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A VLF Effective Ground Conductivity Map of Canada and Greenland With Revisions Derived From Propagation Data

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CONTENTS

ABSTRACT

NRL conducted several airborne and ground-based experiments between 1959 and 1961 to investigate the propagation of very-low-frequency (vlf) radio waves over a large portion of Canada and Greenland. The results of these investigations have been reanalyzed in light of theoretical waveguide results to yield revisions to a vlf effective ground conductivity map of those areas developed through a correlation of geological and climatological data with conductivity.

The experimental data confirm the theoretical attenuation rates for a daytime ionosphere with a height of 70 km and a gradient of 0.3/km for several effective ground conductivities from very high, such as seawater, down to as low as 1×10^{-5} mho/m. There were also many indications that the theoretically determined excitation factors were substantiated by the experimental data for several values of receiving terminal foreground conductivity. A comparison of experimental propagation data with calculated values based on the theoretical model was used to modify the conductivity map. The confidence level of the original map was low in all areas where the conductivity was revised. Other propagation data, obtained over relatively long periods of time, were then used to demonstrate the accuracy of field-strength calculations based on the theoretical model and the modified conductivity map. These data also show that the daytime ionospheric gradient for the northern latitude paths investigated changes from 0.3/km around equinox to about 0.5/km in midsummer.

PROBLEM STATUS

This is the final report on one phase of this problem; work is continuing on other phases.

AUTHORIZATION

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INTRODUCTION

Between September 1959 and August 1961, NRL conducted several airborne and ground-based experiments in the Canadian and Greenland areas to investigate the propagation of very-low-frequency (vlf) radio waves over those areas. Preliminary investigations earlier in 1959 had indicated attenuation rates for frequencies near 15 kHz to be greater than 20 dB/M for the Greenland icecap. Such attenuation rates were greatly in excess of theoretically predicted values at that time and, therefore, prompted a more thorough investigation.

The original analysis of the experimental data resulted in an approximate ground conductivity map for the Canadian and Greenland areas, but the inherent limitations of the investigation prevented a detailed analysis of the highly varying ground conductivity in those areas.

In 1964, Wait and Spies (1) published the results of their theoretical study, which indicated an attenuation rate for low conductivity, such as the conductivity expected for the Greenland icecap, to be in close agreement with the NRL experimental results. In 1965, Morgan and Maxwell (2) published an effective ground conductivity map of North America and Greenland for a frequency of 10 kHz. The attenuation rates given by Wait and Spies (1) for ground conductivities predicted by Morgan and Maxwell (2) for Canada and Greenland showed general agreement with the NRL experimental results for those areas.

The vlf effective conductivity map published by Morgan and Maxwell (2), and referred to here as the DECO map, was derived from a comparatively few conductivity measurements and a correlation with various geological information. This conductivity map, and the theoretical results of Wait and Spies (1), afforded the basis for a detailed reanalysis of the vlf propagation data recorded by NRL in the Canadian and Greenland areas. This reanalysis has resulted in a revision of the DECO map. It has also demonstrated an ability to accurately predict field strengths for vlf propagation over low-conductivity terrain, even in arctic areas, at least for paths all in daylight during periods of little or no auroral or polar-cap absorption disturbances. The revised DECO map will be referred to here as the DECO-NRL map.

EXPERIMENTAL APPROACH

A series of radiowave propagation experiments was conducted in September 1959 and August 1961 to investigate vlf propagation over Canada and Greenland when the propagation paths were entirely in daylight. The September 1959 experiment consisted of the recording of the field strengths of transmissions from the vlf transmitting station NPG (Jim Creek, Washington) and NSS (Annapolis, Maryland) in an airplane while in flight over eastern Canada, Greenland, and the vicinity. In August 1961 a similar airborne experiment was conducted using the NPG and NAA (Cutler, Maine) transmission. In addition, during this latter period, ground-based observations were made at Thule and Sondrestrom, Greenland; Goose Bay, Labrador; and Keflavik, Iceland. Both of these experimental programs were supplemented by data recorded continuously for various periods between 1959 and 1964 at Hammerfest, Bodo, and Varhaug (near Stavanger), Norway.

Another series of airborne and ground-based experiments was conducted in the same areas in February 1961 to investigate the nighttime propagation effects. The general instabilities of the nighttime ionosphere, particularly in the arctic, combined with the greater excitation of high-order propagation modes, make the analysis of the nighttime data extremely difficult. The analysis of these nighttime data is inconclusive and is continuing and, therefore, will be only briefly mentioned.

The overall accuracy of the field strengths reported here is believed to be within ±1 dB. The precise location of the aircraft is another factor affecting the analysis presented here. Using conventional navigational aids, every effort was made to monitor the location of the aircraft as frequently as practicable. The accuracy of the aircraft location was undoubtedly a variable, and the tolerance of the various position fixes is unknown.

ANALYTICAL DATA ANALYSIS

The theoretical results of Wait and Spies (1) presented in Figs. 1 through 8, plus the vlf effective ground conductivity map (Fig. 9) from Morgan and Maxwell (2), provide the basic information required for calculating field strengths of vlf radio waves propagated over North America and Greenland. Assuming a daytime ionospheric height of 70 km and using the information from these two sources, field strengths were calculated at many locations along the various experimental flight paths considering ionospheric gradients β of 0.3 and 0.5/km. The field strengths calculated in this manner for an ionospheric gradient of 0.3/km showed general agreement with the daytime, experimental data recorded aboard the aircraft. The experimental data, having been obtained during periods near autumnal equinox, indicate attenuation rates considerably higher than the theoretical rates for the 0.5/km ionospheric gradient. Furthermore, most instances of disagreement between the experimental data and the theoretical calculations based on an ionospheric gradient of 0.3/km indicate yet higher attenuation rates than the theoretical values given for the conductivity shown on the DECO map. Some of the experimental data indicated that an even lower β might be representative. However, in many areas the theoretical attenuation rates and excitation factors for the conductivities given by the DECO map showed excellent agreement with the experimental data. These instances will be detailed later in the discussion of the data from each flight. The generally good agreement of the experimental and theoretical results provided the basis for confidence in the results of Wait and Spies (1), in the use of the ionospheric gradient of 0.3/km for daytime propagation over the paths investigated around the time of autumnal equinox and in the acceptance, for the most part, of the DECO map.

The field-strength calculations were made by using the simplified form of the waveguide mode equation

$$E = K + P_r + \Lambda_t/2 + \Lambda_r/2 - 10 \log f - 10 \log [a \sin(d/a)] - \Sigma \alpha_i d_i, \qquad (1)$$

where E is the field strength in deciBels relative to $1 \mu V/m$, K is a constant depending on the ionospheric height (97.4 dB for a height of 70 km), P_r is the radiated power expressed in deciBels relative to 1 kW, Λ_t and Λ_r are the excitation factors in deciBels considering the ground conductivity in the vicinity of the transmitting and receiving antennas, respectively, f is the transmission frequency in kiloHertz, α_i is the attenuation rate in deciBels per megameter of a distance increment, d_i in megameters along the transmission path of total length d, and a is the radius of the earth in kilometers. The attenuation rates and excitation factors used in the calculations were in accordance with the conductivities given by the original DECO map (Fig. 9) or the revised version referred to as the DECO-NRL map (Fig. 10), as appropriate. Also, certain guidelines were adhered to for computing the field strengths:

1. All attenuation rates and excitation factors were derived from the results of Wait and Spies (1) for an ionospheric height of 70 km and a gradient of 0.3/km, with the assumption that the medium was isotropic. The latter assumption is considered to produce little error, since most of the propagation paths involved were near the magnetic north pole where the dip angle is such as to minimize the directional effects produced by the anisotropic medium.

2. The excitation factor for the airborne receiving terminal Λ_r was not altered for changes in the conductivity of the terrain over which the plane was flying until the foreground had at least 50 km of the new conductivity.

3. Except for propagation paths less than 2200 km, only the first-order mode was considered. For these occasional, short paths, a correction factor, which roughly approximated the effect of the second-order mode, was applied. This correction factor, which was never greater than 2 dB, was one-half of the difference between the field strengths calculated for the first-order mode only and the summation of the first- and second-order modes considering the propagation path to be all over seawater. The arbitrary choice of one-half of this difference was to approximate the actual multimode effect resulting from propagation over the true path which was not all seawater and usually contained segments of very-low-conductivity terrain.

4. Only propagation paths under all daylight conditions were used.

After the calculated field strengths were compared with the airborne data, the ground conductivities and boundaries given by the DECO map were modified to yield better agreement. Each time a modification was made to the DECO map, the field strengths for the paths to the various aircraft locations affected were recalculated and compared with the experimental data. The use of the three transmitting stations, NPG, NAA, and NSS, and the various aircraft flight paths, in many instances, allowed for cross checking in the determination of a change in the conductivity of an area and/or the location of its boundaries. No change in conductivity given by the DECO map was made without first determining that the change was a logical possibility based on the techniques used by Morgan and Maxwell (2). All modifications to the DECO map, which resulted in what is referred to here as the DECO-NRL map (Fig. 10), have been discussed with Mr. Morgan (3), and he has stated that all the modifications which are delineated in Fig. 11 are quite possible when consideration is given to the variability of the area geology and the paucity of conductivity measurements and geological data.

All modifications made to the DECO map were based on the various airborne, experimental data. After these modifications were completed, calculations of field strengths based on the same technique were made for the locations of the ground-based observations. The ground-based, experimental data were thus used to appraise the accuracy of the DECO-NRL map.

RESULTS

NRL has not conducted vlf propagation experiments, such as those reported here, in enough areas to yield an analysis of the ground conductivity of all of Canada, Alaska, and Greenland. The limitations of the data presently available exclude northwestern Canada, Alaska, and some portions of Greenland from the analysis presented here. Maps showing the time and location of the various experimental flights and graphs of the field-strength data recorded during each flight are presented in chronological order in Figs. 12 through 41. In the graphs, the measured field-strength data points are for special, locked-key transmissions. Since during those transmissions, the transmitter modulation-duty-cycle was eliminated and the transmitting antenna current was measured for determining radiated power, these data points constitute the most accurate measurements. Included with each field-strength data graph are plots of the bearing and distance of the aircraft from the transmitting station and a plot of the receiving terminal excitation factor Λ_r. In the calculation of field strength using Eq. 1, this excitation factor is divided by two. The transmitting terminal excitation factor is constant over the sector of propagation paths involved in any one flight presented here. It should be noted that the excitation factors presented in the graphs are for the conductivities given by the DECO-NRL map.

Changes in the original conductivity map of Morgan and Maxwell (2) indicated by the analysis of these experimental data are shown in Fig. 11. The discussion of the data to follow will be handled on an area basis. That is, the various geographic areas where modifications were made to the conductivity, as shown in Fig. 11, are discussed in order, along with all the experimental data that contributed to the analysis resulting in the particular modificiations. The individual areas discussed are identified (Fig. 11) as

1. Area A, Eastern Quebec and Newfoundland;
2. Area B, Mid and Western Quebec and Western Newfoundland;
3. Area C, Keewatin and Mackenzie districts;
4. Area D, Baffin Island; and
5. Area E, Greenland.

The five areas listed above contain all the sections of Canada and Greenland where modifications have been made to the DECO map except for a small area in British Columbia and Alberta. This small area is relatively close to the NPG transmitting station and is common to many of the propagation paths analyzed for those transmissions. The modification of the conductivity of that area is discussed primarily along with several of the other areas.

The conductivity of the various areas shown on the maps presented here are identified by numbers from "1" through "10." A difference of two numbers between "1" and "9" represents a conductivity change of one decade. All seawater shown has a conductivity of 4 mhos/m; however, the symbol "10" is not printed on the maps. It should be noted that the maps presented here do not have any areas with a conductivity of 1×10^{-1} mho/m ("9").

Area A, Eastern Quebec and Newfoundland

The field-strength data recorded during six flights (Figs. 18, 24, 27, 36, and 39) for transmissions from NAA (14.7 kHz) and NSS (15.5 kHz) indicated the need for modifying the conductivities as given by the DECO map for eastern Quebec and Newfoundland, area A. The field strengths measured for the transmissions propagated over this area were roughly 5 dB below the calculated values using the conductivities given by the DECO map (Fig. 9). Changing the conductivities of area A from 1×10^{-3} mho/m ("5") and 3×10^{-4} mho/m ("4") to 1×10^{-4} mho/m ("3") (Fig. 11) increased the attenuation rates over that area to bring the calculated field strengths into close agreement with the measured data. At 14.7 kHz, the decade change in conductivity from "5" to "3" increases the attenuation rate by 9 dB/Mm, while the "4" to "3" change gives a 6.2-dB/Mm increase. Similarly, at 15.5 kHz, the attenuation rate is increased by 9.4 dB/Mm for the conductivity change from "5" to "3" and by 6.5 dB/Mm for the "4" to "3" change.

There were only two regions, other than area A, where the conductivity could have been changed to improve the agreement between the calculated and the available, measured data: the Greenland icecap and the region of New Brunswick-Gaspe Peninsula. Morgan and Maxwell (2) indicated a moderate level of confidence in their conductivity values for this latter region. Also, NSS (15.5-kHz) data recorded during a flight from Keflavik to Goose Bay on September 29, 1959 (Figs. 18 and 19), indicate agreement with the DECO map conductivity for this region. Moderate confidence was also indicated by Morgan and Maxwell (2) for their Greenland icecap conductivity, and several groups of data substantiate this. Thus, the modification of area A seemed the best alternative.

A detailed discussion of the data from each of the six flights pertinent to the area A modifications is given below.

Thule to Sondrestrom to Keflavik Flight (August 11, 1961), NAA (14.7 kHz) - Three of the six flights, or portions thereof, that provided data for establishing the modifications to area A were nearly identical except in direction of flight. The portions of each of these three flights pertinent to this discussion were between Sondrestrom and Keflavik, and in each instance the transmissions observed were from NAA. One of these flights was made on August 11, 1961, as a part of the flight from Thule to Sondrestrom to Keflavik (Fig. 24). The field strengths recorded for NAA (14.7 kHz) during this flight are presented in Fig. 25. The data from 1630 UT to the end are for the segment of the flight from Sondrestrom to Keflavik.

All the measured NAA field strengths presented in Fig. 25 are roughly 5 dB below the calculated values based on the original DECO map. Various modifications to the DECO map bring the calculated fields into close agreement with all the measured data presented, but only the data after 1630 UT are for paths traversing area A, eastern Quebec and Newfoundland (Fig. 11). After 1630 UT area A modifications account for most of the difference between the calculated fields based on the DECO map and those based on the DECO-NRL map. However, the change in the receiving terminal excitation factor around 1700 UT contributes to the agreement of the slope of the calculated curve with the measured data around that time. The modification of the conductivity of the east coast of Greenland, area E, from 1×10^{-4} to 1×10^{-5} mho/m ("3" to "1") also affects the calculated values after 1745 UT. Nonetheless, the propagation path lengths over the modified portion of area E during this Sondrestrom to Keflavik flight were comparatively short; consequently, this modification accounts for less than half of the difference in the calculated fields based on the two conductivity maps.

The data presented in Fig. 25 from the beginning of the flight to 1630 UT will be discussed later in the section covering area B modifications.

Keflavik to Sondrestrom, North, and Return to Sondrestrom Flight (August 22, 1961), NAA (14.7 kHz) - On August 22, 1961, the initial segment of the flight from Keflavik to Sondrestrom, to the north, and then returning to Sondrestrom (Fig. 27) was nearly identical to that same portion of the flight made on August 11, 1961. The data obtained during the August 22, 1961, flight are presented in Fig. 28, but only the data from the start of the flight to 1249 UT pertain to the portion of the flight between Keflavik and Sondrestrom with NAA propagation paths over area A. These data, for that portion of the flight, show excellent agreement with the data for the same paths previously discussed for the August 11, 1961, flight. The receiving terminal excitation factors shown in Fig. 28 are virtually constant, since the values given by Wait and Spies (1) for infinite conductivity (seawater is assumed to have infinite conductivity) and 1×10^{-5} mho/m (Greenland icecap) are nearly equal. The excitation factors of approximately 4 dB given for some data points in Fig. 25 are due to portions of that flight being over the western coast of Greenland (see Fig. 24), which has a conductivity of 1×10^{-4} mho/m. There are no calculated data points given in Fig. 28 at a time when the airplane was over similar terrain.

Keflavik to Goose Bay Flight (August 28, 1961), NAA (14.7 kHz) - The NAA propagation paths to the aircraft during the flight from Keflavik to Goose Bay on August 28, 1961 (Fig. 39), never crossed Greenland. Therefore, this and a similar flight on September 29, 1959, provide the most useful data for analyzing the conductivity modifications in area A. The NAA (14.7-kHz) data gathered during this flight are given in Fig. 40. The calculated data based on the DECO-NRL map show an overall improvement in the agreement with the measured data over the use of the DECO map. However, between 1300 and 1500 UT the measured data are approximately midway between the two groups of calculated field strengths.

At 1515 UT the aircraft was at the same bearing from NAA as the locations previously discussed, where the field strengths from NAA showed a perturbation. No such perturbation was observed in this August 28 flight data at that bearing. At this location, Greenland was on the other side of the aircraft from NAA, and the measured field strength of NAA was higher by about 2 dB than the calculated value based on the DECO-NRL map. At that same bearing from NAA, approximately 35 degrees, the three previously discussed Keflavik-Sondrestrom flights show perturbations where the measured data are lower by about 2 dB than similarly calculated values. Since the measured NAA field strength for the same bearing, but at a greater distance, on August 18, 1961 (Fig. 24) again is higher than the calculated values (1300 UT, Fig. 26), a modification in ground conductivity producing a change in attenuation rate cannot compensate for this approximately 4-dB discrepancy at the 35-degree bearing from NAA.

The modifications to the DECO map, resulting in the DECO-NRL map, were made to yield the best agreement between the calculated field strengths, based on this modified map, the simplified single-mode model, and all the reliable experimental data available. If the NAA data around 1900 UT on August 11, 1037 on August 22, and 2017 on August 27, all in 1961, were neglected or assumed to have been lowered by modal effects, better agreement of calculated and measured data between 1300 and 1530 UT (Fig. 40) could be obtained. This would require an additional modification in area A as indicated by the cross hatching in Fig. 39. This additional modification would simply involve the moving of the boundary line between the "3" and "5" conductivities in the eastern-most part of area A to the west by about 50 km. This would also improve some of the calculated field strengths for NSS (15.5 kHz) to agree better with the data obtained during the flight on September 29, 1959 (Figs. 18 and 19).

