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NRL Report No. R-1300
Data on Wave Propagation

REPORT NO. R-1300

DATE 20 August 1936

SUBJECT

Data on Wave Propagation

(10 kilocycles to 60 megacycles)



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NAVAL RESEARCH LABORATORY

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BuEng.Prob. W5-4

NAVY DEPARTMENT
BUREAU OF ENGINEERING

Data on Wave Propagation
(10 kilocycles to 60 megacycles)

NAVAL RESEARCH LABORATORY
ANACOSTIA STATION
WASHINGTON, D. C.

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Date: August 1935 - August 1936.
Prepared by: R. S. Baldwin
R. S. Baldwin, Assistant Physicist
L. C. Young
L. C. Young, Radio Engineer
Reviewed by: A. Hoyt Taylor
A. Hoyt Taylor, Prin. Physicist
Superintendent, Radio Division
Approved by: H. M. Cooley
H. M. Cooley, Captain, U.S.N.
Director
Distribution: BuEng (5)

LP

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AUTHORIZATION

1. This problem was authorized by the Bureau of Engineering in reference (a). Other correspondence pertinent to the subject is given in references (b) to (d).

- Reference: (a) BuEng let.A6-2(F)(7-8-W8) of 10 July 1935.
(b) BuEng let.A6-2(F)(9-24-W8) of 3 Oct.1930.
(c) NRL let.A6-2(A4206) of 17 Oct.1930 with enclosed "Guide to Naval Radio Communications".
(d) NRL Report No. H-1259.

STATEMENT OF PROBLEM

2. The object of this problem was to collate available theoretical and observational data of the frequency range 10 kilocycles to 60 megacycles and above for service use.

GENERAL FACTS

3. The factors concerned with radio communications from one point to another may be divided into two classes; those susceptible of variation by the transmitting operator and those conditions concerned with the propagation of radio waves through space which must be accepted as they exist at the time of the transmission.

4. The possible number of variations which may occur in these conditions is so great that deviations of 100% from any general rules set up from experience are not uncommon.

5. Hence it must constantly be remembered that whatever may be hereinafter set forth constitutes only a general guide to be followed, not a set of rules which will invariably yield the desired result.

6. It will be assumed in this report that optimum radio reception conditions always exist; that is, that the field strength of the radio wave is of sufficient intensity at the receiving station to give the necessary audio output considering the particular type of radio receiver available.

7. Generally, the factors variable at the will of the operator are but two: the frequency of the transmission and the radiated power. Frequencies useful for radio communications are classified in the following groups: long waves or low frequency to include the range from 15 to 100 kilocycles (wave length λ 20,000 to 3,000 meters respectively); medium waves or medium frequency to include the range from 100 to 1,500 kilocycles (λ 3,000 to 200 meters respectively); intermediate waves or medium high frequency to include the range 1,500 to 6,000 kilocycles (λ 200 to 50 meters respectively); short waves or high frequency to include the range 6,000 to 30,000 kilocycles (λ 50 to 10 meters respectively) and very short or ultra short waves or super or ultra frequency to include all greater than 30,000 kilocycles (λ less than 10 meters).

8. The classification is an arbitrary one adopted by an international radio committee in 1929 for greater clarity or uniformity in technical literature and attempts to group waves of similar properties. Opinions as to the line of demarcation between groups are widely different. For the sake of some simplification in treatment, this report will consider the long and medium waves as one group and the intermediate and short waves as one group.

9. Radiated power involves the power of the transmitter itself, the efficiency of the means employed to transfer the power of the transmitter to the antenna and the efficiency and type of the antenna itself, including the associated ground circuit. Any or all of these factors may influence greatly the desired radio contact, but again it will be necessary to assume that the maximum possible radiated power is being propagated with the available equipment just as it was assumed that the receiving equipment was used with maximum possible efficiency.

10. The most important factors beyond control of the operator are: the distance to be covered by the transmission; the direction or bearing of the path along which the radio waves travel in passing from the transmitting point to the receiving point, this path to be hereafter referred to as the Great Circle Path; the "height" of the Kennelly-Heaviside Layer; and the presence, if such there be, of magnetic and electric storms.

11. The phenomena of radio propagation are so intimately inter-related that it is not possible to distinguish clearly the effect due to a change in one of the factors by itself. This fact must be kept in mind throughout this report. The broader, more useful view of a given phase of the subject may be included in several sections even though the general facts may be grouped for purposes of classification in one section.

SPECIFIC SUBJECTS

Frequency and Distance

12. Plates 1 and 2 are general curves of the possible distances covered by the indicated frequencies for the conditions noted respectively on each plate. These particular curves were drawn for an assumed radiated power of 5 kilowatts. This was done because they indicate coverage up to distances equal to half way around the world, which is approximately 10,800 nautical miles. All other conditions remaining the same, if the assumed radiated power is reduced, then the ICW signal would be reduced by the power ratio, and the CW signal reduced by the square root of the power ratio.

13. The cross hatching of the curves indicates the time of year when the frequencies should serve for the various distances. The dotted portions, "experimental variations", indicate possibilities provided other factors concerned in the propagation are favorable. The boundaries of the various areas are only guides as to what may be expected. The curves, of necessity, represent a composite picture of what has been obtained on the average. Under favorable conditions or over water transmission, however, (especially in the 2,000 to 6,000

kilocycle band) the daytime ranges may be extended to a considerable distance beyond those shown by the chart. No systematic investigation has been conducted for a universal set of operating conditions. Each investigator, who has published results on the ranges attained with various frequencies, has been concerned with his own particular problem, hence it is extremely difficult to present a picture which might be called accurate for all the various factors which may be encountered in the propagation of radio waves.

14. Radio propagation of the frequencies between 15 and 1500 kilocycles is partly due to electromagnetic waves traveling along the ground, called surface waves, and partly to sky waves. Between 1,500 and 30,000 kilocycles the waves proceed largely through space either between the ground and the Kennelly-Heaviside Layer or by reflection, refraction or both from the Kennelly-Heaviside Layer and these are called sky waves. Contact may be obtained by one type or the other or by a combination of the two. In this range, particularly the lower portion of it, the term sky waves is not wholly accurate but most nearly fits the characteristics of the propagation.

15. Above 30,000 kilocycles, the propagation may be said to be by virtue of space waves, with the ranges limited principally to those distances for which a direct optical path exists between the transmitter and receiver. In the case of these very short waves, the optical range in nautical miles, corrected for refraction is expressed by the equation,

$$d = 1.064 (\sqrt{h_1} + \sqrt{h_2})$$

where

d = distance in nautical miles,

h_1 = height of transmitting antenna in feet, and

h_2 = height of receiving antenna in feet.

In some locations, and under favorable conditions, ranges up to four or five times the optical distance may be obtained, but can not be considered as normal reliable communication circuits. Practically, if there are obstacles which are large compared to the wave length of the radiation between the transmitter and receiver, the range may be less than that given by the above formula. On the other hand, if the radiation beam is not too narrow, there may be reflection from an object to one side of the direct path, and the resulting range may be greater than that given by the formula.

16. The use of directional antennas at the transmitter and receiver may increase the reliable range to 25% beyond the optical distance, but a greater advantage is the allowable reduction in transmitter power for a given distance.

17. For frequencies above 300 megacycles, difficulty is encountered in obtaining more than a few watts of antenna power due to tube and circuit limitations. However, these wave lengths are sufficiently small so that a highly directive antenna occupies a small space. Only a few watts of energy are then required to communicate up to the optical distance.

26. For the low and medium frequency range and the distances usually covered by them, the direction is not so important. But for the medium high and high frequency range, the direction might be termed all important. It is with these frequencies that long range communication is obtained, and the conditions or status of the Kennelly-Heaviside Layer along the path may be quite different.

27. When both the short and long path between the transmitting and receiving points are considered, it will be found that the daylight-darkness distribution over the path may have any one of the following possibilities; (a) all daylight, (b) all darkness, (c) daylight to darkness, (d) darkness to daylight, (e) daylight to darkness to daylight, (f) darkness to daylight to darkness. Moreover, one station may be experiencing a different season of the year from that of the other station.

28. These two factors, daylight-darkness distribution and season of the year, determine that state or degree of ionization existing in the Kennelly-Heaviside Layer, and it is this degree of ionization which may affect so greatly the frequencies which must be used to establish and maintain radio contact.

