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ROYAL AIRCRAFT ESTABLISHMENT

FARNBOROUGH, HANTS

TECHNICAL NOTE No: RAD.536

A SURVEY OF LOW REFLECTION COEFFICIENTS FOR VARIOUS TYPES OF LAND AND FROZEN SEA FOR NORMAL INCIDENCE AT 1600 Mc/s

by

J.K.GARLICK, B.Sc., A.M.I.E.E.

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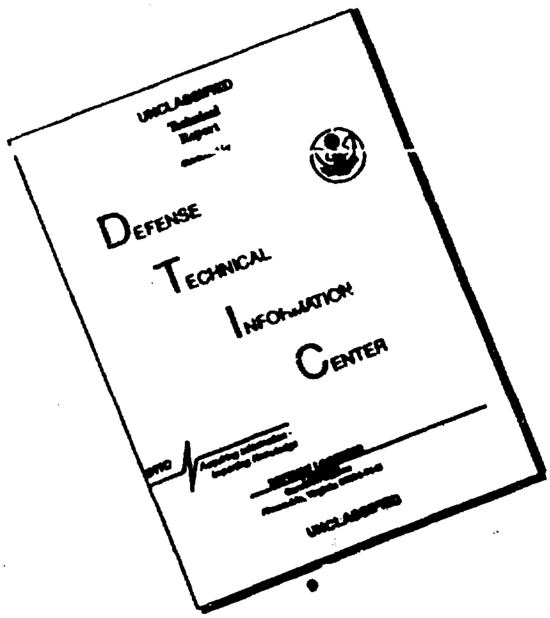

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Technical Note No. Rad.536

January, 1953

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A Survey of Low Reflection Coefficients for Various Types of Land and Frozen Sea for Normal Incidence at 1600 Mc/s

by

J.K. Garlick, B.Sc., A.M.I.E.E.

SUMMARY

During development on radio terrain clearance indicators work was done to measure the reflection coefficients from terrains expected to have the lowest values. The measurements were made at a frequency of 1600 Mc/s. They depended upon the reception in an aircraft flying over the terrain, of a signal transmitted vertically downwards from the aircraft and reflected back to it.

The reflection coefficient of desert sand agreed with a figure obtained earlier at 400 Mc/s. by other authorities. It had been considered to be the lowest reflection coefficient to be found from any natural terrain.

Measurements over barren frozen arctic terrain or sea covered by several feet of ice produced reflection coefficients equal to those from desert sand.

Over terrain deeply frozen and covered by deep snow and vegetation however, appreciably smaller reflection coefficients were measured.

LIST OF CONTENTS

LIST OF APPENDICES

1 Introduction

For an airborne installation, weight, size and power consumption of any equipment are closely limited, especially when the equipment is for general installation. A terrain clearance indicator, as an ancillary piece of equipment, should clearly accept these limitations. As a piece of military equipment, however, it is required to operate to a prescribed standard over every type of terrain, so that adequate power must be produced.

The strength of a signal transmitted from and received back in the aircraft depends on the reflection coefficient of the terrain over which the plane is flying. Since the transmission is vertically downwards no problems of plane of polarisation exist.

It has long been known that dry desert sand gave a low reflection coefficient. Measurements had been made much earlier[1] at 400 Mc/s, and other authorities have made measurements more recently[2] at 10,000 Mc/s. The value for the reflection coefficient measured by us at 1600 Mc/s agreed closely with that at 400 Mc/s. The figure for 10,000 Mc/s would seem to be appreciably smaller.

Calculations were made of the reflection coefficients of frozen arctic terrains, and much valuable information was extracted from a report by Dr. J.A.Saxton[3].

It was shown, by calculating on a simplified basis, that arctic terrain could be as bad as, or even worse than barren desert. All available sources of U.S. and Canadian information were approached for results of theory or measurement of arctic reflection coefficients, but no satisfactory information was collected. It was therefore decided to make actual measurements over sub-arctic terrain in Northern Canada in midwinter when complete freezing takes place to a depth of several feet.

2 Method of Measurement

The measurements of reflection coefficient were made by comparing the strength of a reflected signal from a given terrain with a signal reflected from open sea. The figure for the reflection coefficient of sea water was taken as 0.85 as given in the paper by Dr. Saxton[3].

It was possible in most cases to make direct comparison with an open water reflection. The desert measurements were made over coastal sand in the Sinai Peninsular. The frozen ground and sea measurements were made in North Canada, either near to Hudson Bay, where there is almost always a wide open stretch of water, or else near to the Great Lakes, where open water was also found. Further checks were made on all occasions of the overall loop gain of the equipment in flight.

The equipment used was an experimental model of a terrain clearance indicator working on a frequency of 1600 Mc/s. The transmitter produced pulses of about 0.5 microsecond duration with a pulse repetition frequency of 10 kc/s. The pulses reflected from the ground were displayed on a cathode ray tube on a circular time base as a radial reflection.

The gain was checked using an attenuator and a delay line of coaxial cable of sufficient delay to allow the pulse to be seen outside the zero height break through pulse. The attenuation of the cable was corrected for temperature from the known characteristics of the cable. Two levels were checked at full gain, to determine a pulse which was just limiting on the cathode ray tube, or a pulse which was just visible above the noise.

