well as for antenna pattern measurements. Mr. Cohen noted that their boresight measurements are made to an accuracy of ± 0.02 milliradians and their backscattering measurements have a 60 - 70db dynamic range.

The basic design of the ESSC range is similar to the Lincoln range. It was pointed out that the test cubicles were of considerable value at the higher frequencies to minimize external RF and weather disturbances.

APPENDIX B

VISITS TO OPTICAL FREQUENCY RANGES

On August 6, one of the authors (D. J. S.) visited the Air Force 2802nd Inertial Guidance and Calibration Group, Heath Annex, Newark, Ohio. The Heath facility has been established to serve as a standards and calibration laboratory for the Air Force and other government agencies and contractors.

The laboratory is divided into four general functions:

1. Mechanical-Optical Measurements
2. Image Analysis
3. Radiometry
4. Testing of Components .

Mechanical-Optical Measurements are concerned with alignment, position accuracy, motion rates, response timing, distance, radii of curvature, configuration accuracy, flatness, refractive index, and properties of materials.

Image Analysis includes a combination of mechanical and radiometric measurement techniques applied in determining image quality.

Radiometry measurements are made of the radiation and radiation modifying characteristics of materials. The primary reference standard for this type of measurement is a calibrated black-body. Auxiliary standards are calibrated materials, surfaces, filters, and special radiation sources.

The Heath facility makes the bulk of their tests with a collimator on an optical bench. They have a 16x16 foot tunnel 100 feet long that can be used, but they expect that it will only be necessary for measuring the accuracy of tracking systems and some radiometry measurements. The optical bench is situated to allow use of the tunnel by mounting the test items on the bench.

The whole area is maintained as an ultra-clean facility. The temperature is maintained to within ± 0.1°. The entire facility is mounted on a deep slab of concrete originally designed for mounting a several-hundred ton press. Even so, critical equipment is mounted on vibration isolation pads.

The laboratory design and selection of equipment were made by the Aerojet-General Corporation, Azusa, California.

The optical bench and image analyzer is a black granite slab type, with air suspended nodal slide and an image analyzer with an analog plotter for recording aberrations of optical receivers up to 25 inches in diameter. The vertical and horizontal displacement of the nodal slide is accurate to 10^{-4} inches, and the rotation is accurate to 1/2 second of arc about the vertical axis. The over-all alignment accuracy is one second of arc and the primary mirror is flat to 1/10 of a wavelength of light.

This bench (16 feet long) is capable of plotting the following parameters: astigmatism, radial and tangential distortion, focal lengths, plane of best definition, blur circle evaluation, image density distribution. Typical tests are Foucault knife edge and Ronchi grating.

The Infrared Detector Tester console is capable of testing (cooled or uncooled) lead sulfide (PbS), lead selenide (PbSe), lead telluride (PbTe), and gold-doped germanium (AuGe), etc., for the following parameters: noise equivalent power (NEP), responsivity, detectivity, spectral response, time constants, parameter linearity, etc.

The spectrophotometer is capable of determining the spectral response of infrared detectors, spectral transmission of broadband pass and narrow band pass filters, spectral emittance of radiant sources (black bodies) from 1μ to $40\,\mu$ with an accuracy of $\pm .015\,\mu$ to $\pm .060\,\mu$, and reproducibility (.005 to .050).

The types of detectors that can be tested at the laboratory are:

Photoconductive
Photovoltaic
Photoelectromagnetic (PEM)
Pyroelectric
Thermoelectric
Thermister
Thermocouples
Bolometers .

A typical list of detectors falling in the above catagories are:

Lead Sulfide (PbS)
Lead Selenide (PbSe)
Lead Telluride (PbTe)
Indium Antimonide (InSb)
Gold-doped Germanium (AuGe)
Indium Arsenide (InAs)
Germanium Mercury (GeHg)
Zinc Germanium ([illegible]
Cadmium Sulfide (CdS) .

Some of the specific types of measurements which can be made on this test set are:

Spectral Response
Time Constant
Noise Spectrum
Noise Equivalent Power (NEP)
Responsivity
Detectivity
Parameter Linearity
Sensitivity Contour .

On August 21, 1963, a visit was made to the Astrionics Division of the Aerojet-General Corporation, Azusa, California. Aerojet has about ten different optical ranges in the Azusa facility. These are all located in the basement of the laboratory-office building of the Astrionics Division. The ranges are rectangular rooms generally 60 to 100 feet in length. Temperature and humidity are controlled by the building's airconditioning system.

The biggest problem with all of their ranges is their susceptibility to vibration. The airconditioning compressor, which is located more than 100 feet away from the tunnels, has to be shut down for many of the critical measurements. Another serious problem is electromagnetic interference with the test instruments. Aerojet personnel indicated that they felt it was absolutely necessary to provide electromagnetic shielding for a range.

Aerojet personnel also stated that the track through the range should be extremely stable. They suggested that the techniques used for the supersonic track at Holloman Air Force Base might be used in the NASA tunnel. This track maintains a two-second accuracy over its length. They also suggested the use of an air-supported table, such as is made by Barry Controls, for the track mounting.

Aerojet has one small evacuated chamber, 16 feet in length, in which they perform optical measurements. They could not, however, provide any assistance on the evacuation equipment for the large NASA tunnel.

Aerojet had helped design the Air Force Heath facility.

A conversation was held with Carroll Evans, Naval Ordnance Test Station, Inyokern, California. Mr. Evans said that NOTS used an old cable tunnel three feet under an asphalt surface for optical and infrared tests. The tunnel is about four feet in diameter. He indicated that they had severe problems with air turbulence in the tunnel. The asphalt surface heated the ground above the tunnel, causing large temperature variations throughout the tunnel. This tunnel was not satisfactory for most of the testing that they required.

Mr. Freeman Hall of ITT Laboratories, San Fernando, California, was contacted in reference to an optical range built recently. Mr. Hall indicated that this tunnel had proven very satisfactory for testing guidance, tracking and radiometry systems. The tunnel is six feet in diameter, 100 feet long and buried six feet under the floor of a laboratory building. The location under the floor of an airconditioned building allows them to maintain the temperature to within $\pm 0.1^\circ C$. This adequately prevents air turbulence. The walls of the tunnel are concrete. He indicated that the total cost of the tunnel was about

$40,000. He pointed out two problems: (i) that access to the ends of the tunnel was not provided for large, heavy equipment, and (ii) that the tunnel was too small to allow personnel to walk through without discomfort.