29. Experience has shown that often-times a transmitting station may make contact by the long path instead of the short path. On the other hand, if the receiving station becomes the transmitting station it may be found that contact may be made over either the long or the short path. In addition, one station may be totally unable to act as the transmitting station, not because of any particular peculiarity at the station itself, but simply because of the layer conditions along the path. Moreover, there is plenty of evidence of the reception of signals which have traveled past the reception point then continuing on around the world and received after completing the circuit. This is the phenomenon sometimes called "multiple signals" or "echoes", being a "forward" or "backward echo" according as the direction of departure was originally by the short or long path.

30. Besides the effect of the Kennelly-Heaviside Layer conditions along the path, there are other factors which enter into the propagation such as the presence of magnetic storms or local electric storms and the distribution of land and water. When the path passes close to either of the magnetic polar regions, satisfactory communication is often difficult, and the period of time for which any given frequency may be used is considerably reduced. If the transmission is largely over water, then the attenuation of energy is less than over land, heavily forested areas in particular causing increased absorption or dispersion of the wave energy.

31. Experimental results particularly in the 2 to 6 megacycle band indicate that usually a mile of overland transmission results in several decibels (9 decibels on 4.5 megacycles) less regional field strength than for one mile over water. Also, in the case of ship to shore transmission moving either ship or shore station so that it is one mile back from the coast line increases the attenuation some 8 decibels.

32. From the accumulated data in the medium high and high frequency range, it is evident that, for a given distance and radiated power, it is desirable to use a higher frequency on a N-S transmission circuit

than on an E-W circuit for a given time of day or night, which, in general, results in higher efficiency for N-S circuits.

33. For a given distance, the frequency must be changed more often throughout the 24 hour period to maintain communication on an E-W circuit than on a N-S circuit, provided that the N-S path does not traverse a magnetic polar region. If the N-S path does traverse such a region, then it may be necessary to change the frequency more often on the N-S rather than on the E-W circuit, although, even by attempting frequent changes, the maintenance of communication will be very uncertain, and it would be far more expedient to relay the message by one or more stations so that the relayed path does not pass through the magnetic polar regions. On a N-S circuit the greater differences exist, of course, between the summer and winter seasons in a given hemisphere. The conditions during the spring and autumn seasons are similar.

34. It is worth repeating that the direction and extent of the Great Circle Path and season of the year determine the daylight-darkness distribution over the radio path and consequently the Kennelly-Heaviside Layer conditions encountered.

Kennelly-Heaviside Layer

35. To account for the phenomena of the transmission of radio waves over long distances, Heaviside and Kennelly independently postulated the existence of a conducting atmosphere above the surface of the earth.

36. Subsequent investigation showed that the idea was correct and that the existence of the layer is brought about by radiation of one type or another from the sun. Due to the effect of the earth's magnetic field, ionization is also effected in that portion of the layer not directly illuminated by the sun.

37. It is known that the lower boundary of the layer is fairly well defined and that the ionization or electron density increases with altitude to a series of maxima and then falls off as the height is further increased. It is customary to speak of "the layer", as though there were but a single region and for purposes of explanation of radio waves this concept is sometimes adequate. Experimental work has shown that there are several layers which may be effective in influencing the propagation of the wave. These layers have been called the E, F₁ and F₂ layers, the F₁ and F₂ layers apparently merging at night into one, called the F layer. A recent published summary on the range of the virtual heights of these layers has given for the E layer a height of from 59 - 65 nautical miles, for the F₁ layer a height of from 97 - 130 nautical miles, for the F₂ layer a height of from 151 - up nautical miles, and for the F layer a height of from 129 - up nautical miles.

38. Although these heights may seem rather large, relatively they are quite small when compared to the size of the earth and the ranges which may be obtained on various frequencies.

39. The virtual heights and the electron density show marked diurnal and lesser seasonal changes, the layer being lower and the electron

density greater during a strong sunspot cycle and in the daytime and in summer than at night and in winter respectively.

40. The radio wave has a greater velocity in the region of greater electron density and since this region is on the side of the layer, as a whole, away from the earth, the effect on the wave is to tip the wave front forward and hence bend the wave back to the earth.

41. The exact path of the wave depends on the frequency, the electron density and the angle of incidence of the wave on the layer. If the angle of incidence is less than a certain "critical angle" for a given frequency, the wave passes through the layer and does not return to the earth. For values of the angle of incidence greater than this "critical angle", however, the wave will eventually be bent back to the earth. This phenomenon of the return of the wave to the earth from the layer, reflection from the earth to the layer and subsequent return to the earth may occur only once, a few times or many times (15 - 20 for great distances); the exact number of times depending upon such variables as the frequency and the original angle of incidence upon the layer.

42. For the medium high and high frequency range, as a result of the various factors previously mentioned, the question of whether communication may be maintained at a given time of day, season and for a given frequency has as many possible answers as one may care to include between the terms "excellent reception" and "complete silence".

"Skip Distance" and "Dead Spots"

43. As the distance from the transmitter increases, the attenuation of the "ground wave" increases fairly rapidly with increase in frequency. Beyond this region of "ground wave" reception, there is virtually no reception until the point is reached at which the sky wave first returns to the earth. It is this intervening distance which is called the "skip distance". The magnitude of this depends upon the frequency, the layer height, and the original angle of incidence of the wave on the layer. In general, the skip distance increases with increased frequency. Since the radiation from the antenna is not the ray assumed for explanatory simplicity but a cone of energy, the zone of reception after the first skip distance may be large. Also in case of transmission over water, the attenuation of the ground wave may be so small that in the case of the medium high frequency range, ships may find an absence of the first skip zone. In the case of high power high frequency radiation, the first zone may be filled by scattered reflections. As the distance is still further increased, one may pass from the first reception zone of the sky wave into another or "second" skip distance zone, and so on alternately depending on the original conditions of propagation. Usually the term skip distance is considered as applying to the first silent zone, but there is no inherent reason why there may not be a number of them, if the frequency is near the critical frequency.

44. In addition, there may be silent zones at irregular distances and of irregular shapes due to two possible causes. At distances normally within ground wave reception from the transmitter, there may exist a

reflected sky wave of such magnitude and phase as to annul the ground wave either partially, sometimes giving slow fading and sometimes rapid fading, or completely. "Dead Spots", so caused, have limited the service areas of broadcasting stations in a number of instances.

45. The second cause is the action or effect of the earth's magnetic field on the sky wave, which is split into two components each traveling with slightly different velocities along slightly different paths. The two components may both be returned to the earth at the same point but be of such phase as to cancel one another similarly to the case of the ground and sky wave combination. Only a very slight change in the Kennelly-Heaviside Layer conditions or the frequency may be sufficient to change the "dead spot" into one of good reception. On the other hand, the condition of poor or no reception may persist for several hours.

Sunspots, Magnetic and Electrical Disturbances

46. Since the degree of ionization or electron density in the Kennelly-Heaviside Layer is affected by the sun, disturbances on the sun cause changes in the layer conditions.

47. Plate 3 shows the yearly averages of great solar disturbances, which apparently pass through maxima at intervals of slightly more than 11 years. During these periods of maximum disturbance it has been found that, for a given distance and time of day or season of the year, it is necessary to use a higher frequency than during a period of minimum disturbance.

48. Plate 4 shows the relative increase for daytime and Plate 5 for nighttime. Attention should be drawn to the fact that, for a given distance, time of day or night and period of a sunspot cycle, the upper and lower frequency limits of both Plates 4 and 5 differ by an amount approximately equal to the lower limit. Sufficient data is lacking for distances greater than 6,500 nautical miles so that the dotted portion of the curves indicates that they have been extrapolated on the basis of general knowledge of frequencies which may be used for distances greater than 6,500 miles, rather than on specific data taken during the periods of maximum and minimum sunspot activity. The portion of each plate relating to weak sunspot period was for the period 1933-34 and the strong period is for the time 1927-29.

49. Plate 3 shows that another maximum is being approached, culminating perhaps sometime between 1938 and 1940, and present day experience on the use of these frequencies would indicate that the number of sunspots at the maximum will be even higher than during the 1927-29 period.

50. There is also a correlation between reception conditions and the day to day variations in the sunspot activity, but the effect is not so noticeable as the longer period variation. In either case, the effect of the disturbance is to increase the electron density effectively lowering the layer and hence requiring a higher frequency to maintain communication.

51. On the low frequencies both during and a few days after magnetic storms, the daytime field strength is found to be increased with a less pronounced drop during sunset and a night field somewhat below the non-storm period average. On the higher frequencies, the effect of magnetic storms may be so severe as to render communication impossible during the storm and result in low field strengths for perhaps a week or more afterwards. This is particularly true if the Great Circle Path passes through either of the magnetic polar regions, for which condition, the disturbance may be effective for a period twice as long as for those paths which do not pass through these regions. Magnetic disturbances lower the maximum usable frequency and increase the absorption along the path. The north magnetic pole is located approximately at 96° W 71° N and the south magnetic pole at approximately 156° E 73° S. Recent experience has shown that about each pole there are two regions in which the magnetic storms are of such intensity as to make the regions "dead" zones and "disturbed" zones as regards radio circuits whose paths pass through either of these zones. The so-called "dead" zone has a radius of about 900 nautical miles and the "disturbed" zone a radius of about 1700 nautical miles.