This analysis fundamentally was based on a single-mode model. However, the calculated field strengths given in Fig. 40 after 1530 UT contain an approximated correction to allow for modal interference, since the path lengths were less than 2200 km. This correction for the calculated value at 1736 UT, the last point, lowered the field strength by about 2 dB and contributes to a good agreement with the experimental data. The calculated value at 1723 UT was lowered by nearly the same amount by this correction and appears to have had a deleterious effect. There is, however, another consideration concerning the deviation of the calculated value at 1723 UT. At that time the airplane was over seawater near the coast (Fig. 39) with only about 60 km of seawater in the transmission path foreground of the receiving terminal. Since 50 km of foreground had arbitrarily been chosen for the limit in changing excitation factors, the seawater rather than the land conductivity excitation factor was used in that calculation. The use of the excitation factor for the lower conductivity of the land would have raised the calculated value and given better agreement with the measurement.

Keflavik to Goose Bay (September 29, 1959), NSS (15.5 kHz) - The flight from Keflavik to Goose Bay on September 29, 1959, although between the same terminals as the flight on August 28, 1961, followed a rather devious course as shown in Fig. 18. Since the NAA transmitting station was not in existence at this earlier date, the NSS (15.5-kHz) field strengths were measured during this flight and are given in Fig. 19. These data, for somewhat different paths, afford a cross check of the area A modifications based

traversed portions of Baffin Island where no changes in conductivity were made, but this will be treated further in the discussion of area D.

Thule to Sondrestrom to Keflavik Flight (August 27, 1961), NAA (14.7 kHz) - The Thule to Sondrestrom portion of the flight on August 27, 1961 (Fig. 36), was very similar to portions of the flights on August 10, 11 and 22, 1961, already discussed. The NAA (14.7 kHz) field strengths calculated using the DECO-NRL map for the flight on August 27, however, agree more closely with the measured values as shown in Fig. 37 (1200-1530 UT) than the corresponding data for these other three flights (Figs. 23, 25, and 28). The rapid increase in the measured field strength around 1520 UT could be interpreted as an excitation factor change as the receiving terminal foreground changed from seawater to the west coastal area of Greenland (1×10^{-4} mho/m). Such a change in NAA field strength was not observed, however, under similar conditions but flying in the opposite direction during the August 22, 1961, flight (1255 UT, Fig. 28).

The portion of the August 27, 1961, flight between Sondrestrom and Keflavik, roughly 1700 to 2100 UT in Fig. 37, has been treated in the discussion of the area A conductivity modifications. Prior to 1400 UT the NAA propagation paths traversed Baffin Island, and the data for that period will be treated further in the area D discussion.

Sondrestrom to Churchill Flight (August 23, 1961), NAA (14.7 kHz) - Unlike the previous four flights discussed relevant to the conductivity modifications in area B, the flight path on August 23, 1961, from Sondrestrom to Churchill (Fig. 30) was such that none of the propagation paths from NAA traversed any part of Baffin Island. The NAA (14.7 kHz) field strengths recorded during this flight, and shown in Fig. 31, were 4 to 6 dB lower than the values calculated using the DECO map. The excellent agreement between the measured and calculated data using the DECO-NRL map results solely from the conductivity modifications in area B. Modifications to the conductivity in New Brunswick and the Gaspe Peninsula areas could have accounted for only a portion of the original disagreement, and other flights indicated that these areas should not be changed. Since the path lengths for the data for this flight were less than 2.2 Mm, the correction factor approximating the second-order-mode effect has been applied to each calculated data point. At 1900 UT (Fig. 31) this factor appears to produce disagreement between the calculated and measured data. However, considering all the data for this flight, the factor provided a general improvement.

Churchill to Thule Flight (August 25, 1961), NAA (14.7 kHz) - The need for increasing the attenuation rates for portions of area B over those given for the conductivities shown on the original DECO map was again demonstrated by the NAA (14.7 kHz) data gathered during the flight from Churchill to Thule (Fig. 33) on August 25, 1961. It can be seen in Fig. 34 that the measured field strengths were, in some instances, more than 10 dB lower than the calculated fields based on the DECO map. The calculated values based on the DECO-NRL map, however, showed considerably better agreement with the measurements. One exception can be noted at 1612 UT, where a 5-dB discrepancy still remains. The data around 1800 UT for the August 23, 1961, flight (Fig. 31) were at the same bearing from NAA with excellent agreement between the measured and calculated field strengths. Considering these data and those from other flights, there appears to be no logical modification to the conductivity map which would eliminate the discrepancy at 1612 UT.

Prior to 1725 UT, the improvement of the calculated NAA data for August 25, 1961, flights was almost entirely due to the area B modifications. Modifications in the Keewatin region, area C, accounted for less than 1.5 dB for any of these data. After 1725 UT the propagation paths from NAA traverse Baffin Island; consequently, the calculated data based on the DECO-NRL map are affected by the area D modifications in addition to those in area B. The calculated data based on the DECO map did not indicate a dip between 1720 and 1800 UT as observed in the measured data. These NAA data, when compared with data from other flights and other transmitters, gave evidence for the need to modify the conductivity of a small portion of northern Quebec to 3×10^{-5} mho/m, having an attenuation rate at 14.7 kHz of 27.3 dB/Mm. This particular modification in the northern part of area B had much less geophysical justification than any of the other conductivity changes shown in Fig. 11. However, these NAA data, and also data from NSS and NPG to be discussed later, attest to such a highly attenuating region.

Goose Bay to Thule Flight (September 23, 1959), NSS (15.5 kHz) - The previous seven flights discussed concerning the conductivity modifications in area B all involved transmissions from NAA observed in 1961. The NSS (15.5-kHz) field strengths (Fig. 13) recorded on September 23, 1959, during a flight from Goose Bay to Thule (Fig. 12) provided a basis for a more accurate location of some conductivity boundaries in area B, since the propagation paths had somewhat different bearings than for the other flights. Also, the general agreement of these data and those for NAA at nearly the same frequency but observed 2 years later indicated a relatively high degree of repeatability for propagation in the polar regions.

The undulations of the NSS field strengths (Fig. 13) at the beginning of the flight cannot be predicted based either on the original or the modified conductivity maps. Modifying the conductivity map to provide for such undulations would require relatively rapid changes in conductivity over a relatively small area. Also, there are no other data available to verify this particular pattern. The boot-shaped, "3" conductivity boundary in the southern part of area B (Fig. 11) contributed to the agreement of the calculated (DECO-NRL map) and measured data minimum at 1626 UT. This area also provided an improvement for the NAA data for August 23 and 25, 1961 (Figs. 31 and 34). A geological factor influenced the shaping of this boot-like boundary. The foot portion of this boundary encloses Laurentides Park, which is made up of a group of mountains averaging about 4000 ft in elevation and is twice as high as the rest of the hilly terrain along the northwest bank of the St. Lawrence River. The calculated field strengths based on the DECO-NRL map average about 2 dB below the measured data but do show better agreement than the calculated data based on the original map. After 1736 UT, the NSS propagation paths traversed Baffin Island, and the effects of that terrain (area D) on these data will be discussed later.

Thule to Keflavik Flight (September 25, 1959), NSS (15.5 kHz) - The field strengths for NSS (15.5 kHz) presented in Fig. 16 were recorded during a flight on September 25, 1959, from Thule to Keflavik (Fig. 15). Data were recorded for only a small portion of this flight because of severe precipitation static, which frequently limited data recording in the Arctic. The NSS paths for this flight were over the same range of bearings as the data from the September 23, 1959 (Fig. 13), flight after 1706 UT. The two sets of data, however, show considerable disagreement. At 1330 UT on September 25, the measured NSS field strength was about 3 dB higher than for the same location at 2029 UT on September 23. The only significant difference in the propagation path for the data around 1410 UT on September 25 and 1930 UT on September 23 is the addition of a small amount of Greenland, but the measured data differ by about 8 dB. The added Greenland terrain does not explain this difference except that there may be an effect produced at the coastline resulting from the severe change in conductivity from that of seawater to the 1×10^{-5} mho/m Greenland icecap.

The DECO-NRL map, however, provides for considerably better agreement between the calculated and measured data in Fig. 16. This improvement was due to the modification in both areas B and D (Fig. 11) for data prior to 1530 UT, and only the one calculated data point after that time reflects the area B modifications alone.

Sondrestrom to Churchill Flight (August 23, 1961), NPG (18.6 kHz) - Unlike most of the NAA and NSS data already discussed, many of the NPG (18.6-kHz) field-strength measurements, which were for considerably different propagation paths, were higher than those calculated based on the original DECO map. The NPG data (Fig. 32) recorded during the early part of the flight on August 23, 1961, from Sondrestrom to Churchill (Fig. 30) show this tendency. The data for the latter part of the flight after 1530 UT, however, show the reverse. The modifications of the conductivities in area B do not affect the data prior to 1500 UT. From that time until approximately 1730 UT the changes in area B improved the DECO-NRL map predicted field strengths, the agreement with the data being best at 1600 UT. Good agreement is also achieved at 2130 UT, which is for a receiving location at the same bearing from NPG as for the data at 1600 UT but considerably closer to the transmitter. This substantiates conductivity modifications along that path both east and west of Hudson Bay.

Between about 1700 and 1900 UT the NPG (18.6 kHz) measured field strengths are 3 or more dB below the calculated values, which are about the same when using either conductivity map. The two maps yield the same calculated field strength for some of the times, because some of the conductivity modifications result in excitation factor and attenuation rate changes canceling each other. A careful analysis of the data between 1700 and 1900 UT in light of other data indicates that the calculated field strengths could have been lowered only by a modification of conductivities relatively close to the transmitting station NPG. Since there were no other data available for these particular propagation paths and since there was no other information that could be used for establishing where to modify the conductivity, no modifications were made to improve the calculations for these particular situations.

Goose Bay to Thule Flight (September 23, 1959), NPG (18.6 kHz) - The NPG transmissions paths involved for the initial part of the flight from Goose Bay to Thule on September 23, 1959 (Fig. 12), until 1616 UT traversed portions of area B. These paths were at the same bearings from NPG as portions of the flights on August 23, 1961 (Fig. 30), and August 28, 1961 (Fig. 39). The NPG (18.6-kHz) field strengths recorded during the September 23, 1959, flight and given in Fig. 14 are lower than the calculated values based on the DECO map for the first part of the flight. The area B conductivity modifications lowered the calculated field strengths, but the agreement with the measured data between 1400 and 1500 UT is not greatly improved. The calculated field using the DECO-NRL map at 1402 UT is nearly 5 dB below the measured value. However, the calculated (DECO-NRL map) and measured NPG field strengths at 1700 UT (Fig. 41) for the flight on August 28, 1961, are very nearly equal. The propagation path in this instance differed from that for 1402 UT on September 23, 1959, only by about a 200-km additional seawater path. Any conductivity modifications that would have improved these September 23, 1959, calculations would have had a deleterious effect on the calculated data for the August 28, 1961, flight and other flights.

The NPG data after 1616 UT on September 23, 1959, will be treated in the discussion of the conductivity modifications in areas C and D.

Keflavik to Goose Bay Flight (August 28, 1961), NPG (18.6 kHz) - The NPG propagation paths for the August 28, 1961, flight (Fig. 39) from Keflavik to Goose Bay after 1500 UT crossed area B. The area B conductivity modifications improve the calculated field strengths by 4 to 7 dB for the latter part of this flight, as shown in Fig. 41, and bring them into nearly perfect agreement with the measured data. At 1612 UT the full width of the "2" conductivity area in northern Quebec was crossed, and these data tend to validate that modification. The only large discrepancy between the field-strength measurements and those calculated using the DECO-NRL map is at 1512 UT, where the difference is about 3.5 dB. However, the NPG data at 1517 UT on August 23, 1961 (Fig. 32), and at 1543 UT on September 23, 1959 (Fig. 14), suggest that this measurement at 1515 UT was unusually low. All three of these measurements were for the same propagation path except for differences in seawater path length.

The propagation paths from NPG for the first part of the flight on August 28, 1961, until 1500 UT crossed areas C, D, and E; consequently, that data will be treated later.

Keflavik to Goose Bay Flight (September 29, 1959), NPG (18.6 kHz) - The NPG (18.6-kHz) data recorded during the flight on September 29, 1959, from Keflavik to Goose Bay (Fig. 18) are presented in Fig. 20. Of all the data available, this is the only entire group of data that shows general disagreement between the measured field strengths and those calculated using the DECO-NRL map. The calculated values based on the original DECO map show generally better agreement with the measurements. However, the shape of the DECO-NRL map calculated curve better matches the shape of the measured curve. If all the measured data were 4 to 5 dB lower, these two curves would agree very well and would also agree with similar data (Fig. 41) for the August 28, 1961, flight. Any attempt to bring these calculated and measured data into agreement by modifying ground conductivities would have adversely affected agreement between calculated values and other data; therefore, none was made.

The NPG field strengths for this September 29, 1959, flight appear to be abnormally high, resulting from abnormal propagation conditions. Any receiving instrumentation errors would have resulted in data from other transmitting stations for that flight being abnormally high also, which was not the case. The radiated power of all the transmitting stations was monitored during each of the experimental flights reported here, and this must also be eliminated as a possible cause for the abnormal data from this flight.

Area C, Keewatin and Mackenzie

The conductivity of the districts of Keewatin and Mackenzie, northwest of Hudson Bay, has received particular attention in the NRL investigation of vlf propagation in the Arctic since the very beginning in 1959. The field strengths of NPG (Fig. 14) recorded during a flight from Goose Bay to Thule on September 23, 1959 (Fig. 12), indicated a highly attenuating area along a bearing from NPG through Keewatin. This path also crossed Baffin Island, which was believed to be of very low conductivity, but the path length over that Island was rather short. The NPG (18.6 kHz) data from this flight, as shown in Fig. 14, received particular attention not only because of the depth of the null around 1830 UT but also because of its narrowness and the steepness of its sides. The data led to the decision to make the flights in 1961 from Sondrestrom to Churchill and then to Thule (Figs. 30 and 33) around Hudson Bay and through the District of Keewatin to investigate the attenuation through this region.

The major modification of conductivity in area C as shown in Fig. 11 is the change of a considerable portion of the Keewatin and Mackenzie districts from 1×10^{-4} mho/m ("3"), as given by the original DECO map, to 3×10^{-4} mho/m ("4"). The modified boundaries between the "3" and "4" conductivities are approximately along radials from NPG through that area and account for the sudden change in NPG field strength as observed during the flight from Goose Bay to Thule (Fig. 14). The only other conductivity modifications in area C are a small region near the western shore of Hudson Bay where some areas of "3," "4," and "6" conductivities were changed to "5."

Goose Bay to Thule Flight (September 23, 1959), NPG (18.6 kHz) - As mentioned above, the NPG (18.6 kHz) data (Fig. 14) recorded on September 23, 1959, during a flight from Goose Bay to Thule (Fig. 12) stimulated considerable interest in vlf propagation over the Districts of Keewatin and Mackenzie in Canada. The field strength of NPG as shown in Fig. 14 indicated a quite severe and abrupt attenuation around 1830 UT. Between 1746 and 1834 UT the field strength of NPG decreased by almost 11 dB. The original DECO map conductivities yielded calculated field strengths very nearly equal to the lowest measured values at 1834 UT, but in general these calculated values were much lower than the measurements after 1550 UT.

Prior to 1616 UT, the changes in calculated field strengths are the result of conductivity modifications in northwestern Quebec, area B, and the southern portion of area C.

during the flight 2 years earlier the frequency was 18.6 kHz. A comparison of these two sets of data at different frequencies for propagation over the same paths provides a check on the frequency dependence of the attenuation rates as a function of ground conductivity. The data from the August 22, 1961, flight pertinent to the area C conductivity modifications are shown in Fig. 29 from 1300 UT to the end.

The data at 1330 and 1730 UT for the latter flight (Fig. 29) are at very nearly the same location, differing only by a short length of seawater path, as the data at 1746 UT for the earlier flight (Fig. 14). The two measurements at 15.5 kHz from the same flight repeated well and are 1 to 2 dB lower than the calculated (DECO-NRL map) values. The 18.6-kHz measurement at 1746 UT on September 23, 1959, was about 1 dB higher than the similarly calculated field strength. Other points which show similar results are at 1424 and 1643 UT on August 22, 1961, and at 1834 UT on September 23, 1959. These data recorded at virtually the same location for NPG transmissions at 15.5 and 18.6 kHz show a fair degree of agreement with the frequency dependence of the propagation parameters given by Wait and Spies (1). The examples cited show the calculated field strengths to have a slight positive slope with frequency, whereas the experimental values are nearly independent of frequency over this limited range.

The major discrepancies between the measured NPG field strengths on August 22, 1961, and those calculated using the DECO-NRL map are around 1525 UT (Fig. 29). No explanation for these discrepancies is available. The calculated data do not predict the field strength decrease between 1450 and 1550 UT. A small dip in the field strength was observed at the same location for the NPG transmissions at 18.6 kHz during the September 23, 1959, flight as shown at 1940 UT in Fig. 14. However, the agreement between the measured and calculated data for this earlier flight, and different frequency, is much better. A partial explanation for the discrepancy in the August 22, 1961, data could be in not knowing the aircraft location accurately. If at 1525 UT the aircraft was actually 50 km north of its stated position, the calculated field strength would have been 2 dB lower than the value given in Fig. 29. Making modifications in the conductivity map to compensate for this discrepancy would have resulted in discrepancies in the agreement with data from several other flights. The only way in which the calculated NPG field strengths at 15.5 and at 18.6 kHz could have been made to agree with the measured data for these particular paths would have been to change the attenuation-rate frequency dependence. However, such a change was not indicated by other data. The NPG data from the first part of the flight on August 22, 1961, between Keflavik and Sondrestrom are covered in the discussion of area E modifications.

Thule to Sondrestrom to Keflavik Flight (August 27, 1961), NPG (18.6 kHz) - On August 27, 1961, another flight (Fig. 36) was made along the west coast of Greenland from Thule to Sondrestrom and then on across Greenland to Keflavik. The first segment of this flight obtained data for nearly the same NPG propagation paths over area C as the flights on September 23, 1959, and on August 22, 1961. The NPG (18.6 kHz) data from the August 27, 1961, flight are given in Fig. 38 and are very similar to the results from the September 23, 1959, flight shown in Fig. 14. The minimum at 1405 UT for the path over the central Keewatin region for the 1961 flight is almost exactly the same as the minimum observed for that same path 2 years earlier. The measured data obtained north of that minimum toward Thule for both of the flights are somewhat higher than the data calculated using the DECO-NRL map but are in better agreement than with the calculations based on the original map. Ground sunrise at NPG did not occur until 1330 UT on August 27, 1961, although at the height of the ionosphere, sunrise was roughly an hour earlier. Therefore, the data around that time may not be truly representative for a daylight ionospheric condition.