52. Natural electrical disturbances, such as thunderstorms, play their role more particularly at the end of the transmission than during the passage of the wave through space. Although the energy of the wave normally reaching the receiving point might be sufficient for good reception, the presence of a local electrical storm may so decrease the ratio of signal to "noise" or "static" level as to make intelligible reception impossible. Except by using directive receiving antennas and highly selective receivers, nothing can be done about it. Relatively, the static level is greatest at the lowest frequencies and in the tropical regions than elsewhere. At the low frequencies in the northern latitude the static intensity is greater at night and in summer. At moderate frequencies, however, static of relatively distant origin may be transmitted with little attenuation and the level at night be equal to or greater than the daytime intensity, the daytime static being usually of local origin and troublesome because of the poor propagation of the moderate frequency carrier wave during the daytime. On the high frequencies, the static is more of a localized character and whatever long distance static may exist usually shows diurnal and seasonal variations in intensity similar to long distance short wave signals of the same frequency.

Polarization

53. For the low frequency range, the received waves are usually plane polarized vertically with the plane of polarization remaining approximately constant except for slight variations during the sunrise and sunset periods, the magnitude of the variation depending upon the distance between transmitter and receiver.

54. In the medium frequency range, the received waves are usually circularly polarized with a time variation in the plane of polarization.

55. For the high frequency range, the received waves are usually elliptically polarized with a more rapid variation of the plane of polarization. Moreover the state of polarization at considerable distances from the transmitter appears to be independent of the original state of polarization at the transmitting antenna.

Direction Finding

56. In general, ordinary loop direction finders give good bearings (on signals of sufficient strength) at any frequency, under such conditions that only a normally polarized (i.e. electric vector in a vertical plane) wave is received. Close to the transmitter the ground wave or normally polarized direct ray gives such conditions up to the distance at which a reflected wave component may become appreciable.

57. Loop collectors operating in vertical planes show 90° errors when the signal polarization is rotated 90° from normal. Such a rotation may occur in reflected waves and cause errors up to this value, but usually much less.

58. Frequencies from the lowest to about 500 kilocycles usually permit good direction finding during daylight at any distance showing adequate signal. At sunset and sunrise periods, marked directional variations may occur and the night period may show less distinct effects of a similar nature. It is occasionally possible to show sharp directional observations which may vary 30 or more degrees in a few seconds, but they are usually (especially at the higher frequencies) accompanied by balance disturbances resulting in broad minima. These effects may be so rapid as to defy human skill in following them.

59. As frequencies are increased above 500 kilocycles, these sky wave errors creep in during daylight hours as well as at night, since the effective range of the ground wave is decreasing as the frequency increases. The broadening of the minimum is more common at higher frequencies than the displacement of sharp minima.

60. From time to time normal conditions suddenly appear during periods of this so-called "night effect", so that it is often possible to obtain reasonably accurate bearings during extended periods of this sort. When conditions permit several consistent bearings to be taken, each reasonably sharp and with normal balance setting for the azimuth observed, the average of these bearings is usually quite accurate.

61. The lower frequencies usually permit daylight bearings accurate to 1 or 2 degrees. This assumes well calibrated equipment and signal strength for minima not over 5° wide at distances which may range as high as 2,000 miles for the lowest frequencies and as low as 50 to 100 miles at 375 kilocycles. Under conditions of serious night errors, accuracy may be affected at from 100 to 200 miles on low frequencies to 25 miles at intermediate frequencies.

62. At the higher frequencies, the ordinary loop is accurate at distances within the shortest radius at which an appreciable sky wave

may appear. Beyond this point no consistent performance may be expected, although often it may be possible to take occasional bearings with reasonable accuracy. Under these conditions, the most accurate results may be had from use of the Adcock type of collector, employing spaced opposed vertical doublets, carefully balanced, or spaced opposed vertical antennas. This type excludes horizontally polarized components.

63. Such equipment gives consistent bearings on a very large percentage of received signals, and with plenty of signal should generally be within 5° . Scattered reflections from beam high powered stations may give erroneous bearings, as the great circle signal may be weaker than the reflected signal, which may have quite a different Great Circle Path. Stations at or near the antipodes will give bad bearings due to the fact that almost any path is a Great Circle Path. The particular path over which the wave will travel will depend upon the frequency and time of day. As the time of day changes it will generally be found that the bearing will constantly shift indicating that the wave is arriving over a different Great Circle Path.

64. The Adcock type direction finder has been successfully used up to 20 or 30 megacycles in shore stations with carefully selected sites. Such equipment greatly reduces the errors due to downcoming waves of odd polarization from aircraft, flying at right angles to the line of bearing.

65. Above 30 megacycles, most transmission is directed and is mostly effective over optical paths. The same type of directive array used for transmission is useful for reception with the same degree of sharpness, and the resulting directive gain.

66. Shipboard installations, at low frequencies, give results substantially equal to shore stations when well located, compensated, and calibrated, the only important additional error being that in the determination of the ship's course. This may add from 1 to 5° to the possible errors, depending upon the type of ship, equipment, and the weather.

67. Above 500 kilocycles, the difficulties of operating direction finders aboard ship increase very rapidly, owing to the tendencies of rigging or hull structures to resonate with the received frequency. Efforts are being made to solve the problem with the Adcock direction finder.

Illustrative Examples

68. The following examples are given as representing possible problems in radio communication and the principal features of each will be considered in commentary form. As has been pointed out previously, the frequency suggested for the given conditions can not be considered as a "sure-fire" proposition but is the probable frequency for obtaining the desired radio contact. If this suggested frequency is not close to a Navy assigned frequency, then the only recourse is to choose that Navy frequency which comes the closest to the desired one. Furthermore, it may happen that the available transmitter power

is insufficient to give contact, but this does not alter the reasons which must be applied to the original assumed conditions.

69. In all the examples, it will be assumed that the ship located at the various positions desires to transmit at 0600, 1200, and 2000 local time or for the equivalent Greenwich Mean Times for the given position and that the season in the northern hemisphere is mid-summer.

70. Transmitter Location - 50° W 10° N
Receiver Location NAA Washington
Approximate Length
of Short Path 2,300 nautical miles

(a) At 0920 Greenwich Mean Time, the short path is all dark. Reference to Plate 2 shows that for this distance and an all dark path the possible frequencies which might be used lie between 5 and 8.5 megacycles. The choice might then be to take a frequency as near 6.5 megacycles as possible.

(b) At 1520 Greenwich Mean Time the short path is all daylight. Reference to Plate 1 shows that the band from which to choose lies between 14.5 and 17.5 megacycles and that from this 16 megacycles might be the most suitable frequency. At 2320 Greenwich Mean Time the path is about half dark - half daylight. For this condition, experience shows that a frequency approximately midway between the day and night ones is desirable, in this case about 11.0 megacycles.

(c) In the case of this circuit, the long path passes close to Guam, NPN.

(d) Since the long path from the transmitter to Washington passes through the disturbed north magnetic polar regions in addition to the increased length of path, it is unlikely that contact could be made by the long path.

71. Transmitter Location - 50° W 10° N
Receiver Location NBA Balboa
Approximate Length
of Short Path 1760 nautical miles

(a) Since the transmitter location is the same and Balboa is about the same longitude as Washington, the daylight-darkness distribution for the three periods is approximately the same as for the previous case. At 0920 Greenwich Mean Time the 6.5 megacycles might likewise serve for this distance, or if not, decrease the frequency to 5 megacycles. For 1520 Greenwich Mean Time due to the decrease in distance 14.5 megacycles should serve the purpose better than the 16.0 megacycles for the Washington circuits. At 2320 Greenwich Mean Time the frequency would be an intermediate one between the day and night values or about 9.5 to 10 megacycles.

(b) In this case, both the transmitter and receiving points are in regions having frequent electrical storms and liable to interruptions because of them.

72. Transmitter Location - 90° W 10° S
Receiver Location NAA Washington
Approximate Length
of Short Path 3,000 nautical miles

(a) For this circuit, the short path is approximately half dark-half daylight at 1200 Greenwich Mean Time, all daylight at 1800 Greenwich Mean Time and all dark at 0200 Greenwich Mean Time. Reference to Plates 1 and 2 shows that for the daylight and dark conditions 17.5 and 7.5 megacycles are the frequencies to be chosen. Then for the half dark half daylight condition the frequency should be approximately 12 megacycles.

(b) From the transmitter to Washington, the long path passes very close to the south magnetic pole and close to the "dead" north magnetic polar region so that there would be little likelihood of making contact via the long path at any time of the day or night.

73. Transmitter Location - 90° W 10° S
Receiver Location NBA Balboa
Approximate Length
of Short Path 1,270 nautical miles

(a) Here the daylight-darkness distribution is, for 1200 Greenwich Mean Time approximately 3/4 dark 1/4 daylight, for 1800 Greenwich Mean Time all daylight, and for 0200 Greenwich Mean Time all dark. Similarly to the Washington circuit, reference to the pertinent charts gives a 13.0 megacycle frequency for daytime, 5 megacycles for darkness, and since the 1200 Greenwich Mean Time condition has the greater portion of the path in darkness, a frequency of approximately 6.5 megacycles should serve for this condition. It might be well, however, considering that both stations are located in the tropics to choose somewhat higher frequencies for this circuit.

74. Transmitter Location - 20° W 30° N
Receiver Location NAA Washington
Approximate Length
of Short Path 2,850 nautical miles

(a) At 0720 Greenwich Mean Time, the path is practically all in darkness although it is just about sunrise at the ship or transmitter, for which condition 7.0 megacycles would be the frequency. For 1320 Greenwich Mean Time, the path is all in daylight and 17.0 megacycles becomes the appropriate frequency. At 2120 Greenwich Mean Time, the path is 1/5 dark and 4/5 daylight, so that the suitable frequency is one nearer to the daylight frequency than the night value, so that 15.0 megacycles is chosen. In this case, the long path to Washington passes near Tutuila.

75. Transmitter Location - 20° W 30° N
Receiver Location NBA Balboa
Approximate Length
of Short Path 3,490 nautical miles

(a) The daylight-darkness distribution is the same as for the preceding case, but due to the increased distance the frequencies for the three times might be changed to 7.5 megacycles for 0720 Greenwich Mean Time, 18 megacycles for 1320 Greenwich Mean Time and 16.0 megacycles for 2120 Greenwich Mean Time.

76. Transmitter Location - 180° E 30° S
Receiver Location NAA Washington
Approximate Length
of Short Path 7,050 nautical miles

(a) At 1800 Greenwich Mean Time, the short path is approximately 1/10 dark and 9/10 daylight, and if contact is to be made, a frequency of 18 - 22 megacycles would have to be used. Over the long path, the daylight-darkness distribution is 2/3 dark 1/3 daylight, but there is little likelihood that contact could be made by this path for the following reasons. To cover the long dark portion (9,700 nautical miles) a frequency of about 9.5 megacycles would have to be used. But this frequency would be too low because of the increased attenuation to cover the remaining 4,850 nautical miles of daylight path.

(b) At 2400 Greenwich Mean Time, the short path is all daylight and again a high frequency of the order of 18 - 22 megacycles would have to be used without certainty of reliable communication. The daylight-darkness distribution over the long path at 2400 Greenwich Mean Time is approximate 0.23 daylight - 0.74 dark - 0.03 daylight, and again the relatively long daylight portion is too great to permit the use of a night frequency for reasons outlined under the 1800 Greenwich Mean Time condition.

(c) At 0800 Greenwich Mean Time, the short path is all dark and the approximate frequency is 9.5 megacycles.

(d) The more satisfactory solution for all the times would be to relay to Honolulu and thence to Washington rather than attempt direct contact.

77. Transmitter Location - 180° E 30° S
Receiver Location NPM Honolulu
Approximate Length
of Short Path 3,280 nautical miles

(a) The daylight-darkness distribution over the short path in this case is 1/3 dark 2/3 daylight for 1800 Greenwich Mean Time, all daylight for 2400 Greenwich Mean Time and all dark for 0800 Greenwich Mean Time and would require approximately 12, 16 and 7.5 megacycles respectively for the three times.

(b) NPU Tutuila is near the longer portion of this Great Circle Path. It also passes through the south and north magnetic "dead" zones.

78. Transmitter Location - 180° E 30° S
Receiver Location NPG San Francisco
Approximate Length
of Short Path 5,300 nautical miles

(a) The daylight-darkness distribution over the short path is 1/8 dark, 7/8 day for 1800 Greenwich Mean Time, all day for 2400 Greenwich Mean Time and all dark for 0800 Greenwich Mean Time; for which conditions the respective frequencies would be 18, 21, and 9 megacycles. The longer portion of this path passes through the north and south magnetic disturbed zone.

79. Transmitter Location - 150° E 20° N
Receiver Location NAA Washington
Approximate Length
of Short Path 6,350 nautical miles

(a) At 2000 Greenwich Mean Time it is practically sunrise at the transmitter with an all day path requiring a high frequency of about 21 megacycles. At 0200 Greenwich Mean Time the path is about 3/4 day and 1/4 night with 18 megacycles for the frequency. At 1000 Greenwich Mean Time, the path is all in darkness with 9.5 megacycles for the frequency.

(b) In this case the short path passes through the north magnetic disturbed zone and this coupled with the long distance would probably require relaying to Honolulu or San Francisco and thence to Washington.

80. Transmitter Location - 150° E 20° N
Receiver Location NPM Honolulu
Approximate Length
of Short Path 2,890 nautical miles

(a) For both 2000 and 0200 Greenwich Mean Time, the path is all daylight and a frequency of 16 megacycles appropriate. At 1000 Greenwich Mean Time, the path is all dark with 6.5 megacycles for the frequency.

81. Transmitter Location - 150° E 20° N
Receiver Location NPG San Francisco
Approximate Length
of Short Path 4,550 nautical miles

(a) The daylight-darkness distribution over the path is similar to the Honolulu circuit being all daylight for 2000 and 0200 Greenwich Mean Time and all dark for 1000 Greenwich Mean Time. The respective frequencies are 18 megacycles for the daylight times and 8.0 megacycles for the night frequency.

CONCLUSION

82. Radio communication, particularly over long distances, is affected by physical phenomena which are only predictable in advance with a limited degree of certainty. Even commercial concerns working over fixed point to point circuits which have been studied for a number of years, find that they must make allowance for a certain percentage of "lost" time. The Navy has similar point to point circuits, but in addition has many ship to shore and ship to ship contacts to be made and maintained. The latter in particular have the added difficulties

of limited power and limited radiating structures as compared with most of the commercial point to point circuits as well as the difficulty resulting from their daily shifts in position, thereby changing not only the distance but also the course of the Great Circle Path relative to the earth.

83. Consequently, a study of the usual published literature does not supply the Navy with a satisfactory answer to the many problems that always arise in the consideration of the propagation of radio waves and to those special problems which are of particular interest because of the exacting demands of the Naval Service.

RECOMMENDATIONS

84. To provide adequate information for the Navy radio service, therefore, it would appear advisable to make a statistical study of the special conditions under which the service can operate and of the results which may have been obtained in the past, if there are such records, and of the results which are obtained in the future.

85. Any data collected in the future in a systematic fashion, and any past existing data, should be collected at a central point and there correlated and studied by a permanent individual or staff.

86. Immediate results will not be obtained because, with our present knowledge and inability to control the natural elements which so markedly affect radio communications, the study must be a statistical one and such a task takes time.

87. Moreover, at least a certain irreducible minimum amount of information must be supplied to obtain results which have any value whatever. This information should be furnished in such a form that it could be readily transferred to a "punched card" for statistical machine analysis.

88. A conference should therefore be held to determine the manner and the extent to which the service can be reasonably expected to undertake the task of supplying the requisite data, without overburdening the personnel with detail.