After the minimum at 1405 UT and until 1530 UT when the aircraft arrived at Sondrestrom, the measured and calculated (DECO-NRL map) data agreed extremely well with each other and with the experimental data for those same paths from the

September 23, 1959, flight, 1730 to 1835 UT in Fig. 14. The improvement provided by the area C conductivity modifications for this portion of the data is about 8 dB.

Thule to Keflavik Flight (September 25, 1959), NPG (18.6 kHz) - On September 25, 1959, a flight was made from Thule to the west for a short distance and then back over Thule and on over Greenland to Keflavik (Fig. 15). The NPG (18.6-kHz) data recorded during this flight are presented in Fig. 17. At 1600 UT, when the aircraft was about midway across Greenland, the NPG transmissions became undetectable in the presence of precipitation static, which was a frequent limitation during these arctic area investigations. Unfortunately, this loss of data occurred before the propagation path from NPG scanned much of area C. Therefore, these data contributed little in the analysis of the area C conductivity modifications.

The data presented in Fig. 17 indicate an improvement in the calculated data resulting from the area C conductivity modifications up to 1515 UT. The decrease in the measured field strength after that time is unexplained. The oscillatory pattern of the data between 1400 and 1500 UT may be the result of multimode effects. A similar effect, but with excursions of lesser magnitude, was observed at about the same bearing from NPG during the September 23, 1959, flight between 2005 and 1950 UT.

Churchill to Thule Flight (August 25, 1961), NAA (14.7 kHz) - Unfortunately, there was practically no data available from transmissions other than NPG which were useful in analyzing the area C ground conductivities. The transmission paths from NAA for the flight on August 25, 1961, from Churchill to Thule (Fig. 33) traversed some of the Keewatin district but none of the Mackenzie District and, in general, contributed little to this phase of the analysis. Figure 34 shows the NAA data obtained during this flight. A considerable improvement in the calculated data is shown, but scarcely more than 1 dB of this improvement is the result of the area C modifications. Had more data been available, it may have been possible to improve the calculated data around 1600 UT.

Area D, Baffin Island

The primary conductivity modification on Baffin Island was the conversion of the southern portion of the Island from 1×10^{-4} mho/m ("3") to 3×10^{-4} mho/m ("4"), as shown in Fig. 11. In addition, a small area near the center of the Island was changed from 3×10^{-5} mho/m ("2") to 1×10^{-4} mho/m ("3"). The analysis of the conductivities of Baffin Island (area D), which was based on propagation data from NAA, NSS, and NPG, was complicated by the interrelations with the modifications in areas B and C. The confidence factor for the conductivity of the northern part of the Island is not very high, since only a small amount of data was available for the analysis of that area. Also, there was a conflict in the data concerning the Hall Peninsula, which is a part of the area on Baffin Island where the conductivity was changed from "3" to "4." All the September 1959 data and some from the flights in August 1961 indicated agreement with this change. However, data from both NAA and NPG from two flights in August 1961 indicated that the original conductivity ("3") was correct.

Data relevant to the analysis of Baffin Island conductivity were recorded during many experimental flights. However, the amount of relevant data from some flights was small. Consequently, in the following, the results of such flights are discussed in groups rather than individually.

Churchill to Thule Flight (August 25, 1961), NAA (14.7 kHz) - The flight from Churchill to Thule on August 25, 1961, shown in Fig. 33, was the only experimental flight to actually cross Baffin Island. The NAA field-strength data recorded during this flight are presented in Fig. 34. The data relevant to the Baffin Island analysis are from 1728 UT to the end, although the Island had little effect until 1820 UT. The conductivities given by

were about the same as those for the September 23, 1959, flight discussed above. The primary difference is that the receiving terminal was over the Greenland icecap most of the time. The extreme discontinuity in ground conductivity as the radio wave propagates over seawater and then over the icecap may cause additional modes to be excited, thereby making the one-mode analysis employed here insufficient. In general, the NSS data from this flight, presented in Fig. 16, contradicted the conclusions drawn for the Baffin Island conductivity from the September 23, 1959, NSS data. At 1330 UT on September 25, the aircraft was not yet over the icecap, and the NSS path traversed the area with a conductivity of "2" in western Baffin Island. The measured field is less than the calculated (DECO-NRL map) value indicating the need for more attenuation for the calculated value. The September 23 data indicated just the opposite. At 1400 UT when the aircraft was over the icecap the data tend to show disagreement with the modification of the conductivity in the southern part of the Island. However, at 1500 UT the data indicate agreement with the modification of the conductivity for the Hall Peninsula. Because of the possibility of multimode propagation during the September 25, 1959, flight, the September 23 data were given more weight in the analysis of Baffin Island.

Churchill to Thule Flight (August 25, 1961), NPG (18.6 kHz) - The aircraft was flown over Baffin Island approximately along a radial from NPG on August 25, 1961 (Fig. 33). The plane was over the Island from 1820 to 1910 UT. The NPG field strength presented in Fig. 35 shows a leveling off between 1820 and 1835 UT. This probably results from the change in the excitation factor as the receiving foreground changes from seawater to a conductivity of 3×10^{-5} mho/m ("2"), canceling the increasing attenuation as more of this very-low-conductivity land is introduced into the path. Then the NPG field strength decreased very rapidly until the plane reached the other side of the Island at 1910 UT. This sharp drop in the field strength is predicted by the calculated data as shown in Fig. 35 primarily because of the great change in the excitation factor. The excellent fit of the data appears to confirm the ground conductivities given for the area of Baffin Island traversed and the excitation factors given by Wait and Spies (1).

At 1910 UT the aircraft headed northward toward Thule. The differences between the two sets of calculated data after this time as shown in Fig. 35 are due to conductivity modifications in the Mackenzie District. The reasonably good agreement of the calculated data based on the DECO-NRL map with the experimental results from 1930 through 2030 UT verifies the ground conductivity of the northern part of Baffin Island. No explanation is available for the discrepancy at 2045 UT.

Goose Bay to Thule Flight (September 23, 1959), NPG (18.6 kHz) - The data recorded for the NPG transmission during a flight from Goose Bay to Thule (Fig. 12) on September 23, 1959, are presented in Fig. 14. From 1556 UT until the end of the flight, the NPG propagation path crossed Baffin Island. The conductivity modification in southern Baffin Island helped to fit the calculated (DECO-NRL map) data to the measurements between 1556 and 1750 UT. At 1646 UT, for example, the effect of this modification, which included the Hall Peninsula for this particular path, was to increase the calculated value by almost 3 dB. In light of other data, there is no explanation for the poor fit of the calculated field strength at 1726 UT, which was for a path that included the Cumberland Peninsula. However, the Baffin Island modifications did help to improve the fit.

As the plane continued northward, the dip in the NPG field strength around 1834 UT is primarily the result of conductivity changes in the Keewatin District previously discussed in area C. The area with a conductivity of "2" in the western part of Baffin Island was in the NPG path at 1834 UT, but its length was so short that changing its conductivity to "3" would have increased the calculated value by less than 1 dB. The area in the northern part of the Island where the conductivity was changed from "2" to "3" did help somewhat in predicting the increase in the field after 1834 UT. Again, the original conductivities of the northern portion of the Island were reasonably well confirmed by the data from the latter portion of this flight.

Sondrestrom to Churchill Flight (August 23, 1961), NPG (18.6 kHz) - The field strengths of NPG were recorded on August 23, 1961, during a flight from Sondrestrom to Churchill shown in Fig. 30. During the first part of the flight, until about 1510 UT, the propagation paths from NPG crossed the southern portion of Baffin Island where the conductivity had been changed from "3" to "4." The DECO-NRL map field-strength predictions presented in Fig. 32 were increased by the Baffin Island modifications and show generally good agreement with the measured NPG data. At 1334 UT this modification, however, raised the calculated value only slightly more than 1 dB. The rest of the difference in the two sets of calculated data arose from the conductivity change in Keewatin and British Columbia. At 1430 UT, the Baffin Island modification increased the calculated field strength by 2.5 dB, but it is 1.5 dB higher than the measured field. This tends to indicate that the conductivity of the Hall Peninsula should not have been changed as was also indicated by the NAA data from the August 10 and 11, 1961, flights. Only these three sets of August 1961 data show this. Other data recorded during that month and in September 1959 agree with the modification.

Keflavik to Sondrestrom, North, and Return to Sondrestrom Flight (August 22, 1961), NPG (15.5 kHz) - On August 22, 1961, the operating frequency of NPG was 15.5 kHz rather than its normal 18.6 kHz. The field strengths measured for NPG on that day during a flight from Keflavik to Sondrestrom, northward, and then returning to Sondrestrom (Fig. 27) were of considerable value in verifying the frequency dependence of the propagation parameters for various ground conductivities. The NPG data recorded during this entire flight were for paths crossing Baffin Island. However, only the data between 1300 and 1747 UT, as given in Fig. 29, will be discussed here. The data for the rest of the flight were recorded while the plane was over Greenland and will be treated in the discussion of area E, which is Greenland

Much of the improvement in the DECO-NRL map predicted data is the result of conductivity modifications in area C (Keewatin and Mackenzie districts). The Baffin Island modifications, however, did help produce the generally good agreement with the measurements. At 1300 and 1747 UT, the changes on Baffin Island raised the calculated fields by approximately 1 dB. The NPG path traversed the Island area with a conductivity of "2" at 1454 and at 1647 UT. The measurements at those times, when compared with the DECO-NRL map predicted data, tend to verify the conductivity for that area. The attenuation rates for conductivities of "2" and "3" differ more greatly at 15.5 kHz than at 18.6 kHz. If the conductivity of that area of the Island were "3" instead of "2," the calculated values would have been 1.5 dB higher, which would produce poorer agreement with the measured values.

There is no explanation for the great difference, 5 dB, between the measurement and the calculated (DECO-NRL map) data at 1525 UT. This is not consistent with other results. More data from NPG at 15.5 kHz for the paths observed between 1500 and 1600 UT are needed to analyze that situation.

Thule to Sondrestrom to Keflavik Flight (August 27, 1961), NPG (18.6 kHz) - The NPG propagation paths concerned with the data recorded on August 27, 1961, during the flight from Thule to Keflavik via Sondrestrom (Fig. 36) all crossed Baffin Island. However, only the portion of the flight between Thule and Sondrestrom will be discussed in this section with the remainder to be treated in the area E discussion. The NPG (18.6 kHz) data gathered during this flight are presented in Fig. 38. Most of the improvement in the predicted field strengths shown is the result of conductivity modifications in areas other than Baffin Island. However, the changes made on the Island did contribute somewhat to the improvement. At 1345 UT, the NPG path crossed the area where the conductivity was changed from "2" to "3," and the change increased the predicted field by about 1 dB and helped to give a better fit with the measurement. Also, at 1512 UT, the area of Baffin Island where the conductivity was changed from "3" to "4" was in the path.

The improvement here was a little more than 1 dB. At 1245 UT the plane was at nearly the same location as at 1525 UT on the August 22, 1961 (Figs. 27 and 29). The NPG field strength at that location for 15.5 kHz during the August 22 flight was considerably below the calculated value. During the August 27 flight the situation for the 18.6-kHz transmissions from NPG was just the opposite. This measurement on the latter date, however, was made not long after the sunrise transition period and may be contaminated by modal interference associated with the sunrise period.

Area E, Greenland

Data for transmissions from NAA, NSS, and NPG were available for the analysis of the conductivities, attenuation rates, and excitation factors involved for propagation over Greenland. However, most of the data was for propagation paths over southern Greenland. Frequently during flights, when data for the northern portion could have been recorded, the field strength of the appropriate transmissions were below detectability. The only change in conductivity for Greenland from that given by the original DECO map is the change of the east coast area from a conductivity of 1×10^{-4} mho/m ("3") to 1×10^{-5} mho/m ("1") as shown in Fig. 11. Unfortunately, data from only one flight were available for analyzing the northern portion of this modified area. However, the data from several flights substantiated the conductivity modification for the southern portion of that area.

The geophysics of the coastal areas of Greenland show general agreement with the modification, which results in the east coastal region having a lower conductivity than the region along the western coast in the southern half of that island. The Greenland icecap extends almost all the way to the eastern coast. This is possibly the result of the cold ocean current (East Greenland Current) which flows southward along Greenland's east coast. On the other hand, the icecap is much further inland along the west coast, possibly due to the warm ocean current (West Greenland Current) flowing northward along that coast.

Initially, the analysis of the data for propagation paths over Greenland was concerned with determining the attenuation rates and excitation factors for propagation over the icecap area. The results showed good agreement with the rates given by Wait and Spies (1) for a conductivity of 1×10^{-5} mho/m ("1"), which is the value given by Morgan and Maxwell (2) for the Greenland icecap area. Some data, however, indicated that the attenuation rates might be slightly higher. Much of the data recorded while flying over Greenland show an oscillatory pattern, which may be due to multimode interference resulting from mode conversion at the seawater-icecap boundary. As might be expected, data from NAA at 14.7 kHz did not exhibit this to as great an extent as data at higher frequencies. Data recorded over the ocean, well away from the Greenland coast and for propagation paths which traversed Greenland, do not show the oscillatory pattern and confirm the attenuation rates for the icecap conductivity of 1×10^{-5} mho/m.

Flights Between Sondrestrom and Keflavik (August 11, 22, and 27, 1961), NAA (14.7 kHz) - The field strengths of NAA transmissions were recorded while over Greenland and over the ocean area east of Greenland during the flights on August 11, 22, and 27, 1961 (Figs. 24, 27, and 36), between Sondrestrom and Keflavik. It can be seen in Figs. 25, 28, and 37 that these measured data were about 5 dB below the field strengths calculated using the DECO map. The modification of the conductivity along the east coast of Greenland, area E, helped to bring the DECO-NRL map based calculations into better agreement with the experimental data, but the area A modifications also contributed much to this improvement.

Between 1630 and 1745 UT on August 11, 1961 (Fig. 25), the NAA propagation paths to the receiving aircraft crossed portions of Greenland where no changes in conductivity were made. Since the plane was over the icecap at this time, as shown in Fig. 24, the data reasonably confirm the attenuation rates and excitation factors given by Wait and Spies (1) for a conductivity of 1×10^{-5} mho/m. As the flight continued toward Keflavik, the east coast area of Greenland, where the conductivity was modified, came into the path. At 1836 UT, the area E conductivity modification lowered the calculated (DECO-NRL map) field strength by 3 dB. The excitation factors given in Fig. 25, as for all similar graphs, are for the conductivities given by the DECO-NRL map. Around 1800 UT, the plane was crossing the modified east coast area of Greenland. If the ground conductivity of the area were as given in the DECO map, the excitation factor would have changed from -0.6 dB ("1") to 3.6 dB ("3") and to -0.3 dB as the plane crossed from the icecap area to the coastal area and then out over the seawater. The calculated data based on the DECO map show the effect of this change by the dip from 1800 to 1810 UT. The measured NAA data do not show such a dip and, consequently, show further concurrence in the area E modification. These data, for a frequency of 14.7 kHz, may show some multimode effects between 1830 and 1900 UT.

The data collected during the August 22, 1961, flight between 1000 and 1250 UT (Fig. 28) and also on August 27, 1961, between 1736 and 2030 UT (Fig. 37), for NAA propagation paths over Greenland, show much the same results as that discussed above. The data from these flights, as can be seen around 1120 UT in Fig. 28 and around 1855 UT in Fig. 37, also do not show an effect of the excitation factor change that would be expected if the conductivities of area E were as given by the original DECO map.

Keflavik, North, and Return to Keflavik Flight (August 18, 1961), NAA (14.7 kHz) - A flight over seawater east of Greenland from Keflavik to the north and then returning to Keflavik (Fig. 24) was made on August 18, 1961. The NAA field strengths (Fig. 26) recorded during this flight were for propagation paths crossing rather great distances over the eastern portion of Greenland. Ground sunrise occurred at the transmitter around 0930 UT. Therefore, only the data recorded after 1020 UT, the northern-most point of the flight, were used in the analysis. At that time, the NAA propagation path crossed the northern-most part of the modified conductivity area along the east coast of Greenland. These are the only data available for paths over that portion of Greenland. At 1020 UT, the area E modification contributed about 2.5 dB of the difference in the two sets of calculated data shown in Fig. 26, while at 1124 UT, the area E modification accounted for 4 dB of the difference. The remaining differences between the two sets of calculated data result from the area A modifications. The nearly 40-dB change in the field strength of NAA as shown in Fig. 26 between 1020 UT and the end of the flight is primarily due to the attenuation produced by the Greenland icecap. These data exemplify the attenuating effect of Greenland well, since the flight is away from the Greenland coast and entirely over seawater, and the total path length changes by less than 0.6 Mm.

Thule to Keflavik Flight (September 25, 1959), NSS (15.5 kHz) and NPG (18.6 kHz) - During the flight from Thule to Keflavik on September 25, 1959 (Fig. 15), the field strengths of the transmissions of NSS at 15.5 kHz and of NPG at 18.6 kHz were recorded as presented in Figs. 16 and 17, respectively. The propagation paths for these two sets of data are greatly different, but both show generally poor agreement with the calculated data. The conductivity modifications lower the calculated values for NSS in Fig. 16 by 7 to 10 dB, which is a considerable improvement. However, most of the improvement resulted from area B modifications. The erratic pattern of the measured data in comparison to the calculated values suggests modal interference. As suspected for some of the other data, mode conversion at the seawater-icecap boundary may have given rise to higher-order modes even at a frequency as low as 15.5 kHz during daylight. Likewise, the NPG (18.6 kHz) measured field strengths recorded during the same flight (Fig. 17) also had an erratic pattern. Here again the transmissions had crossed the seawater-icecap boundary.

Flights Between Sondrestrom and Keflavik (August 22 and 27, 1961), NPG (15.5 and 18.6 kHz) - The data recorded on August 22 and 27, 1961, during the portions of flights

Table 1
Comparison of Measured and Calculated
Field Strengths for Daylight Paths
August 1961

Receiver Location	Transmitter	Frequency (kHz)	E (dB Rel. to 1 μV/m)		Calc. - Meas. (dB)
			Measured	Calculated*	
Goose Bay	NAA	14.7	47.8	49.4	+1.6
Goose Bay	NPG	15.5	26.5	28.2	+1.7
Goose Bay	NPG	18.6	24.3	25.7	+1.4
Keflavik	NAA	14.7	37.4	38.9	+1.5
Keflavik	NPG	18.6	9.0	8.1	-0.9
Keflavik	NPG	26.1	6.7	5.2	-1.5
Thule	NAA	14.7	23.5	23.5	0
Thule	NPG	15.5	26.0	26.7	+0.7
Thule	NPG	18.6	27.8	25.2	-2.6
Thule	NPG	26.1	25.2	20.4	-4.8
Sondrestrom	NAA	14.7	39.1	37.2	-1.9
Sondrestrom	NPG	15.5	22.2	23.9	+1.7
Sondrestrom	NPG	18.6	23.3	23.2	-0.1
Sondrestrom	NPG	26.1	20.9	17.1	-3.8

*Calculations were made using the DECO-NRL conductivity map, where P = 1 kW, n = 1, and β = 0.3/km.