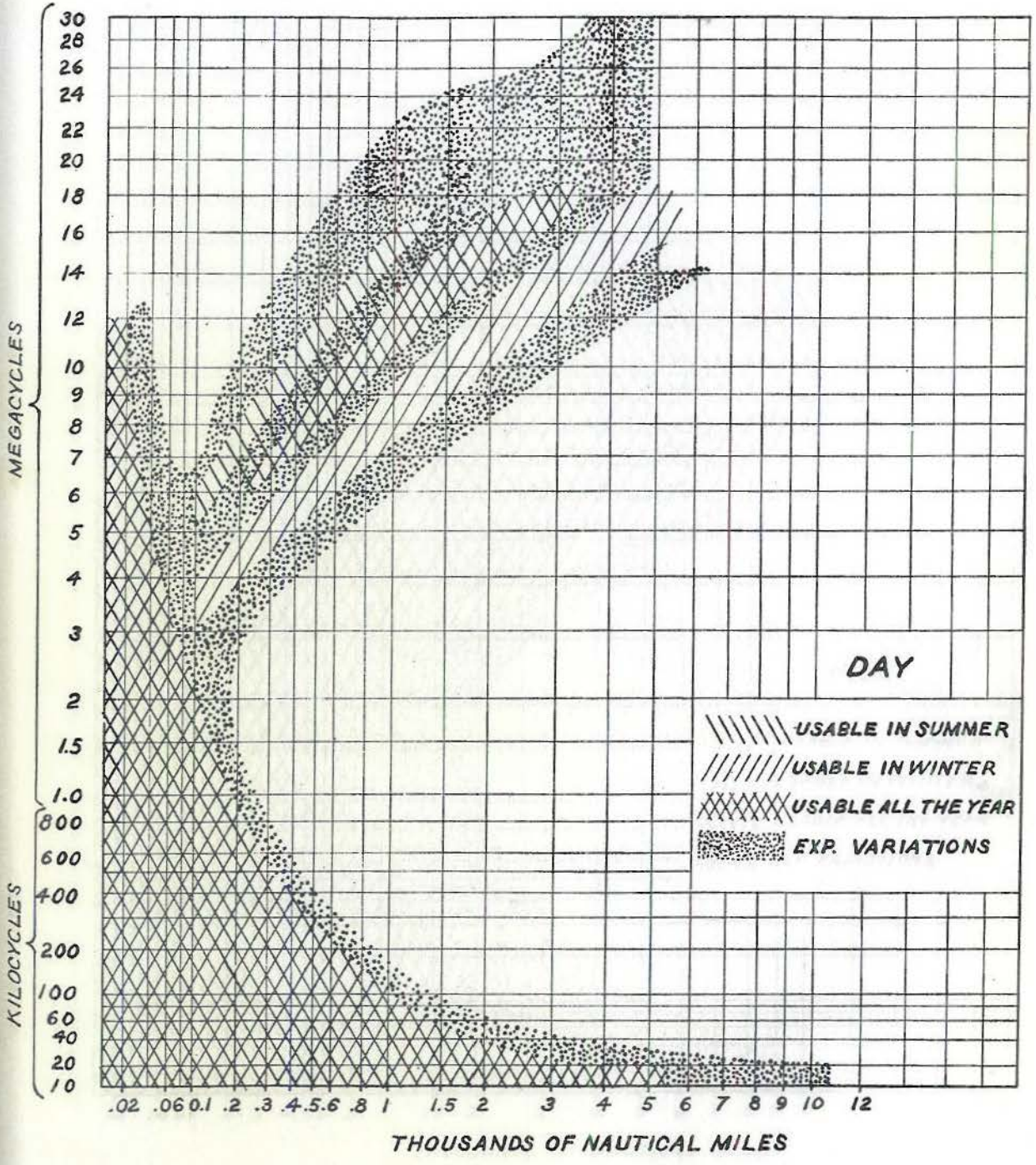


PLATE I

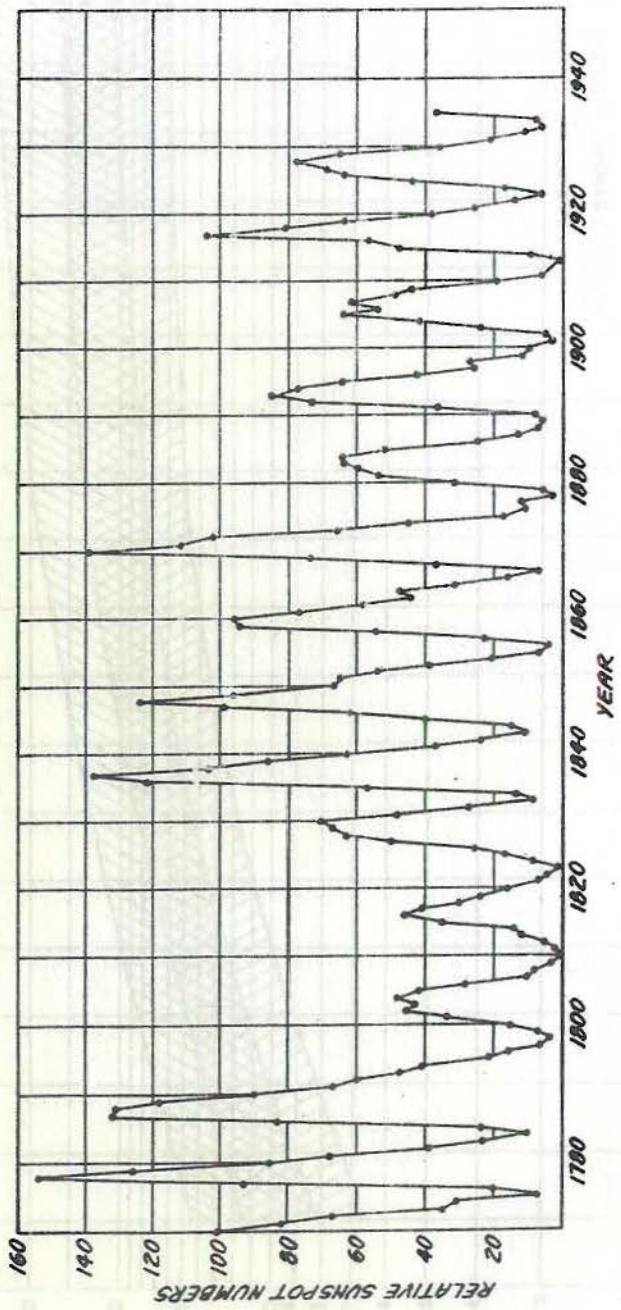


PLATE 3

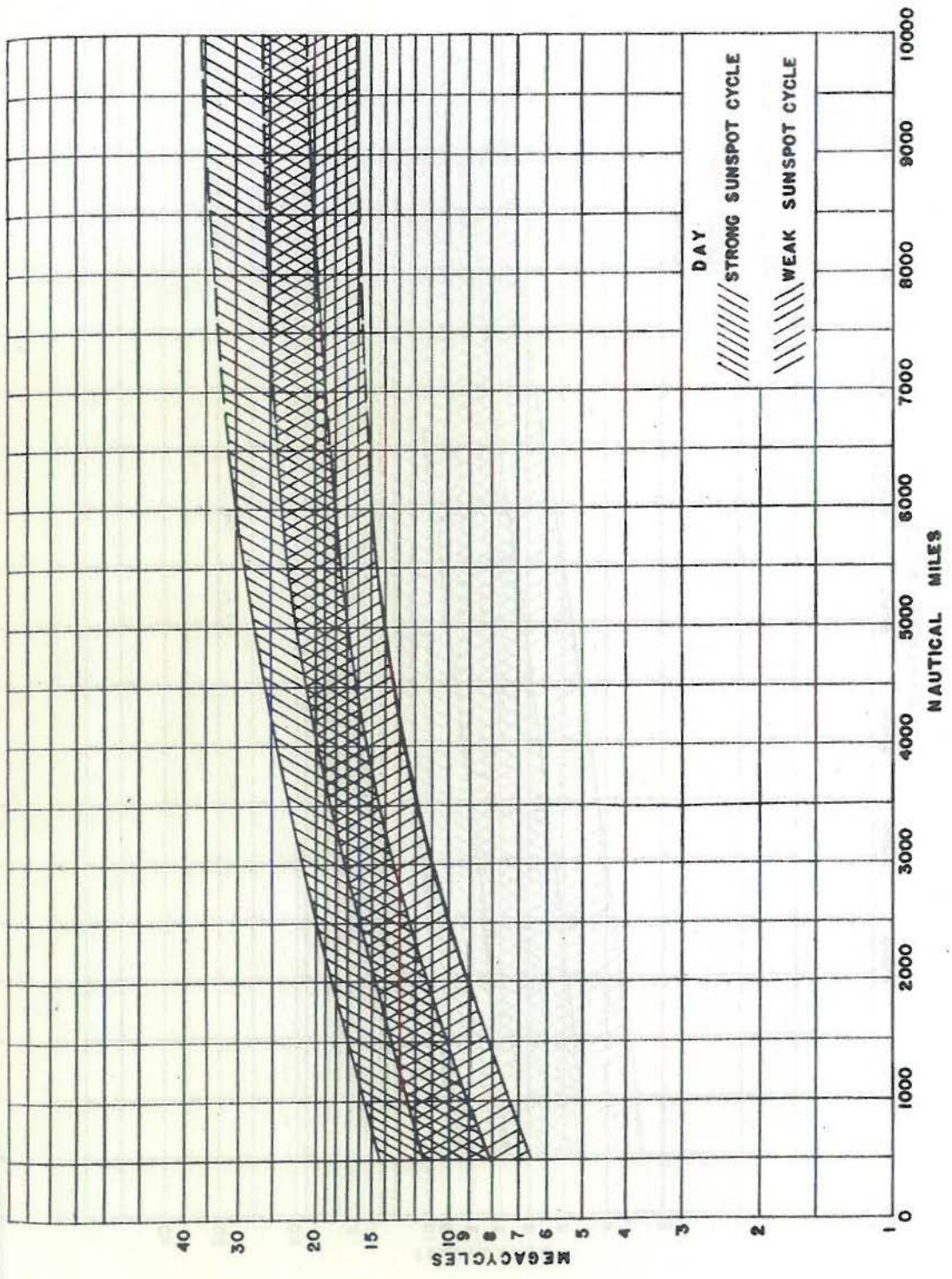


PLATE 4

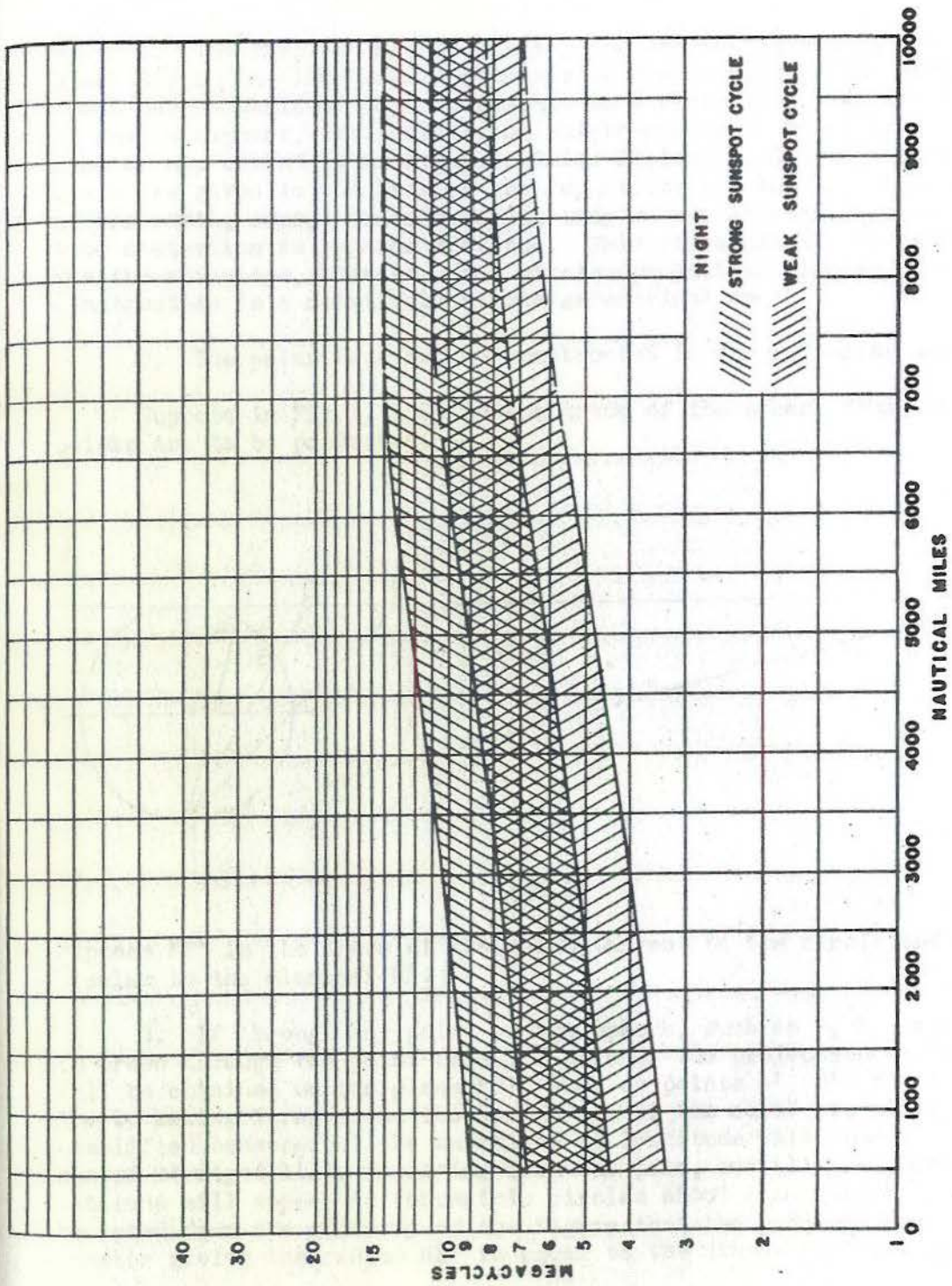


PLATE 5

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APPENDIX I

Stereographic Polar Projection Charts

1. The simplest way of finding the shortest distance (called the Great Circle Path) between two points on the surface of the earth is to use a narrow strip of paper stretched on a good globe. In the absence of such equipment, particularly on shipboard, it is necessary to use that type of map called "Stereographic Polar Projection Charts", samples of which are given in the back of the report, Maps 1 and 2. No plane maps of the earth, except those covering only a very limited region, are free from distortion as regards distance. This stereographic projection type has the advantage, however, that circles project as circles, and the construction is a relatively simple geometrical one.

2. The polar type may be constructed in the following manner:

Suppose in Fig.1, NESW is the trace of the sphere from which the points are to be projected.

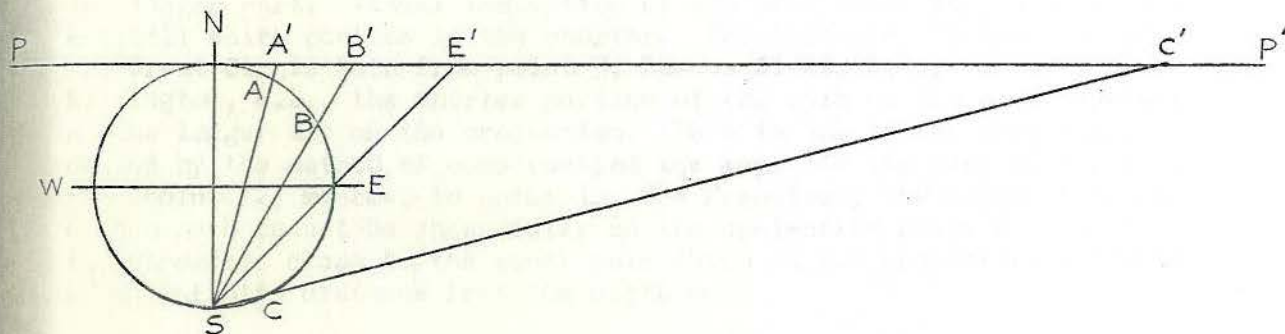


Fig. 1

Suppose PP' is the trace of the plane tangent to the circle and perpendicular to the diameter NS .

3. If through any point on the sphere, such as A , B , or E , a line is drawn through the point from the pole S , the projection of the point will be obtained on the plane PP' , such as points A' , B' , E' respectively. Now by making N represent the North Pole of the earth the plane map is simplified because all the meridians of longitude will appear as equally spaced straight lines radiating from the pole, and all the parallels of latitude will appear as concentric circles about the point N . It will be noted from the geometry of the figure that the projection of the equator giving the radius NE' is equal to the diameter of the sphere NS .

4. Furthermore, it may be shown that for a point of any given latitude the distance in the plane map of the point from the pole will be equal to the diameter of the sphere (the magnitude to be chosen

arbitrarily so as to give any desired size to the map) times the natural tangent of one-half the colatitude of the point. For example, if point A were in latitude 60° N and we chose NS or NE' to be 9 centimeters, A' the projection of A would lie at a distance from N on the plane PP' equal to nine times the natural tangent of 15° , i.e. $NA' = 9 (0.268) = 2.412$ centimeters. Similarly, if B were in latitude 30° N, NB' would equal nine times the tangent of 30° ($NB' = 9 (0.577) = 5.193$ centimeters). For points in south latitude, the distance would be, of course, nine times the tangent of $1/2 (90^{\circ} + \text{latitude})$, $d_{60^{\circ}S} = 9 (\tan 75^{\circ}) = 9(3.732) = 33.588$ centimeters.

5. Beyond 20° south latitude the distortion in the plane map becomes quite evident, and since 60° south latitude includes practically all inhabitable land and most of the navigable waters, 60° S was chosen as the boundary limit.