The field strengths of several vlf transmissions were recorded for long periods of time at several locations in Norway around the times of the airborne experiments reported here. The data recorded for NSS at 15.5 kHz for daylight paths to Varhaug and Bodo, Norway, for several months in 1959 and 1960 are given in Fig. 42. These NSS data are the averages of the hourly field strengths over the course of a month during the periods when the paths were entirely in daylight. In general, each data point represents the average of more than 20 measurements. The data recorded at Varhaug, in the southern part of Norway, closely agree with the calculated value using an ionospheric gradient β of 0.3/km. There is a consistent tendency, however, for the field strengths to increase as the sun progresses toward summer solstice. This indicates that the ionosphere is becoming more reflective during the months when the sun is more directly over the propagation path. This is consistent with results reported by Rhoads and Garner (4), which showed that the ionospheric gradient for midlatitude paths during the summer was 0.5/km. Since the NSS-to-Varhaug path is predominantly over seawater, as shown in Table 2, the data from Varhaug given in Fig. 42 are more significant for establishing the ionospheric gradient than in verifying the conductivity map.

The average field strengths for NSS (15.5 kHz) recorded at Bodo, Norway, near the arctic circle, are also presented in Fig. 42. The total path lengths from NSS to Varhaug and to Bodo are not greatly different as shown in Table 2. The average NSS field strength at Bodo, however, is roughly 20 dB below that at Varhaug. This difference is due to nearly half of the NSS-to-Bodo path being over land, some of which is of very low conductivity. The data for this propagation path, therefore, provide a means for verifying the conductivity map. Using the ionospheric gradient of 0.3/km indicated by the NSS-Varhaug data (Fig. 42), the calculated field strength for NSS at Bodo is approximately

Table 2
Vlf Effective Ground Conductivities Along Great Circle Paths from NSS to Varhaug, Bodo, and Hammerfest, Norway

Conductivity (mhos/m)	Distance (Mm)		
	NSS to Varhaug	NSS to Bodo	NSS to Hammerfest
1×10^{-5}	-	0.49	1.33
3×10^{-5}	-	-	-
1×10^{-4}	-	0.54	0.73
3×10^{-4}	-	0.11	0.32
1×10^{-3}	1.72	1.10	1.01
3×10^{-3}	0.10	0.07	0.07
1×10^{-2}	-	-	-
3×10^{-2}	-	0.23	0.28
1×10^{-1}	-	-	-
4	4.14	3.58	2.56
Total path	5.96	6.12	6.30

3 dB higher than the average measurements. These experimental data do not show the same solar dependence as discussed above for the Varhaug data.

Data similar to that presented in Fig. 42 for daylight paths are presented in Fig. 43 for nighttime paths for comparison. This report is concerned only with daylight propagation conditions, since the single-mode model used in the analysis would be much less accurate for nighttime conditions. The multimode effects would be much greater at night and would increase with frequency. The data shown in Fig. 43 are for a comparatively low frequency where such effects are reduced but certainly not absent at a distance of 6 Mm as shown by Brookes, et al. (5). These nighttime data, therefore, are presented only to give a rough idea of the degree of agreement between the field strengths as measured and as calculated using only the first-order mode.

The NSS propagation path to Hammerfest, in the extreme northern part of Norway, is only a little longer than to Varhaug (Table 2), but about a third of the path is over very low conductivity terrain. The field strengths of NSS (22.3 kHz) as measured at Varhaug and Hammerfest are shown in Fig. 44. These data, being for all daylight paths, are for the months from March through July 1961 and are the averages of 10 or more hourly measurements over the month. Most monthly averages are for more than 40 measurements. The data from both Varhaug and Hammerfest strongly indicate a sun's zenith angle dependency. In March and April the measurements agree well with the calculations based on a β of 0.3/km. This is in agreement with the airborne data which were obtained during months around equinox. It can be seen, however, that as the sun progresses toward summer solstice, the ionosphere for the northern latitude paths becomes more reflective. The data recorded during these summer months tend to agree better with the calculated value based on a β of 0.5/km, the same as for the experimental results for midlatitude, daytime paths during summer months reported by Rhoads and Garner (4). The relative change in the field strengths at Varhaug and Hammerfest, over the period from March to July, indicates agreement with the attenuation rate dependence on the ionospheric gradient and effective ground conductivity given by Wait and Spies (1) and with the DECO-NRL conductivity map.

CONCLUSIONS

The experimental propagation data for daylight paths around the time of equinox indicate agreement between several effective ground conductivities given by Morgan and Maxwell (2) and the corresponding attenuation rates theoretically derived by Wait and Spies (1) for an ionospheric height of 70 km and gradient of 0.3/km. Sufficient data were not available for verifying the attenuation rates for each of the 10 effective ground conductivity values delineated in the maps shown in Figs. 9, 10, and 11. Therefore, for the effective ground conductivity analyses which followed, it was assumed that all the theoretical values of the propagation parameters were correct. Field strengths measured for transmissions at several frequencies, and over various arctic paths, indicate that the frequency and ground conductivity dependence of the excitation factors and attenuation rates used is at least approximately correct. These data also show good repeatability over a 2-year period.

The results show that the strength of vlf fields propagating during daylight over mixed arctic terrain of conductivities from 4 to 1×10^{-5} mho/m can be calculated with a fair degree of accuracy when using the revised ground conductivity map presented and the theoretical parameters of Wait and Spies (1). This is limited, however, to periods when the arctic ionosphere is undisturbed. Others, such as Westerlund, et al. (6), have investigated the effects of polar ionospheric disturbances. Except for the data obtained while over Greenland, the effects of modal conversion and multimode propagation appear to be small for the daylight paths and at the frequencies observed in the airborne experiments (18.6 kHz and below). Therefore, the use of only the first-order-mode waveguide model in this analysis appeared to be justified.

A worldwide, vlf effective ground conductivity map has been prepared by Morgan (7) under contract for NRL. The techniques used in the development of this map were the same as those used by Morgan and Maxwell (2). The ground conductivity analysis reported here was limited by the available propagation data to Greenland and the eastern portion of Canada.

REFERENCES

1. Wait, J.R., and Spies, K.P., "Characteristics of the Earth-Ionosphere Waveguide for VLF Radio Waves," NBS Technical Note 300 and Numerical Supplement, Dec. 30, 1964
2. Morgan, R.R., and Maxwell, E.L., "Omega Navigational System Conductivity Map," DECO Electronics, Inc., Report 54-F-1 for Contract Nonr 4107(00), Dec. 1965
3. Morgan, R.L., Private Communication
4. Rhoads, F.J., and Garner, W.E., "An Investigation of the Modal Interference of Very-Low-Frequency Radio Waves," NRL Report 6359, Oct. 27, 1965
5. Brookes, C.B., Jr., McCabe, J.H., and Rhoads, F.J., "Theoretical VLF Multimode Propagation Predictions," NRL Report 6663, Dec. 1, 1967
6. Westerlund, S., Reder, F.H., and Åbom, C., "Effects of Polar Cap Absorption Events on VLF Transmissions," to be published through the Institute for Exploratory Research, P.O. Box A, Deal, New Jersey 07723
7. Morgan, R.R., "Preparation of a Worldwide VLF Effective Conductivity Map," Westinghouse Electric Corporation, Environmental Science and Technology Department for Contract N00014-67-C-0274, Mar. 15, 1968.

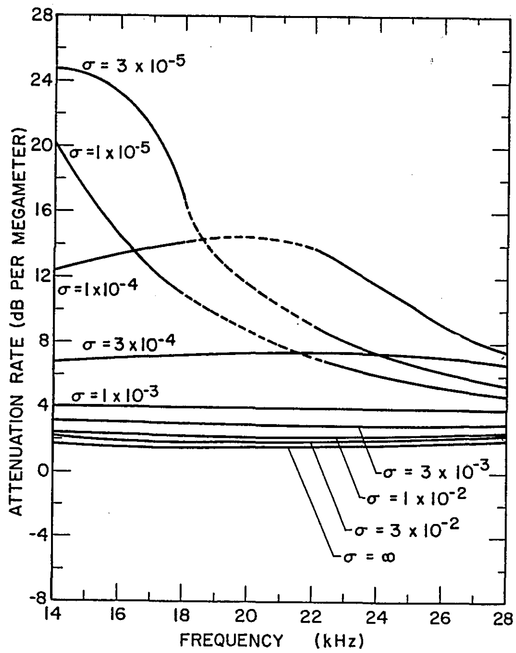

Fig. 1 - First-order-mode attenuation rates from Wait and Spies (1) for β = 0.3/km and h = 70 km. In Figs. 1 through 8 the conductivity σ is given in mhos per meter and n = 1

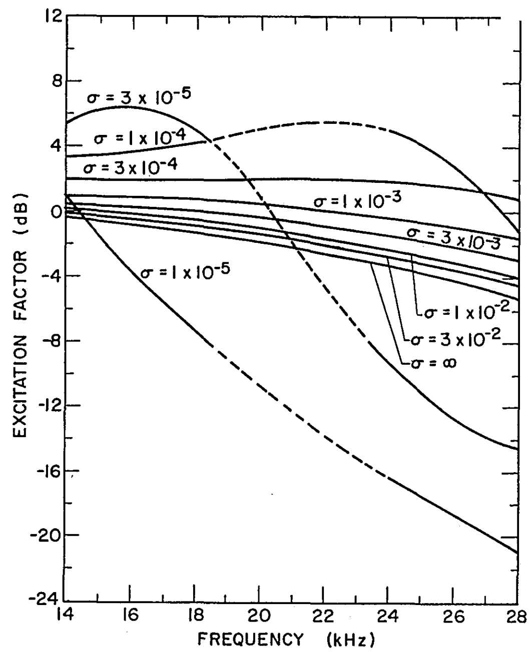

Fig. 2 - First-order-mode excitation factors from Wait and Spies (1) for β = 0.3/km and h = 70 km

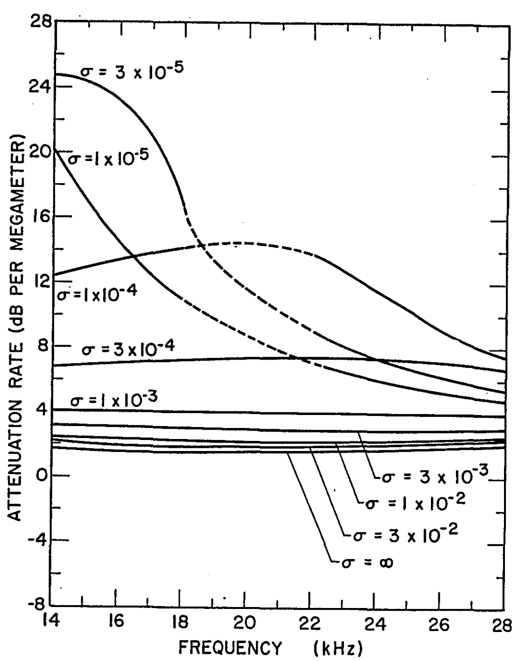

Fig. 3 - First-order-mode attenuation rates from Wait and Spies (1 for β = 0.5/km and h = 70 km

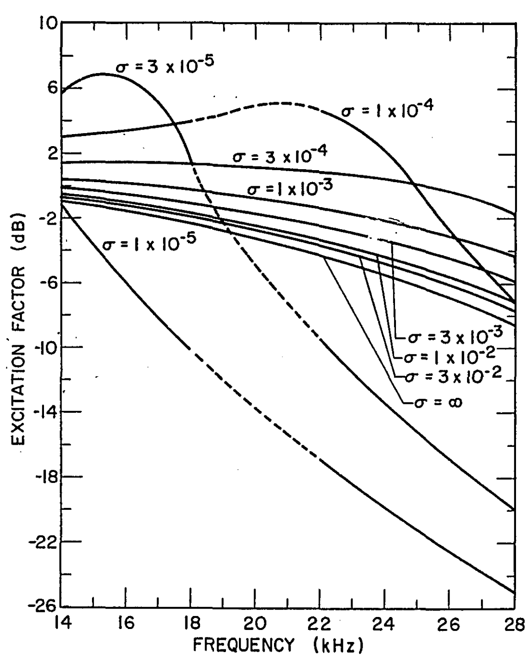

Fig. 4 - First-order-mode excitation factors from Wait and Spies (1) for β = 0.5/km and h = 70 km

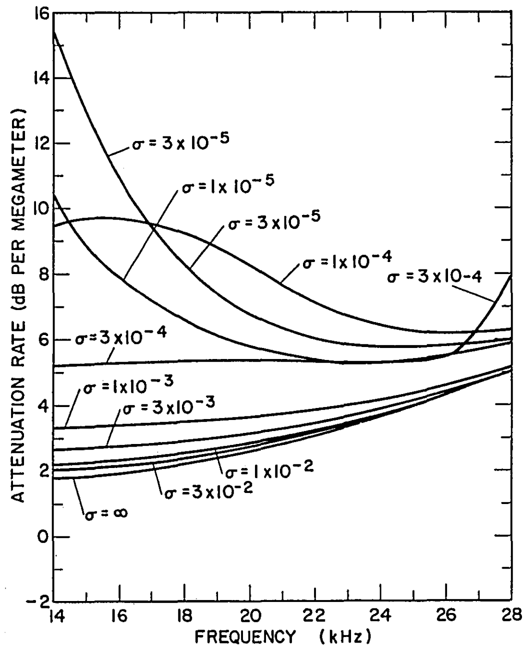

Fig. 5 - First-order-mode attenuation rates from Wait and Spies (1) for $\beta = 0.3$/km and h = 90 km

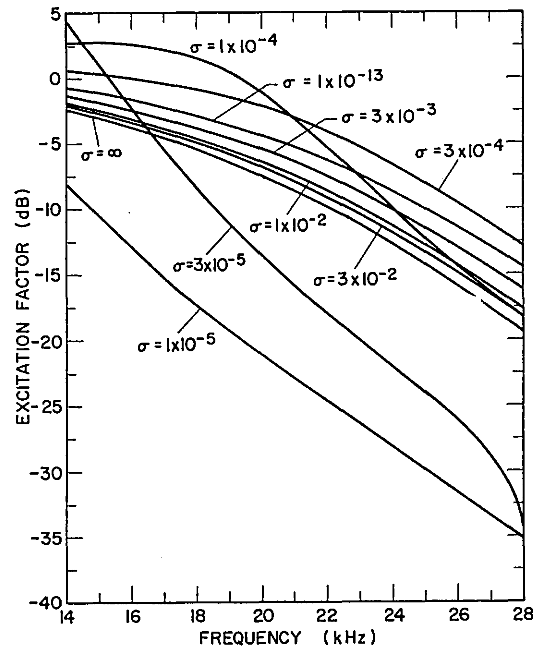

Fig. 6 - First-order-mode excitation factors from Wait and Spies (1) for $\beta = 0.3$/km and h = 90 km

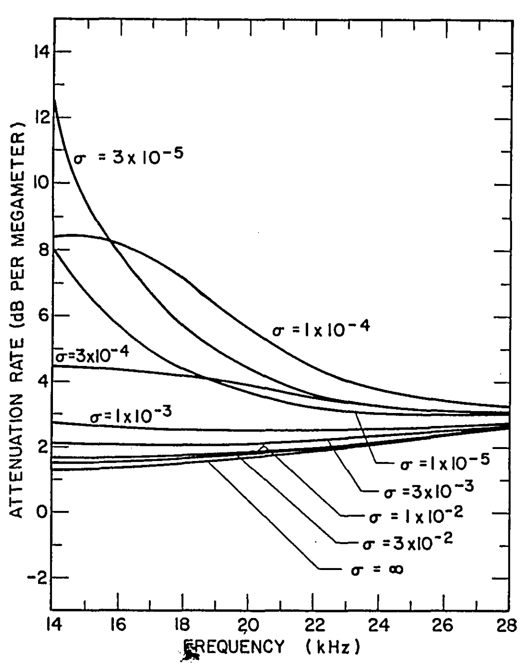

Fig. 7 - First-order-mode attenuation rates from Wait and Spies (1) for $\beta = 0.5$/km and h = 90 km

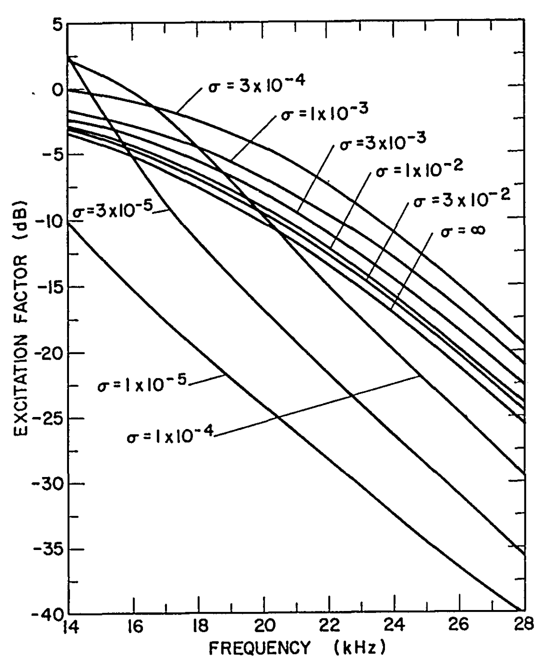

Fig. 8 - First-order-mode excitation factors from Wait and Spies (1) for $\beta = 0.5$/km and h = 90 km

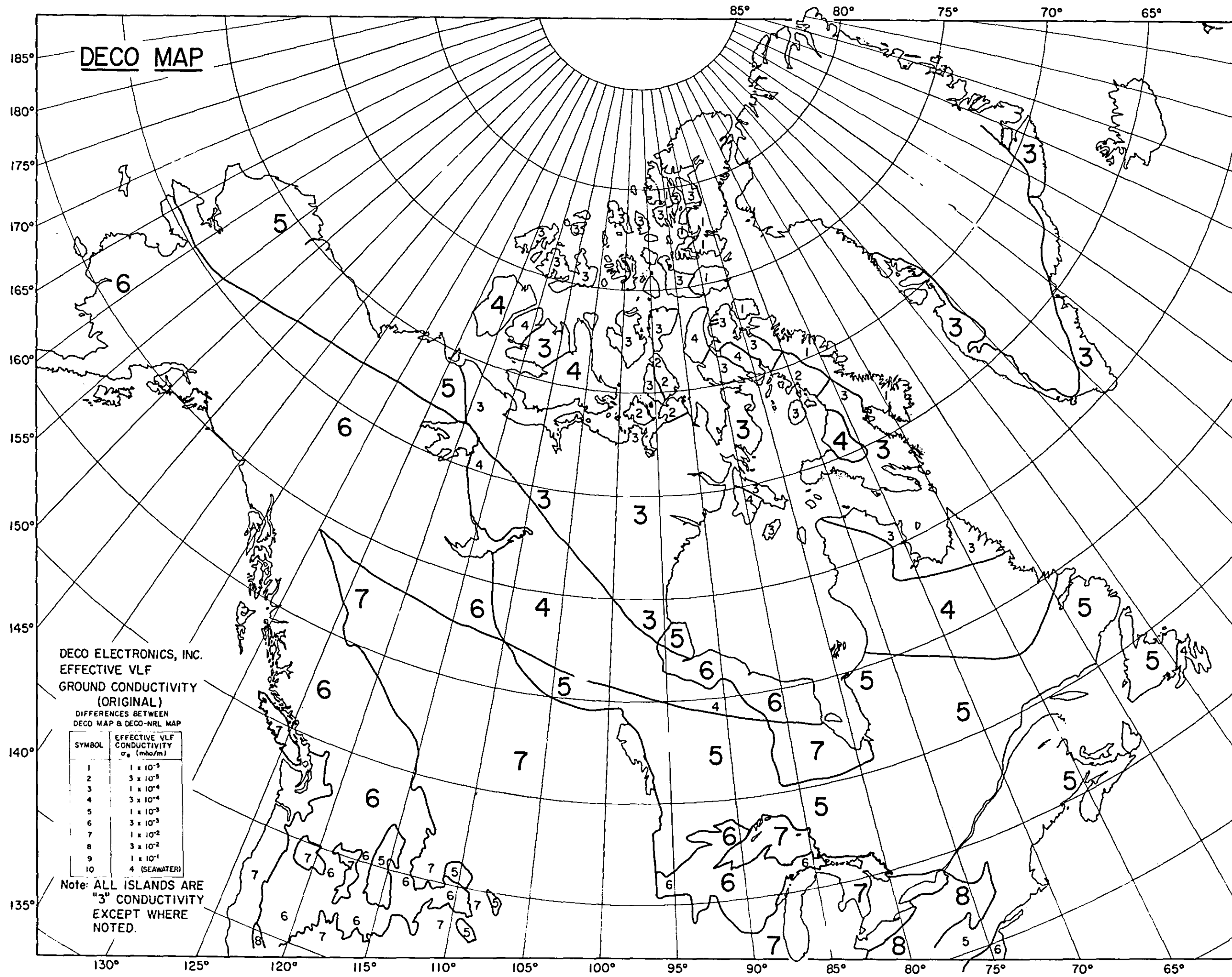

Fig. 9 - Vlf effective ground conductivity map of Canada and Greenland from Morgan and Maxwell (2)

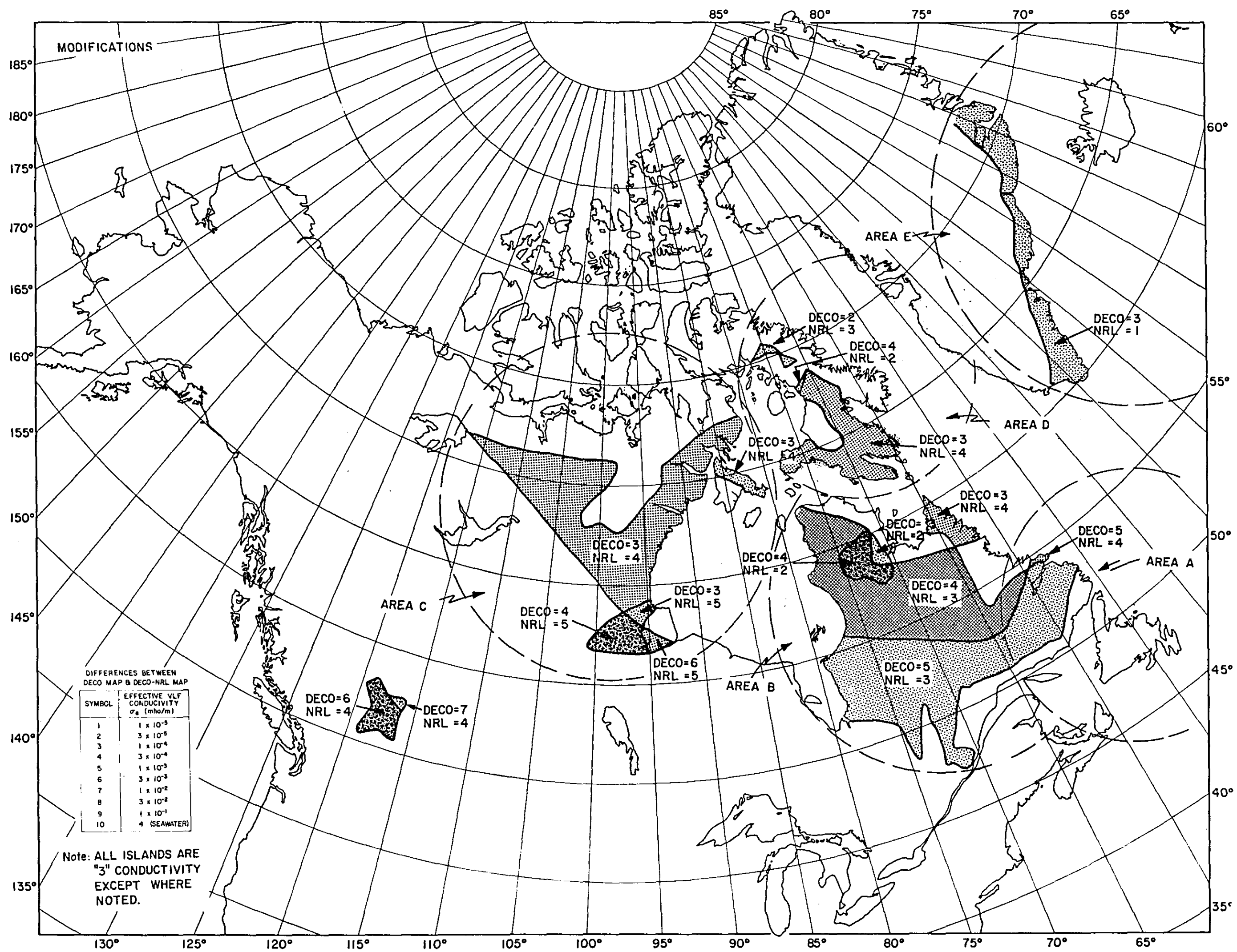

Fig. 11 - Areas in Canada and Greenland where vlf effective ground conductivities given by Morgan and Maxwell (2) were modified by NRL based on radiowave propagation data

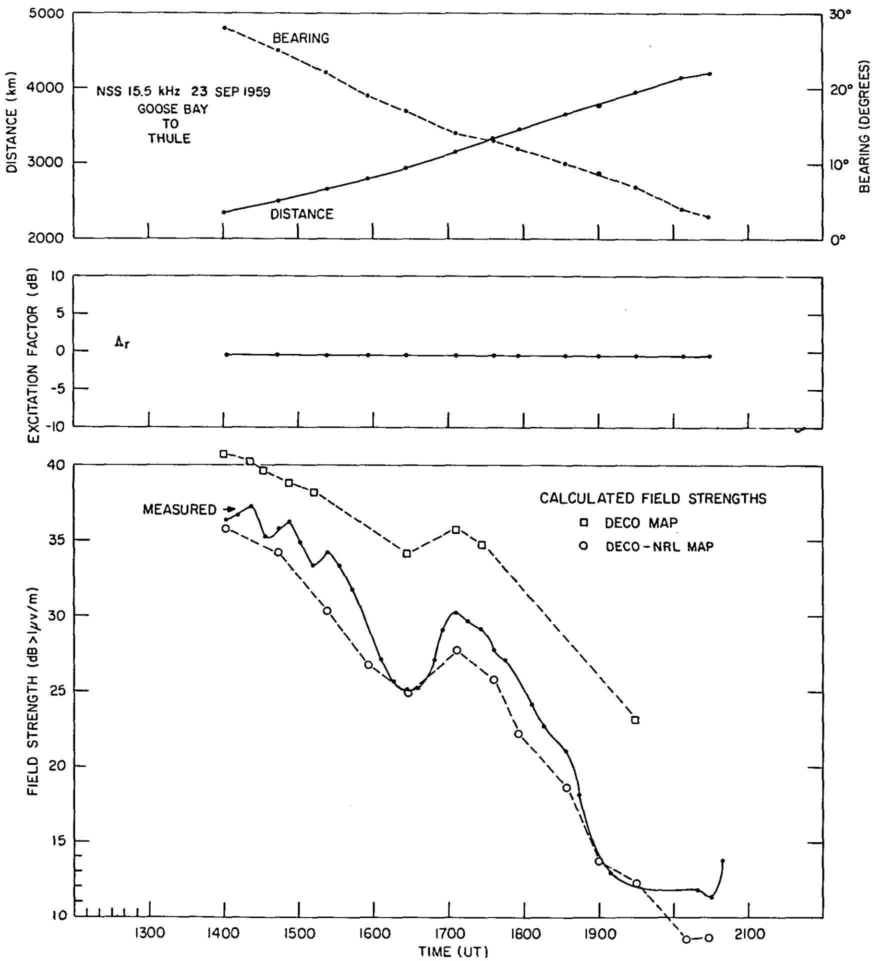

Fig. 13 - NSS measured and calculated data for flight from Goose Bay, Labrador, to Thule, Greenland, on September 23, 1959

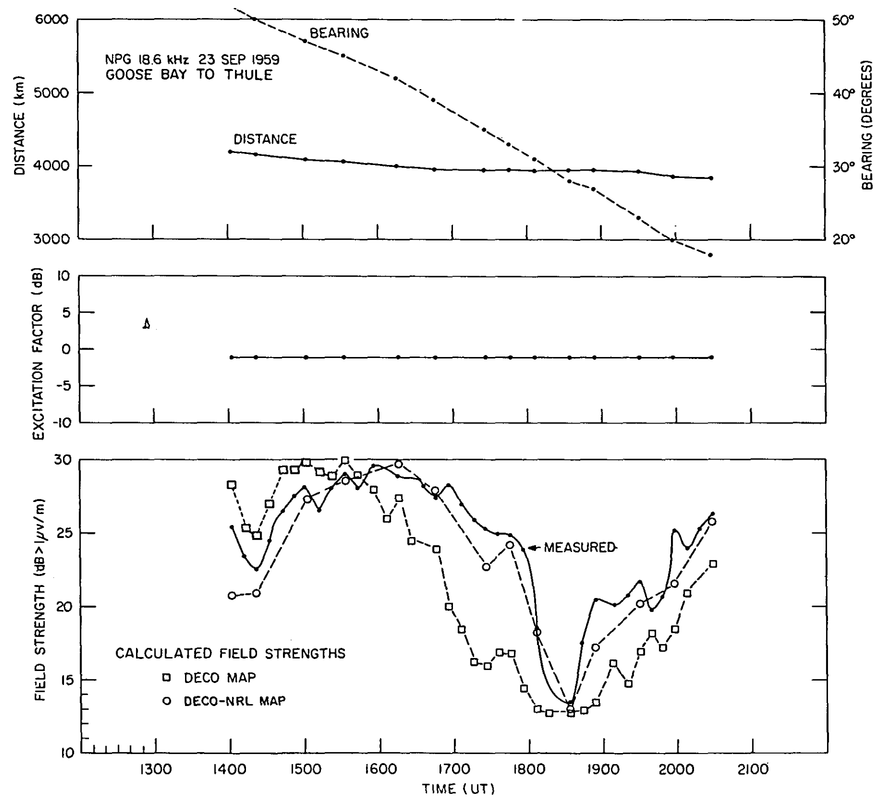

Fig. 14 - NPG measured and calculated data for flight from Goose Bay, Labrador, to Thule, Greenland, on September 23, 1959

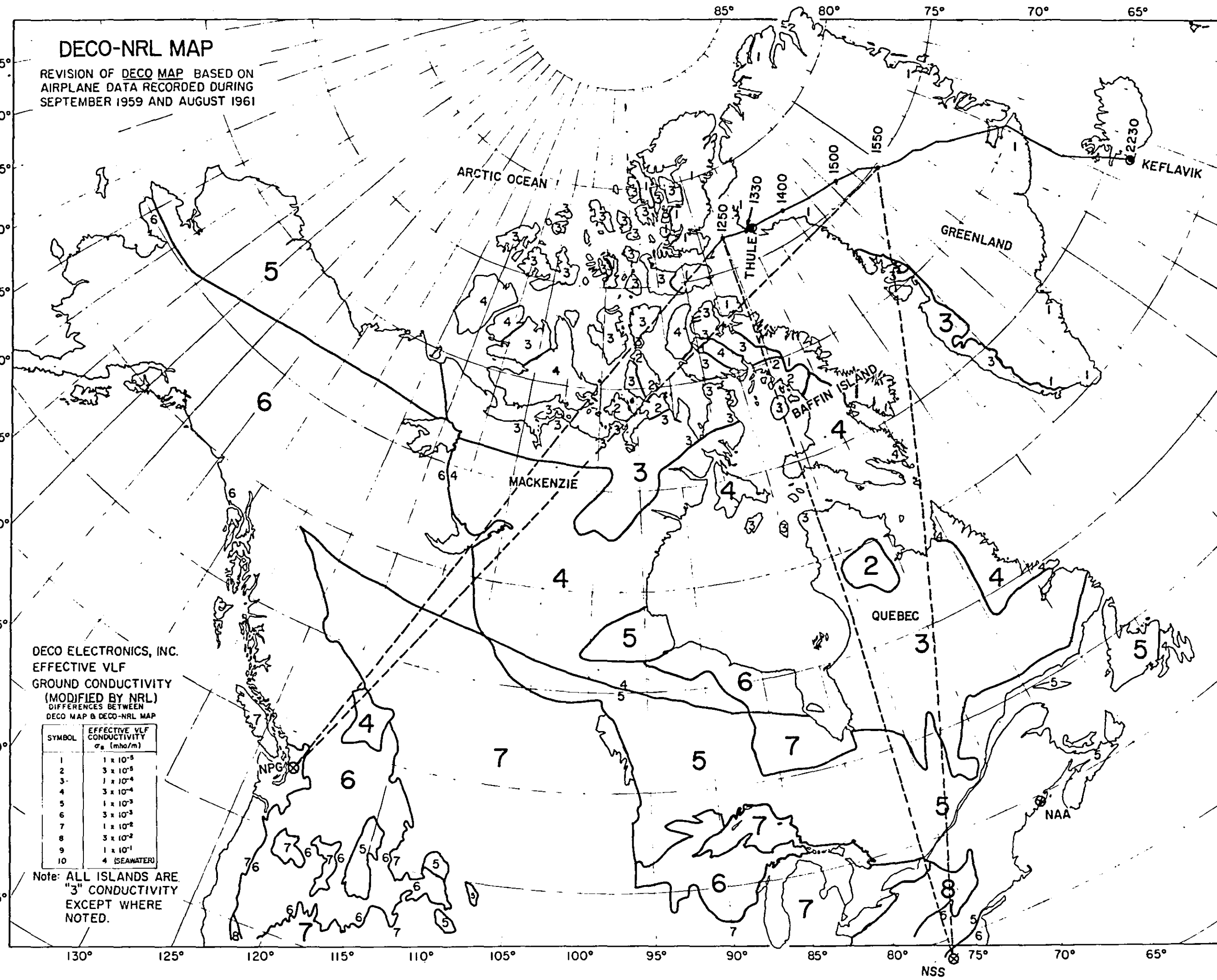

Fig. 15 - Flight from Thule, Greenland, to Keflavik, Iceland, on September 25, 1959

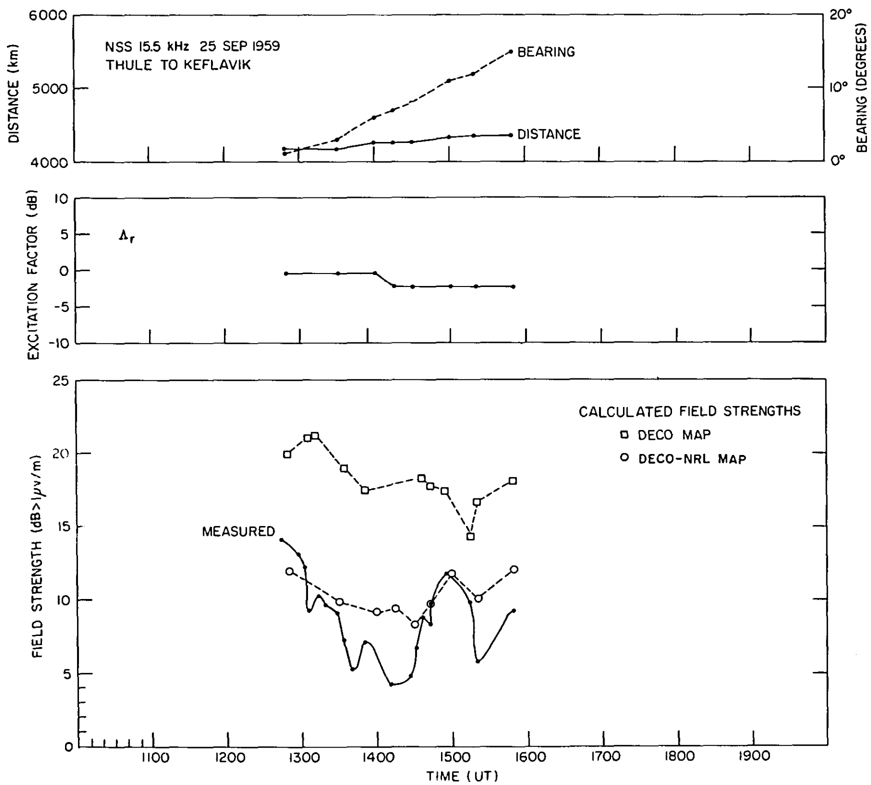

Fig. 16 - NSS measured and calculated data for flight from Thule, Greenland, to Keflavik, Iceland, on September 25, 1959