6. Maps 1 and 2 were originally drawn with the equivalent of NE' equal to 9 centimeters and then photographically reduced to approximately one quarter size.

7. Map 1 gives examples of some of the Great Circle Paths between various points on the surface of the earth. The heavy portion of any circle indicates the shorter part of the path and the dotted portion the longer part. Visual inspection of any path which may be drawn does not tell which portion is the shorter. For instance, in the case of the Great Circle Path from point 3, Buenos Aires, S.A., to point 24, Wellington, N.Z., the shorter portion of the path on the earth appears as the longer one on the projection. This is due to the distortion caused by the method of constructing the map. In the case of the path from point 12, Moscow, to point 16, San Francisco, the longer portion of the path cannot be shown fully on the projection since a part of it approaches close to the south pole which in the projection would be at an infinite distance from the north pole.

8. The centers of the circles showing the Great Circle Path between any two points can be found in a relatively simple manner. Suppose we have two given points such as 10, Melbourne, Australia, and 11, Mombasa, Tanganyika Territory, Africa. Draw the meridian of longitude through point 10 and the north pole. At the pole erect a perpendicular to the meridian, and find the point of intersection of this perpendicular with the equator. Call this point F. At F erect a perpendicular to the line F→10. This perpendicular will intersect the meridian through point 10 and give the antipode 10' of 10. We now have three points 10, 11, and 10' which we know must lie on the same circle. To find the center of the circle, erect the perpendicular bisectors of the lines 10→11 and 10'→11 and their intersection is the desired point. If greater accuracy is desired the antipode 11' of 11 may be found and the perpendicular bisectors of the lines 11'→10 and 11'→10' erected. If care is used the four perpendicular bisectors should intersect at one point. The circle constructed with this point as the center represents the Great Circle Path between the points 10 and 11.

9. No difficulty will be experienced in the construction of any path, except in the case where both points might lie at latitudes greater than 60° north. In such cases the antipode of either point would lie without the boundary circle representing 60° south latitude. Under such circumstances, however, the short portion of the path between the two points would be a straight line to a sufficiently close approximation.

10. Map 2 is similar to Map 1 with the exception that points 25 and 26 of Map 1 have been omitted from Map 2, and the remaining points have not been numbered. The identity of any point of Map 2 may be established by the legend on Map 1 and comparison of latitudes and longitudes. Map 2 has been included so that any other Great Circle Paths than those of Map 1 may be constructed to meet individual needs. Having once obtained a Great Circle Path on this particular type of projection, its location with respect to continents, navigable waters and the magnetic polar regions may be determined by transferring the points of intersection of the path with various meridians of longitude and parallels of latitude to a mercator projection.

11. Map 2 will serve equally well as a map of the world from the south pole to 60° north latitude by merely interchanging the latitude markings on the present map. Those parallels now marked N would become S and those now S would become N.

12. The Great Circle bearing of one point with respect to any other point on the Great Circle Path may be easily determined. Draw the line representing the meridian of the point of departure. At this point of departure, draw that portion of the tangent to the Great Circle Path which extends in the direction (either known or assumed) necessary to reach the point of arrival by the shortest distance. Then the included angle, measured in a clockwise direction, between the meridian and the tangent is the Great Circle bearing and may be measured to within a degree with the usual small protractor. If the assumed direction of departure is by the long path then the measured angle plus or minus 180° , depending on the respective locations of the points on the path relative to the pole, is the bearing via the short path. Owing to the reduced scale of the map, the construction of the tangent must be done carefully to obtain the true bearing within 5° .

13. Latitudes and Longitudes of Points on Map 1 taken as the following:

1. Balboa NBA	79°	46'	24"	W	9°	7'	12"	N
2. Batavia	106	51	55	E	6	12	10	S
3. Buenos Aires	58	31	4	W	34	45	37	S
4. Cavite NPO	120	54	7	E	14	29	37	N
5.* Christmas Island								
South of Java	105	42	57	E	10	29	19	S
6. Geneva								
(Prangins)	6	15	11	E	46	24	26	N
7. Guam NPN	144	43	30	E	13	28	30	N
8. Honolulu NPM	157	57	57	W	21	21	11	N
9. Irkontsk	104	19	45	E	52	16	45	N
10. Melbourne	144	54	9	E	37	46	56	S
11. Mombasa	39	39	51	E	4	3	11	S
12. Moscow	37	17	30	E	55	44	45	N
13. Paris	2	17	39	E	48	51	34	N
14. Peiping NPP	116	25	35	E	39	53	58	N
15. Rugby	1	11	15	W	52	22	10	N
16. San Francisco NPG	122	16	42	W	38	5	50	N
17. San Juan NAU	66	5	40	W	18	23	3	N
18. Shanghai	121	29	0	E	31	14	-	N
19. Sidney	151	3	9	E	33	46	-	S
20. Tahiti	149	29	15	W	17	30	15	S
21. Tutuila NPU	170	45	-	W	14	15	-	S
22. Vladivostok	131	53	15	E	43	7	30	N
23. Washington NAA	77	4	47	W	38	52	5	N
24. Wellington	174	45	55	E	41	16	26	S

* There is also a Christmas Island in the Pacific Ocean at approximately 157° 15' W, 1° 53' N, approximately 20° S of the Island of Hawaii. Both islands are possessions of Great Britain.

14. Great Circle Paths shown on map are:

		<u>Positions approx. on path</u>
Buenos Aires (3) to Wellington (24)		Geneva (6) Paris (13)
Cavite (4) to Washington (23)		Vladivostok (22)
Guam (7) to Tahiti (20)		
Melbourne (10) to Mombasa (11)		Washington (23)
Moscow (12) to San Francisco (16)		
Rugby (15) to Sidney (19)		
Assumed Position SW of Crozet Is (25)	to Assumed Position S of Aleutian Islands (26)	Christmas Island (5)

APPENDIX II

Daylight - Darkness Distribution Chart

1. The transparent scale, Plate 6, is for use with Map 2 to determine the approximate daylight-darkness distribution of any Great Circle Path drawn on the map.

2. The diameter and the arcs of circles marked with the months represent the traces of the dividing line between daylight and darkness as they would be stereographically projected on to a plane. On March 21 and September 23 the shadow line passes through the poles, hence the projection is a straight line. Between these two months, March and September, any portion of the map within the area of the appropriate lines is in daylight and the time scale, around the outer circle, reads in a counterclockwise direction from 6 a.m. local time to 6 p.m. local time. On June 22, the axis of the earth is inclined 23.5° towards the sun so the north pole is in daylight, and the area to be considered is between the outer circle and that arc of the circle which is marked June 22 at one end and December 23 at the other end.

3. However, on December 23, the axis of the earth is inclined 23.5° away from the sun so that the area which was in daylight from March to September is in darkness from September to March.

4. The appropriate arcs of circles have been drawn for the latter part of February, April, August, October, and January, May, July, November. For intermediate periods, the approximate position of the boundary arc can be estimated with sufficient accuracy.