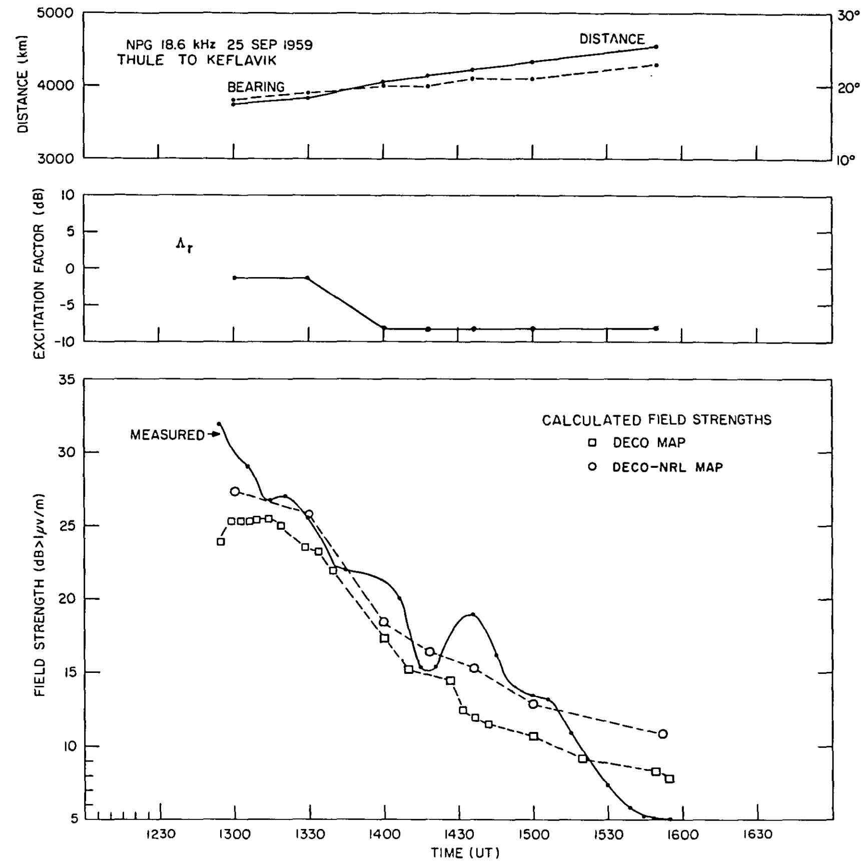

Fig. 17 - NPG measured and calculated data for flight from Thule, Greenland, to Keflavik, Iceland, on September 25, 1959

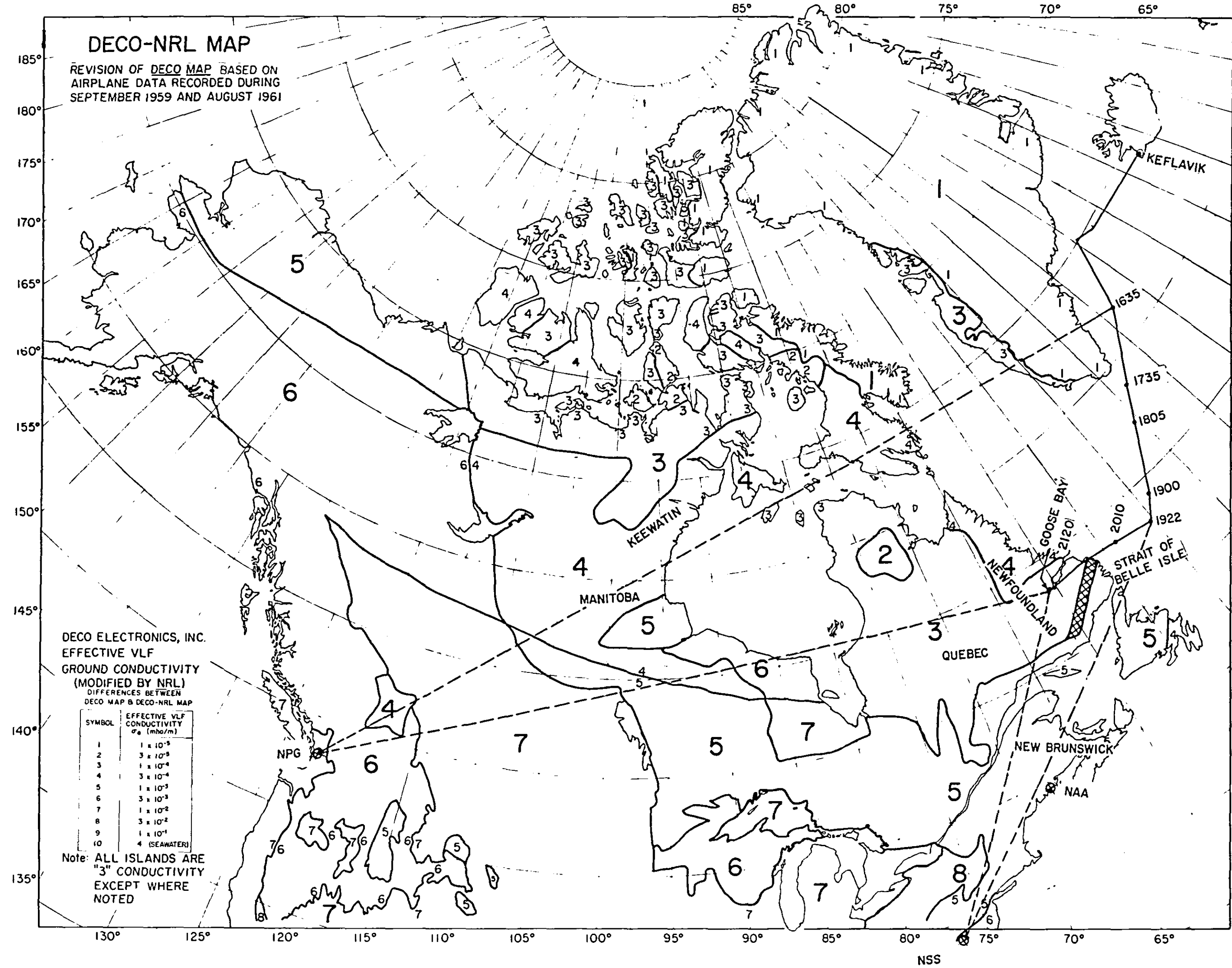

Fig. 18 - Flight from Keflavik, Iceland, to Goose Bay, Labrador, on September 29, 1959

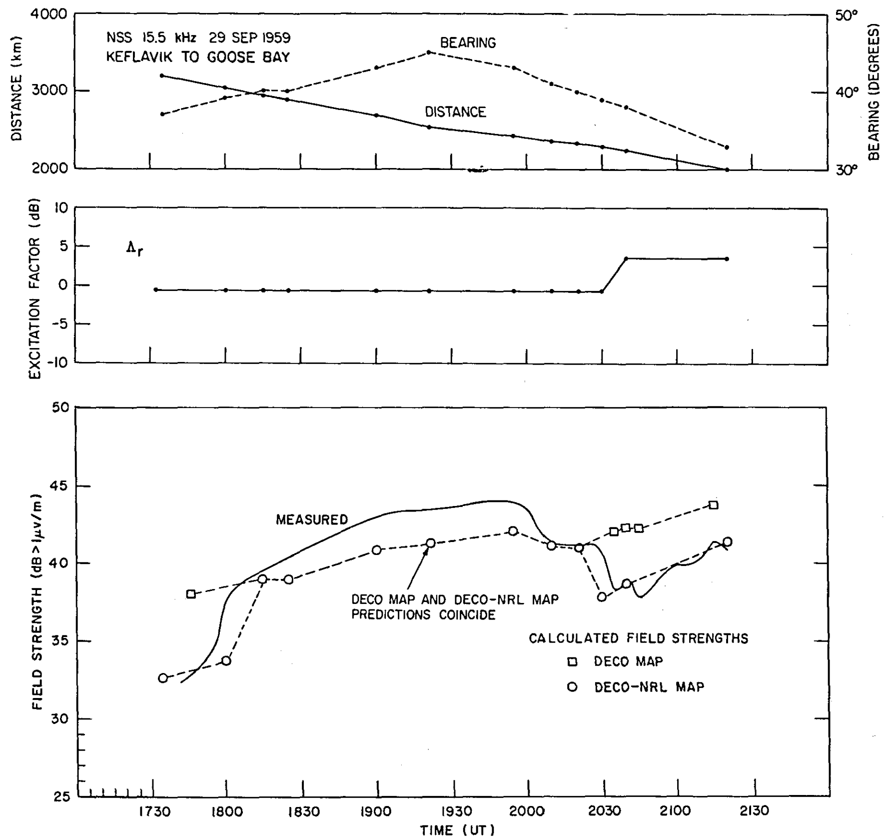

Fig. 19 - NSS measured and calculated data for flight from Keflavik, Iceland, to Goose Bay, Labrador, on September 29, 1959

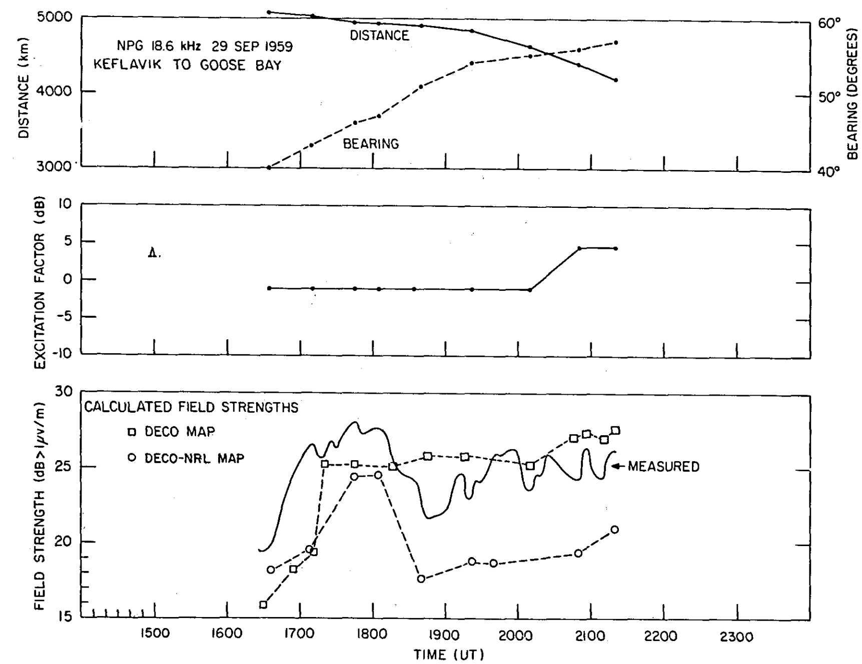

Fig. 20 - NPG measured and calculated data for flight from Keflavik, Iceland, to Goose Bay, Labrador, on September 29, 1959

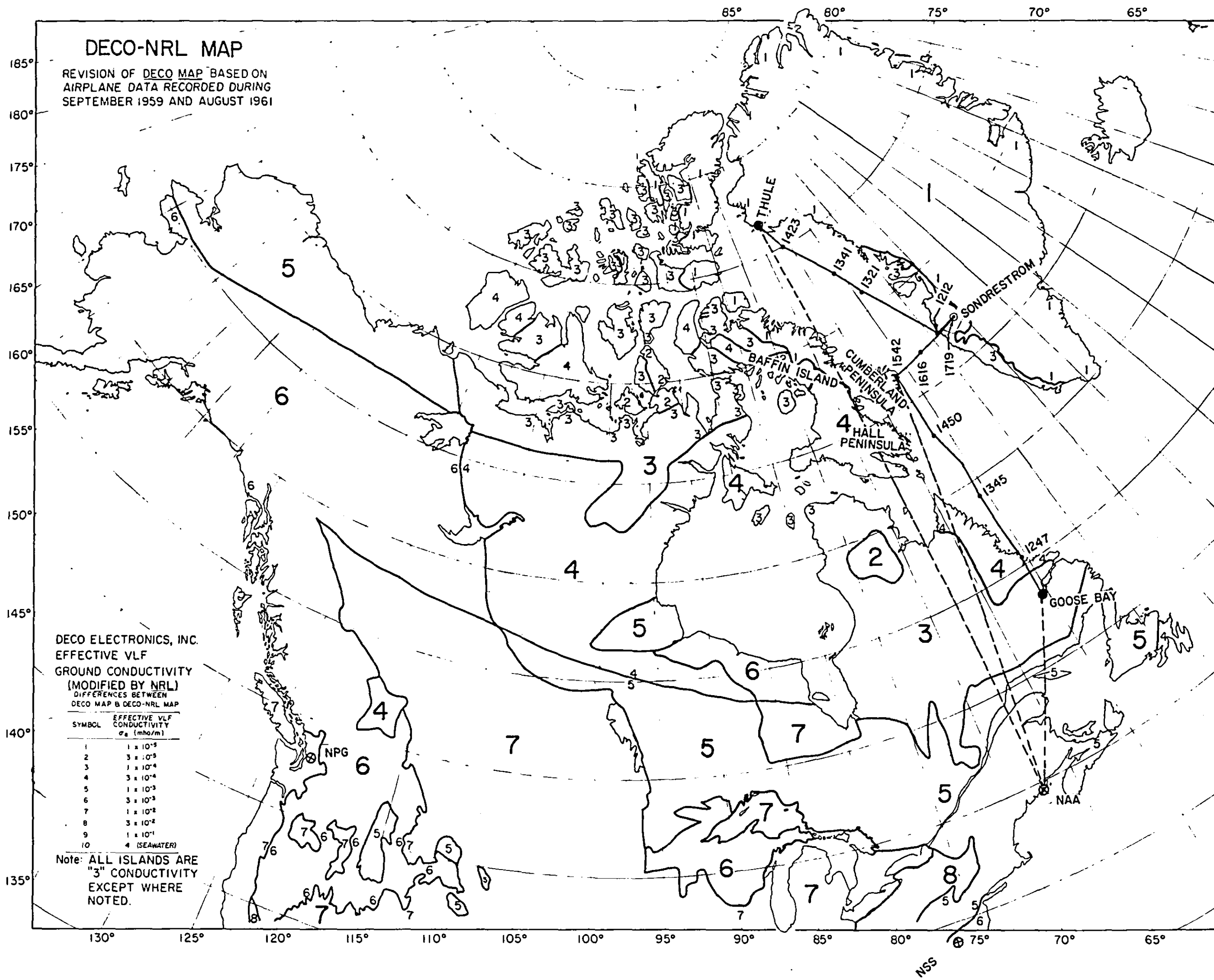

Fig. 21 - Flights from Goose Bay, Labrador, to Sondrestrom, Greenland, on August 9, 1961, and from Sondrestrom to Thule, Greenland, on August 10, 1961

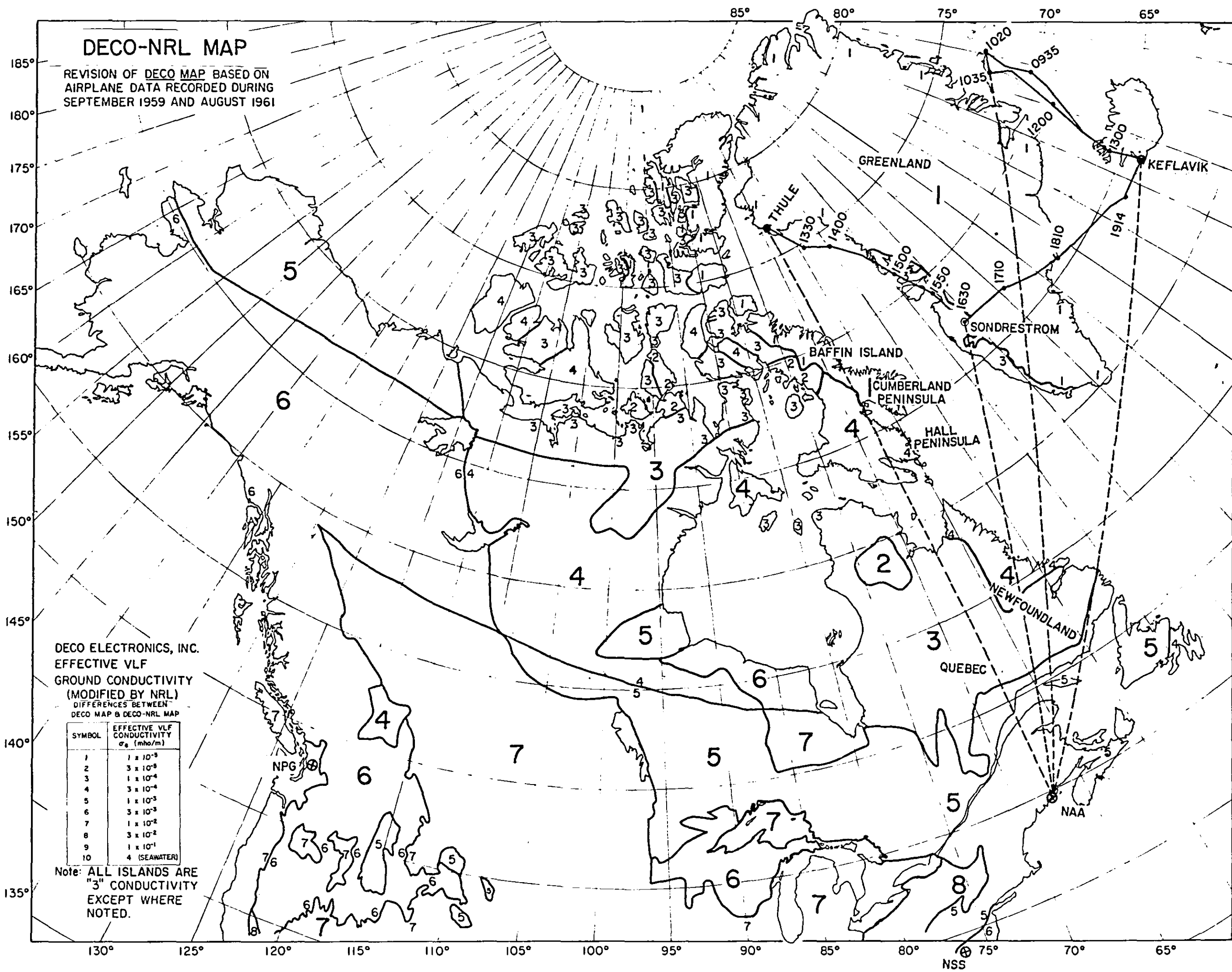

Fig. 24 - Flights from Thule to Sondrestrom, Greenland, to Keflavik, Iceland, on August 11, 1961 and from Keflavik, Iceland, to the north, and return to Keflavik on August 18, 1961

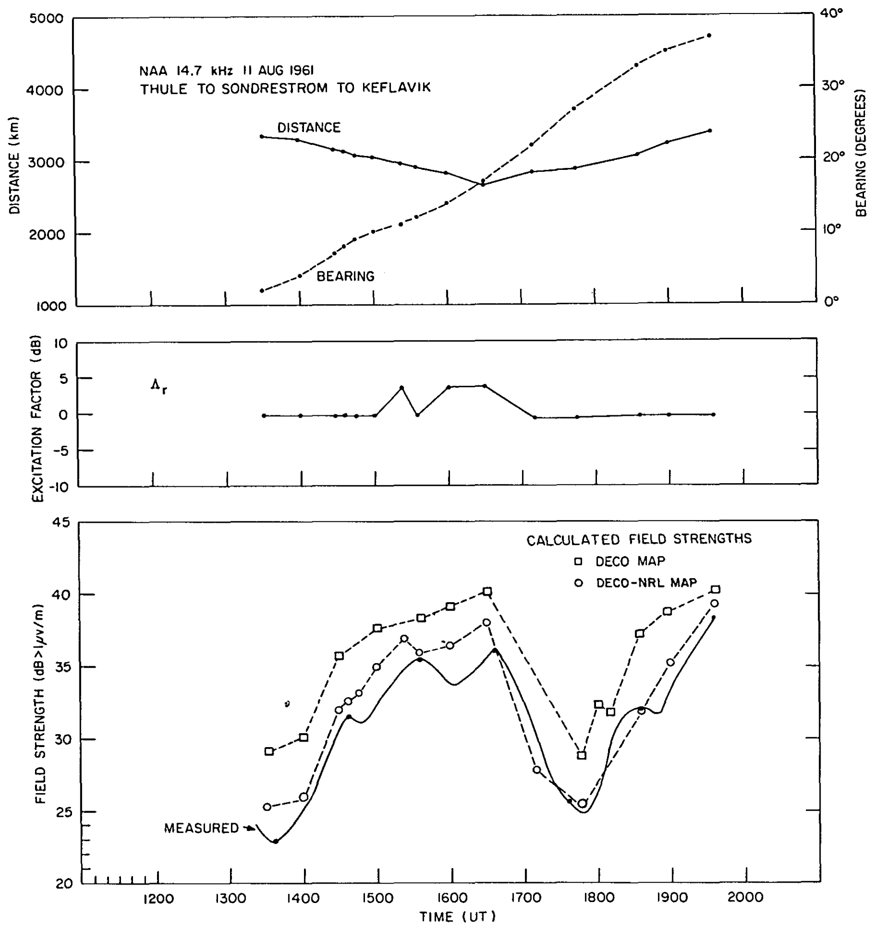

Fig. 25 - NAA measured and calculated data for flight from Thule to Sondrestrom, Greenland, and to Keflavik, Iceland, on August 11, 1961

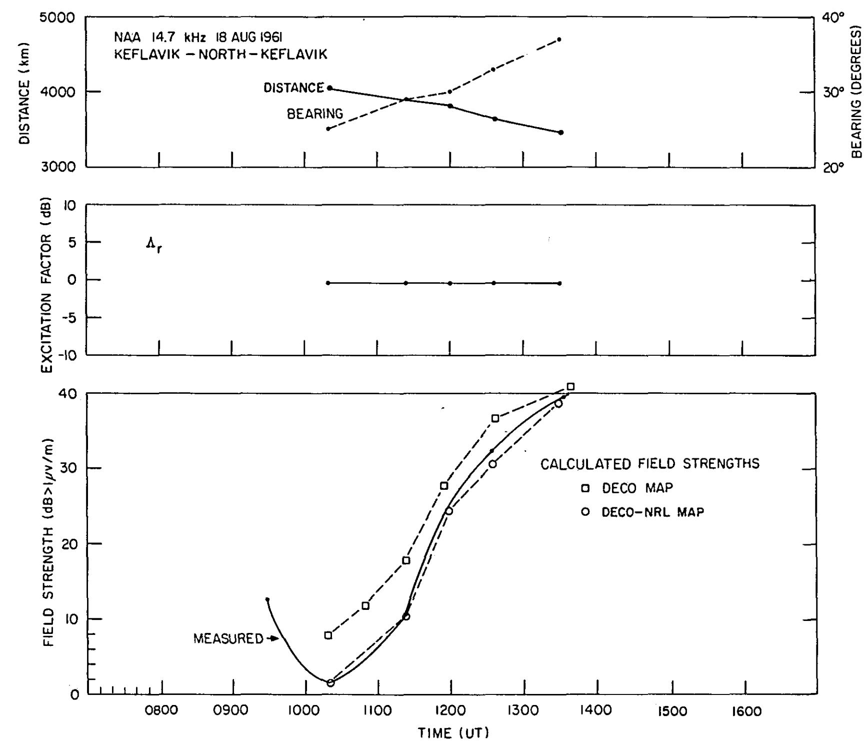

Fig. 26 - NAA measured and calculated data for flight from Keflavik, Iceland, to the north, and return to Keflavik on August 18, 1961

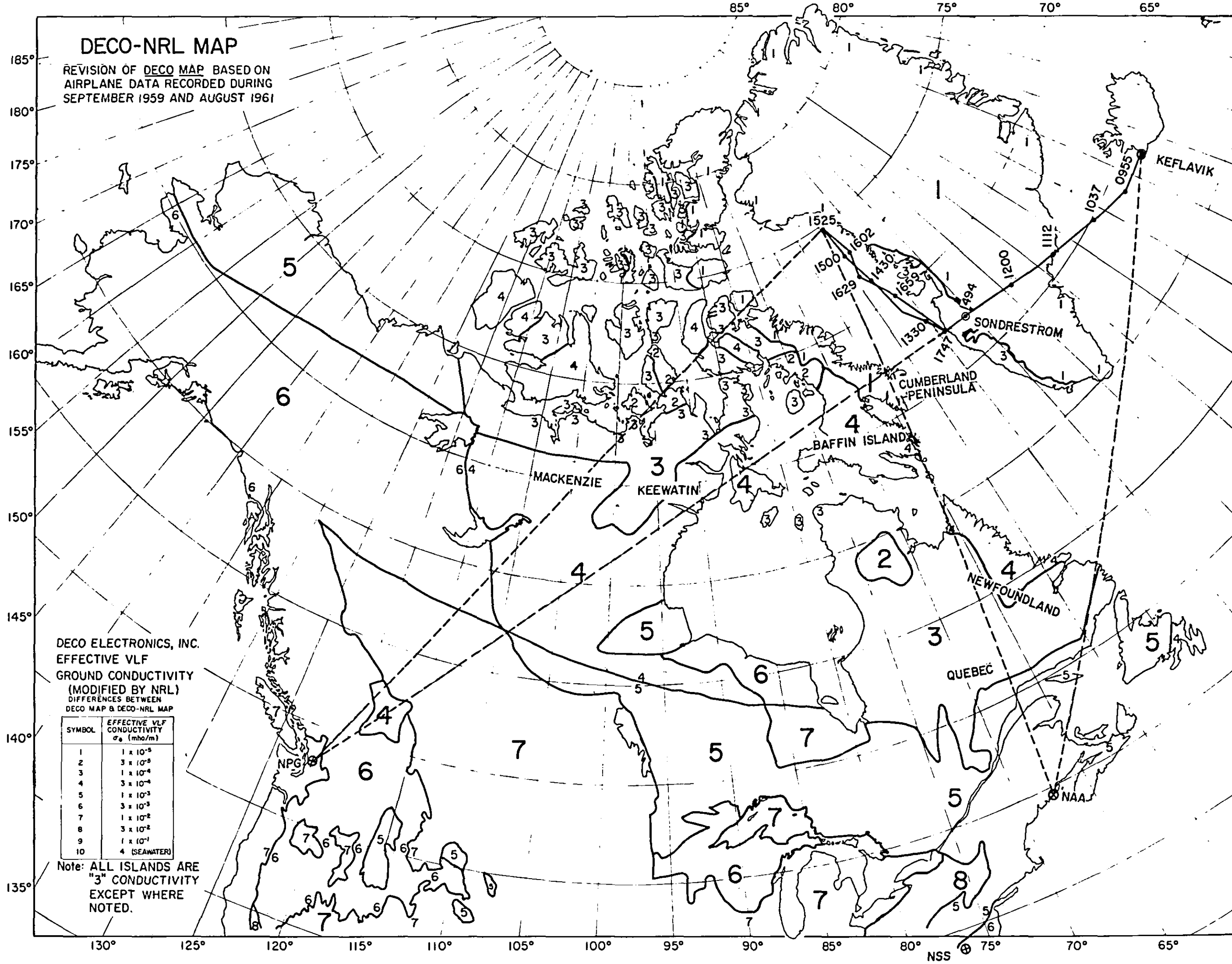

Fig. 27 - Flight from Keflavik, Iceland, to Sondrestrom, Greenland, to the north, and return to Sondrestrom on August 22, 1961

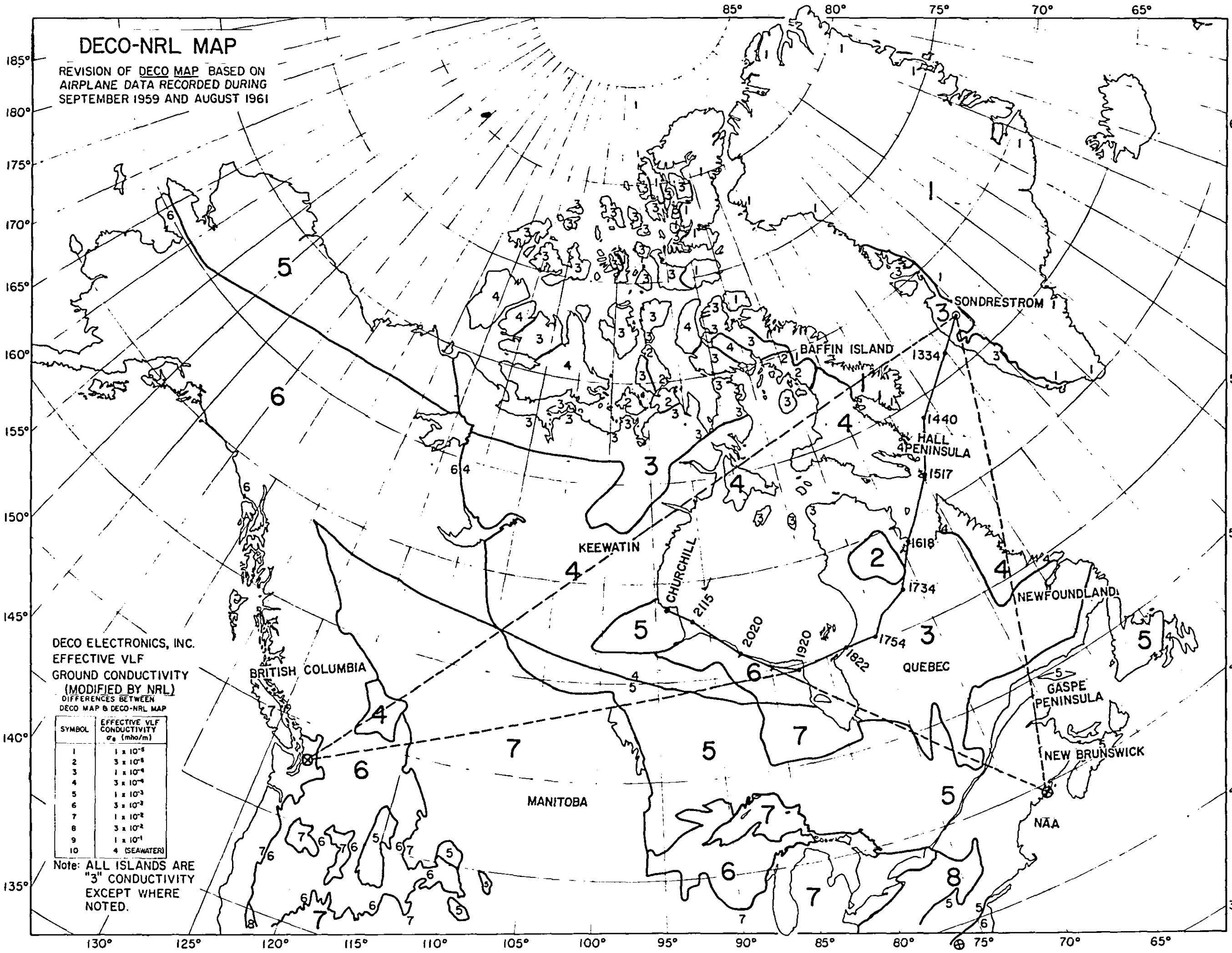

Fig. 30 - Flight from Sondrestrom, Greenland, to Churchill, Manitoba, on August 23, 1961

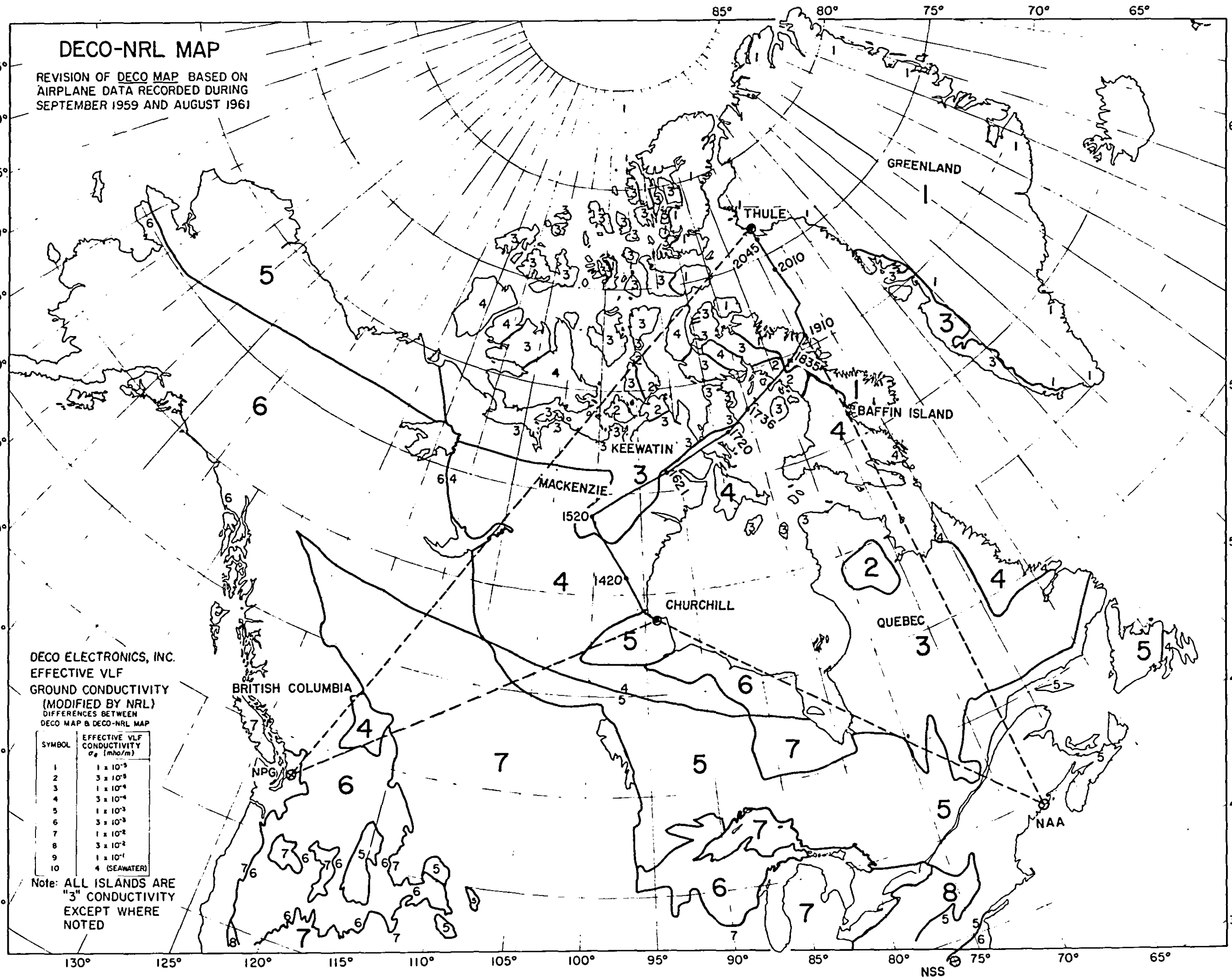

Fig. 33 - Flight from Churchill, Manitoba, to Thule, Greenland, on August 25, 1961

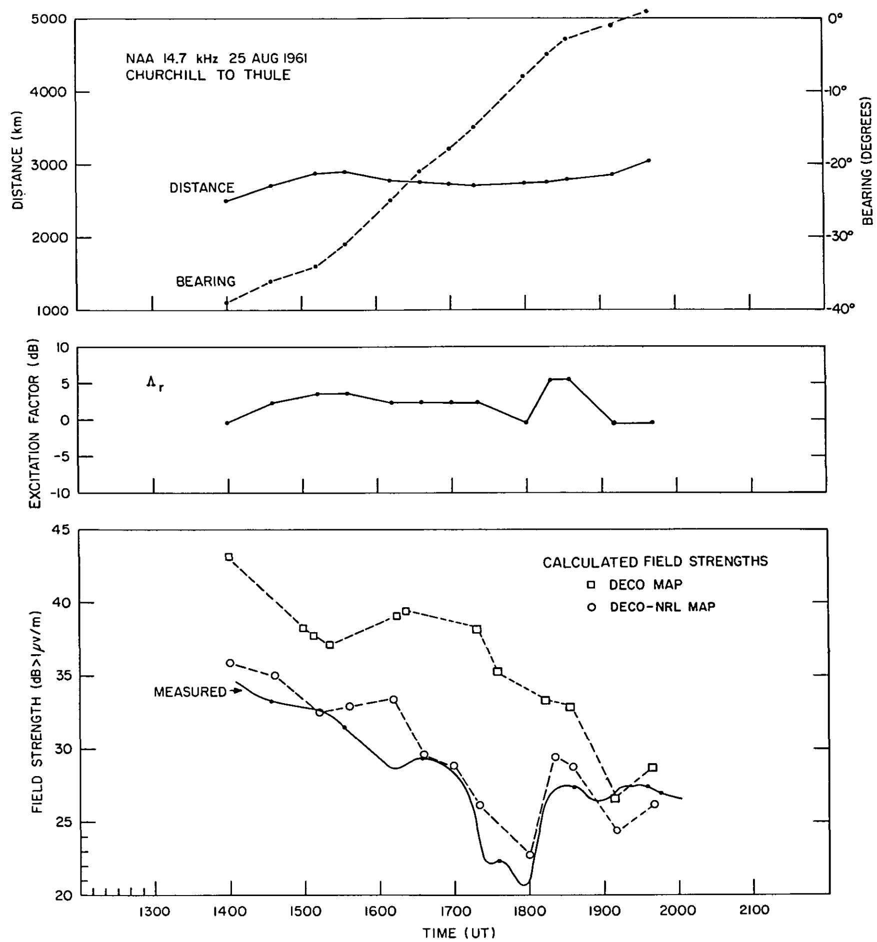

Fig. 34 - NAA measured and calculated data for flight from Churchill, Manitoba, to Thule, Greenland, on August 25, 1961