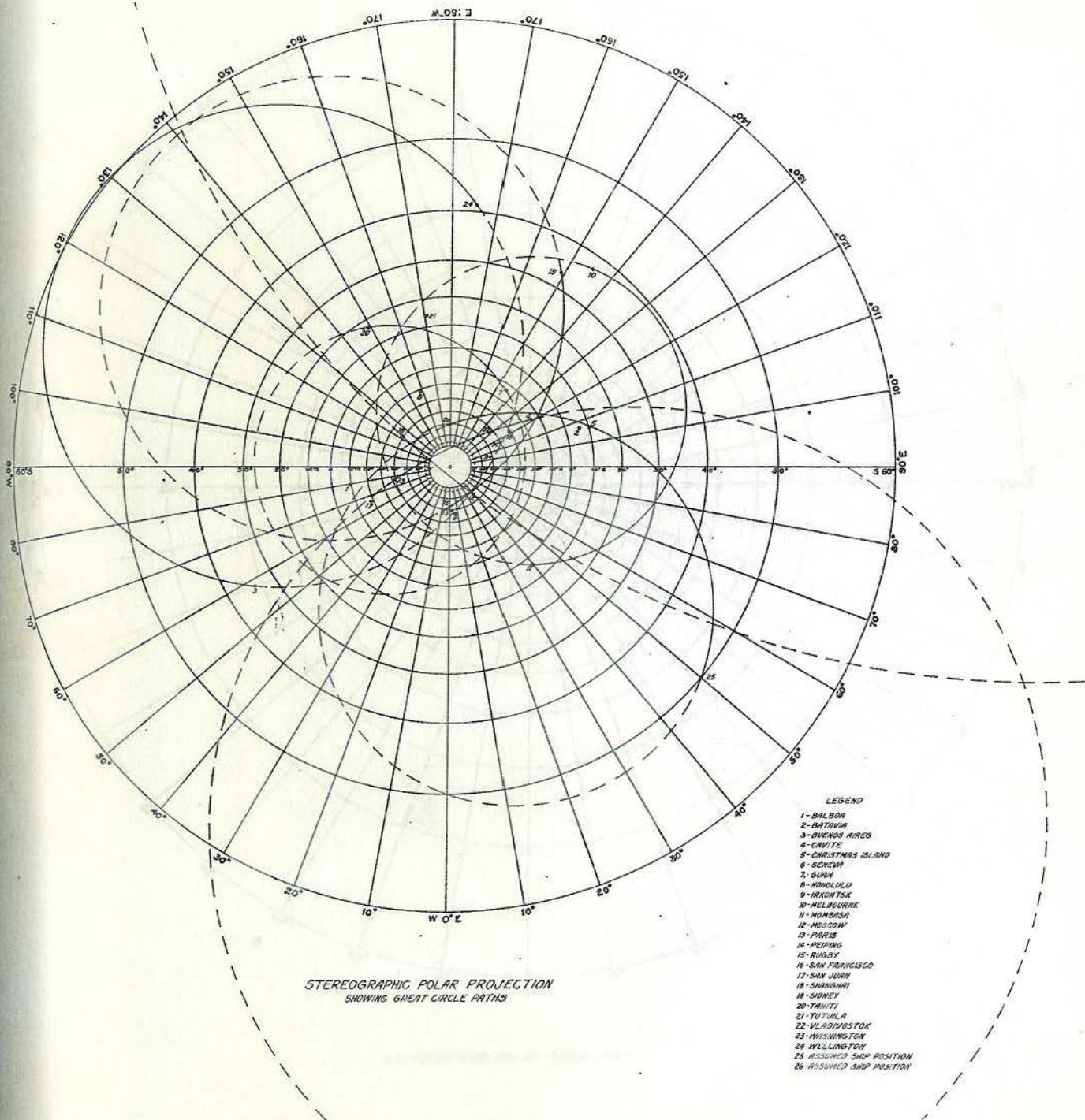
5. From September to March, the time scale still reads in a counterclockwise direction but starts at 6 p.m. and continues through midnight to 6 a.m. local time.

6. Suppose that a Great Circle Path has been drawn on the map as per the instructions in Appendix I. To determine the approximate daylight-darkness distribution over the path, proceed as follows: Place the transparent scale over the map so that the outer circle coincides with the 60° S. latitude parallel. Now rotate the transparent scale about the center until the chosen local time, at which the distribution is desired, coincides with the meridian of the point of departure. Then, that portion of the path which lies within the area bounded by the outer circle and the desired month arc is in daylight if the season is between March 21 and September 23 or in darkness if the season is between September 23 and March 21.

7. The time circle has not been completed but this causes no difficulty. Suppose the point of departure lies on the meridian 20° W. Suppose it is desired to determine the distribution at 10 p.m. the latter part of May. All that is necessary is to place the transparent scale so that the 10 a.m. mark coincides with the 160° E meridian.

This places the scale in the proper position so that the 20° W meridian would coincide with the 10 p.m. mark if the time circle had been completed and the May shadow line is properly placed with respect to the map.

8. The general rule is that, if the desired p.m. or a.m. hour does not appear on the scale, place that time mark, either 12 hours earlier or later, which does appear on the scale, on that meridian which is obtained by adding 180° to the meridian of the point of departure.



STEREOGRAPHIC POLAR PROJECTION
SHOWING GREAT CIRCLE PATHS

- LEGEND
- 1-BALBOA
 - 2-BATAVIA
 - 3-BUENOS AIRES
 - 4-CAVITE
 - 5-CHRISTMAS ISLAND
 - 6-SEVEN
 - 7-OSRN
 - 8-HONOLULU
 - 9-IRKOUTSK
 - 10-MELBOURNE
 - 11-HONGKONG
 - 12-MOSCOW
 - 13-PARIS
 - 14-PERMAN
 - 15-RUSSY
 - 16-SAN FRANCISCO
 - 17-SAN JUAN
 - 18-SHANGHAI
 - 19-SIDNEY
 - 20-TAHITI
 - 21-TUTUILA
 - 22-VLADIVOSTOK
 - 23-WASHINGTON
 - 24-WELLINGTON
 - 25-ASSUMED SHIP POSITION
 - 26-ASSUMED SHIP POSITION

AUG 24 1936 Map No.1

APPENDIX III

Miscellaneous Conversion Factors,

Great Circle Distances and Bearings

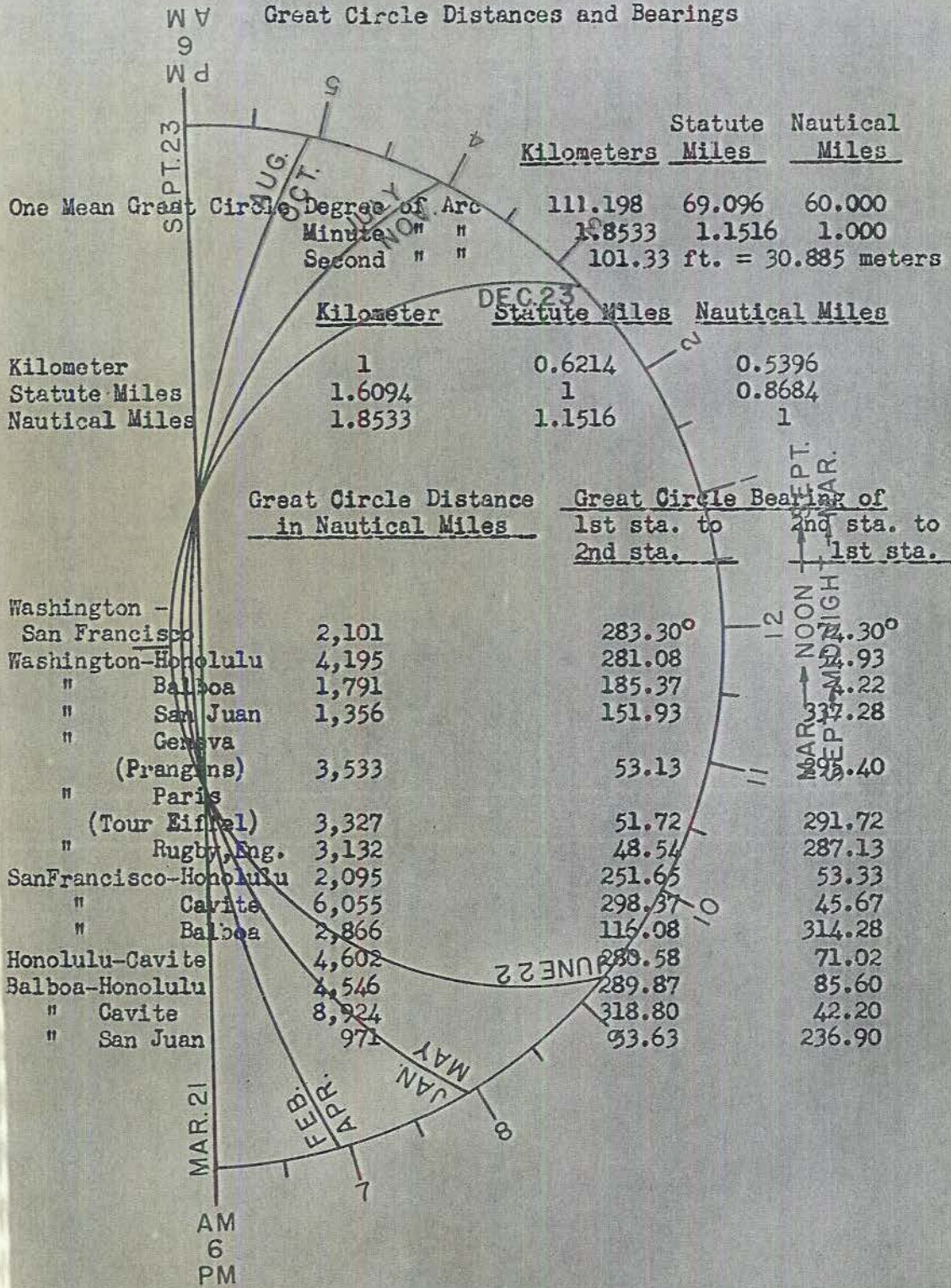


PLATE 6

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