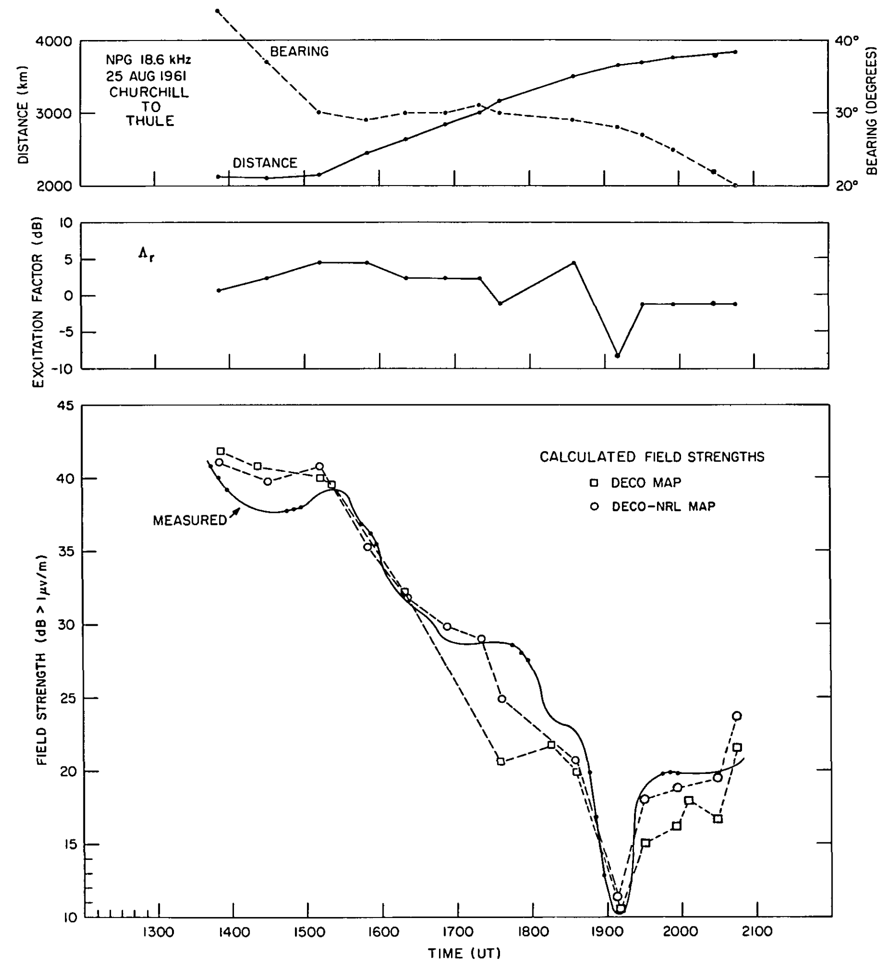

Fig. 35 - NPG measured and calculated data for flight from Churchill, Manitoba, to Thule, Greenland, on August 25, 1961

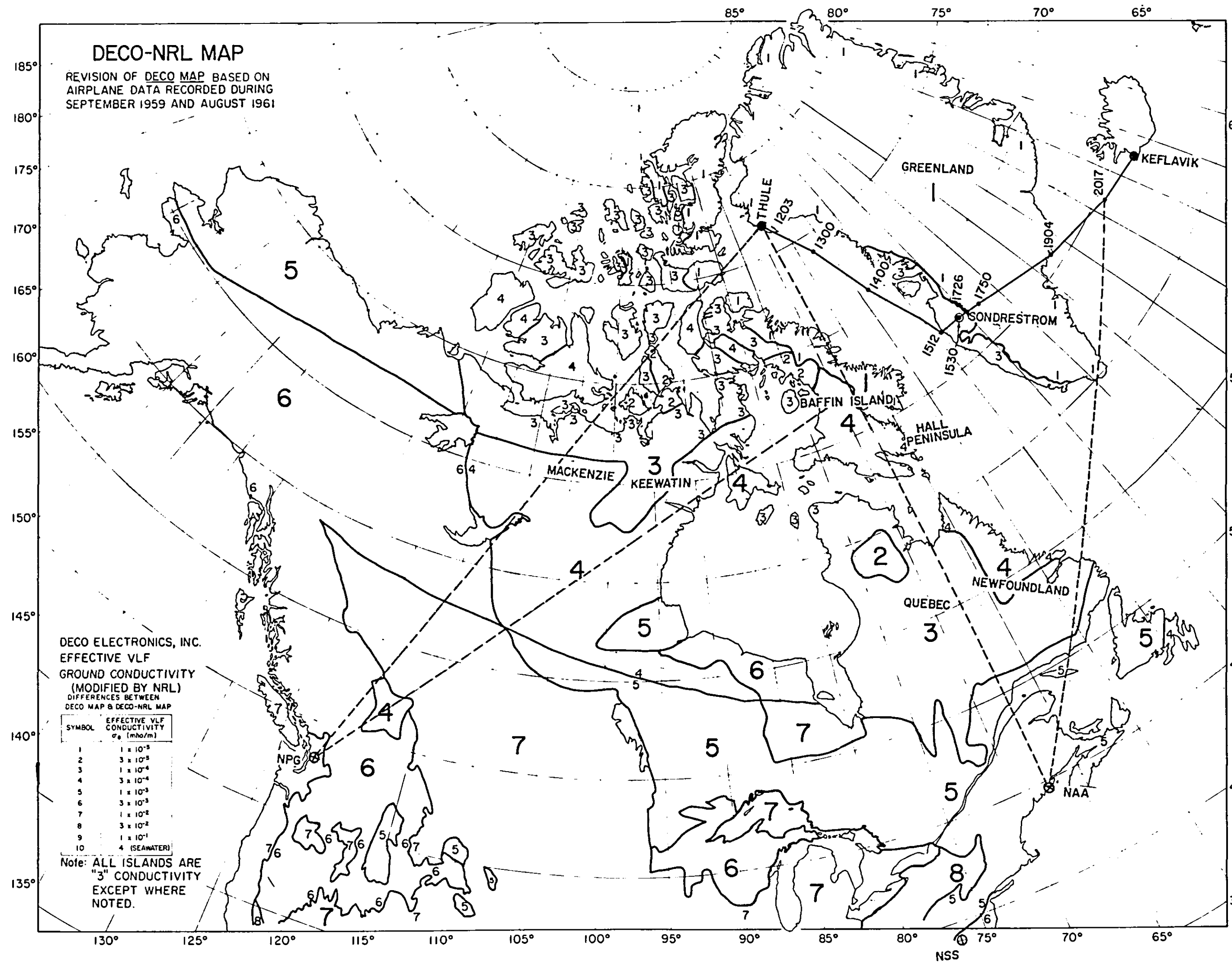

Fig. 36 - Flight from Thule to Sondrestrom, Greenland, and to Keflavik, Iceland, on August 27, 1961

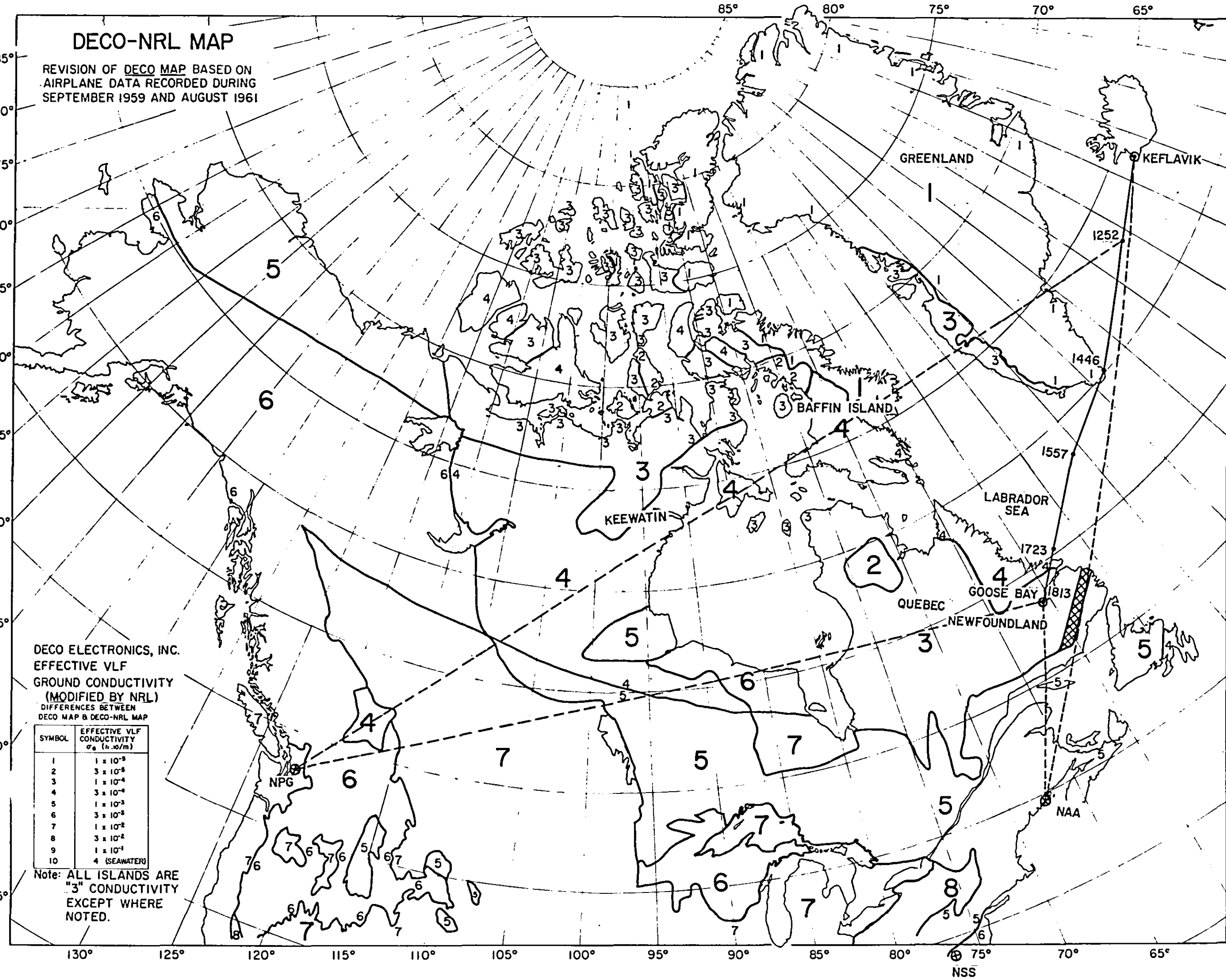

Fig. 39 - Flight from Keflavik, Iceland, to Goose Bay, Labrador, on August 28, 1961

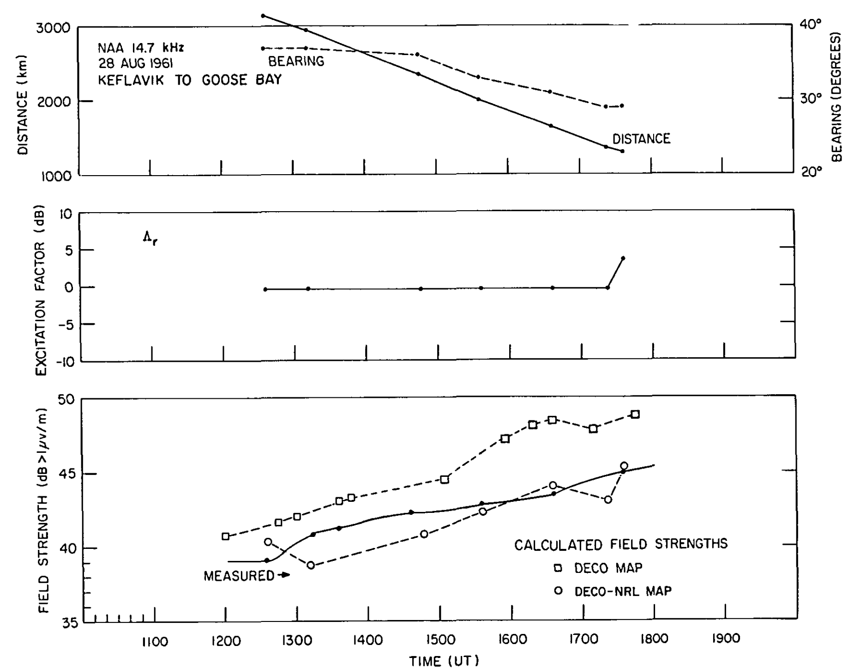

Fig. 40 - NAA measured and calculated data for flight from Keflavik, Iceland, to Goose Bay, Labrador, on August 28, 1961

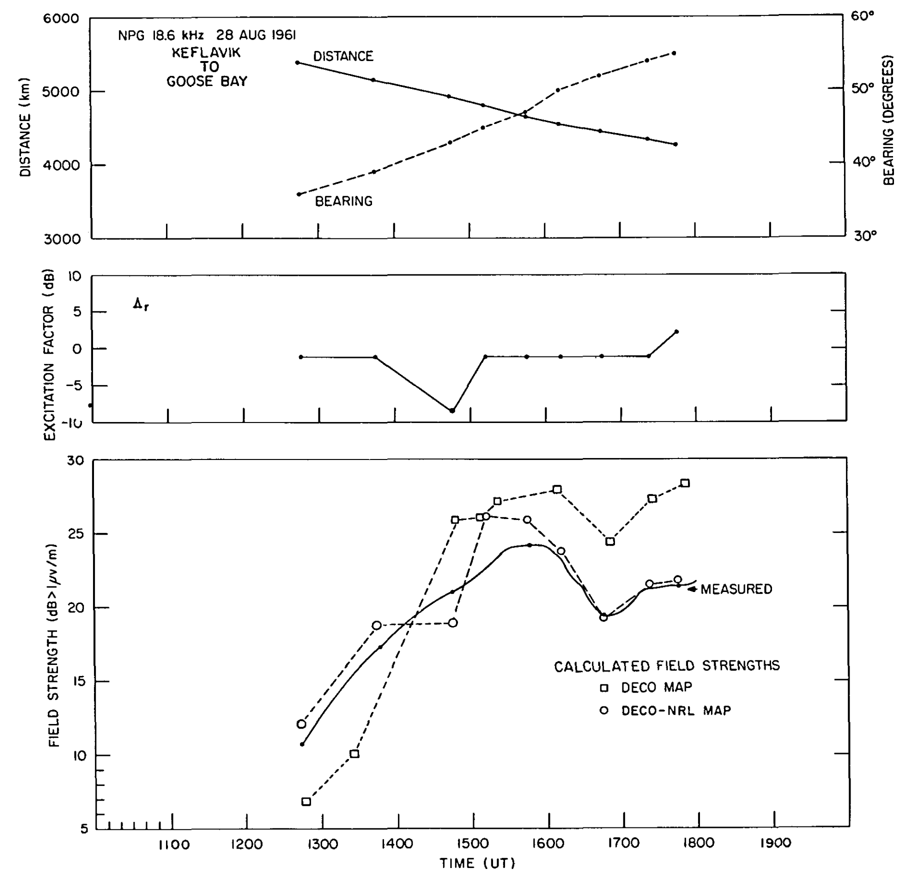

Fig. 41 - NPG measured and calculated data for flight from Keflavik, Iceland, to Goose Bay, Labrador, on August 28, 1961

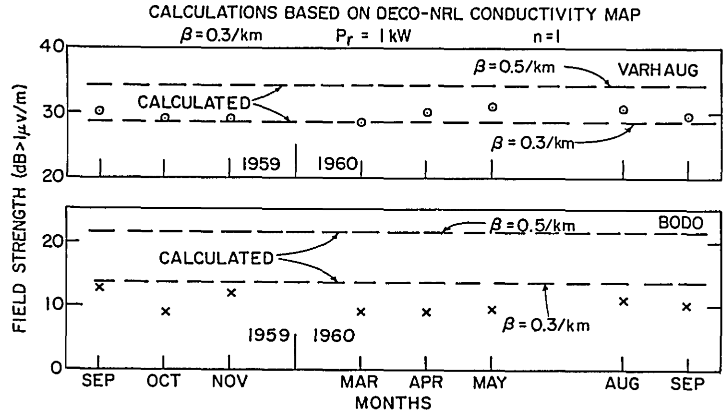

Fig. 42 - NSS, 15.5-kHz field-strength data for all daylight paths to Varhaug and Bodo, Norway

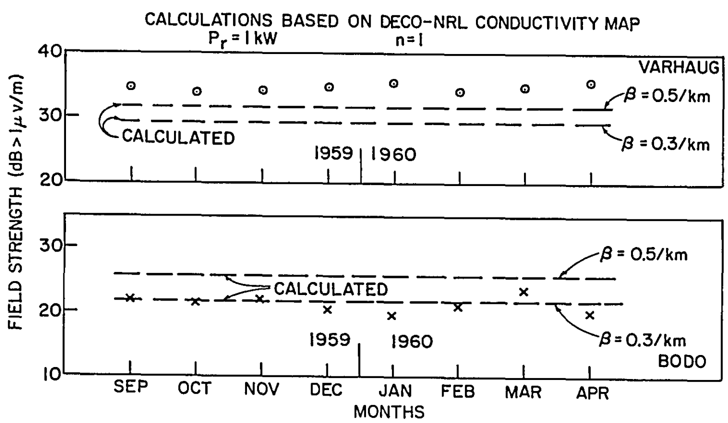

Fig. 43 - NSS, 15.5-kHz field-strength data for all nighttime paths to Varhaug and Bodo, Norway

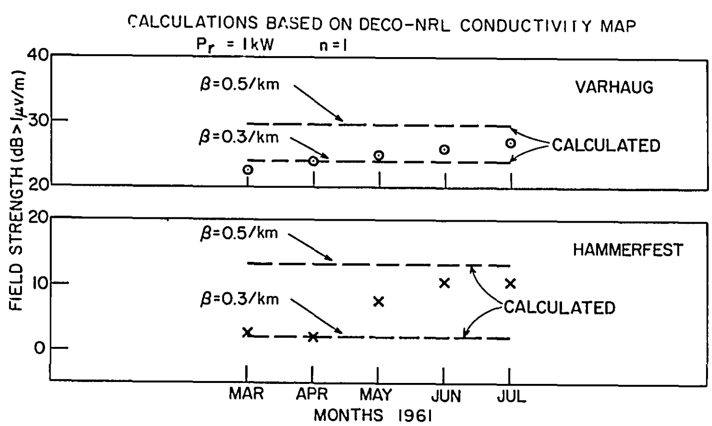

Fig. 44 - NSS, 22.3-kHz field-strength data for all daylight paths to Varhaug and Hammerfest, Norway

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Radio waves						
Very low frequency						
Propagation						
Effective ground conductivity						
Field strengths						
Attenuation						
Excitation factors						
U.S. Navy transmitting stations						
Canada						
Greenland						