The set performance having been checked, lossy cable of known attenuation and negligible delay was introduced into the transmitter or receiver cables to produce a received pulse which could be checked visually and set to a standard amplitude over open sea. Then, over a terrain of lower reflection coefficient, attenuation was removed by known amounts until the received pulse was again of standard amplitude.

A different check was used on some occasions, when, with the attenuation unchanged, the aircraft was flown from one height over sea to a different height over a second terrain to produce signals of standard amplitude. Assuming a law of attenuation with height, the reflection coefficient of the terrain relative to a sea figure can again be obtained. The law of attenuation with height was assumed to be a third power law, for reasons given later in Appendix I. These figures agreed closely with those obtained when the inserted attenuation was varied.

The flying was mostly done at 10,000 feet or at 20,000 feet.

No great accuracy was claimed for these measurements, but two observers made a large number of measurements, and the results were repeatable to better than ± 2 db.

3 Choice of Terrains

It has been known for a long time that the reflection coefficient of dry desert was very low, being the extreme case of the variation of the reflection coefficient with the moisture content of a terrain. In fact it has often been assumed that dry desert provided the lowest reflection coefficient to be found for any terrain. Moreover, since desert areas have been frequently flown over for several years, this fact has been of some importance, and indeed many measurements have been made in desert areas.

Figures had been quoted for the reflection coefficient of desert[1] at 400 Mc/s, but the reliability of this information was not known. It was therefore decided to carry out measurements at the frequency of 1600 Mc/s used by a terrain clearance indicator. Care was taken to select an area of loose, shifting, and completely dry sand. It was desirable that the area should be coastal so that a direct and rapid comparison of sea and sand reflections could be made.

A suitable area was located on the north coast of the Sinai Peninsular between Port Said and El Arish, and it was there that desert flying was done. The north African coast in general is limestone rock, covered often by a little sand but rarely by loose sand dunes. Flying was carried out over much of this area too from El Alamein to the El Adem-Benghasi area.

At the same time as this flying programme was carried out, in June 1950, preliminary considerations showed that low reflection might be expected from snow covered, or frozen areas. Until recently there was little or no flying done over the arctic, but since arctic flying is becoming more frequent, it was decided to investigate the problem. It was too late to arrange for a flying programme over arctic terrain in the winter of 1950-51, and it had to be deferred until the winter of 1951-52.

A recent paper by Dr. J.A.Saxton[3] treated theoretically the reflection of radio waves from snow covered or ice covered terrains for all angles of incidence. It was shown that due to the very low attenuation in snow and ice, the medium below the snow and ice still played an important part in the behaviour of the terrain. The paper dealt with the general case. The present survey was concerned only with the particular case of normal incidence, and it was found that a simple approach could be made by treating the problem as one of impedance change, as shown in Appenix II.

The calculations showed the following points:-

(1) Normal moist land, when snow covered, could give a slight decrease of reflection coefficient if the snow was completely dry.

(2) Dry sand covered by dry snow could give a reflection coefficient much smaller than the already small reflection coefficient of dry sand alone.

(3) Sea covered by ice would have a reflection coefficient appreciably lower than that for open water, but comparable with moist land.

It was considered that in the arctic, where land and sea are frozen to a depth of several feet, and where the temperature is very low, e.g. -50°C at the surface, the surface layers would be so completely frozen that no liquid droplets would remain dispersed throughout the ice or soil. In such a case the soil could be considered to have a similar reflection coefficient to the same soil if completely dry, as the contribution by the frozen moisture content would be negligible. Even if the terrain was completely waterlogged, and then completely frozen out, the reflection coefficient would be expected to be still quite low. This condition might have a close equivalent over the vast tracts of the arctic and sub-arctic areas of tundra or muskeg.

It was therefore decided that a flying programme should be carried out over Northern Canada in the coldest part of the winter to check these results.

The flying was done during January and February 1952 and mostly from Fort Churchill on the S.W. shore of Hudson Bay, Fort Churchill being chosen for various reasons. It offered accommodation and also the aircraft facilities of a heated hangar. It was just about at the edge of the tree line. To the north were vast areas of barren gravel. Inland were areas of muskeg. Further inland was deep forest land, and, of course, there was the ice of Hudson Bay. Moreover, in general, there is usually a stretch of open water, or lead, to be found on Hudson Bay for use as a comparison. Although the Bay freezes over completely, the whole ice cap moves slightly due to winds and there is generally an open water lead which may be up to a mile or so wide and many miles long. This is generally to be found near to the coast and is mostly on the West side of the Bay, i.e. near to, or North of Fort Churchill.

The measurements over ice were done in flights out towards the centre of the ice pack in Hudson Bay. Here the ice was probably up to 9' thick, but with a very rough surface and much ice piled up. The coastal ice would be 3 to 6 feet thick only. But even here the surface was rough with huge pressure ridges where the ice was pushed up to ridges many feet in height.

The areas to the North of Fort Churchill and Eskimo Point to Chesterfield Inlet had vast tracts of barren ground and shingle and shallow lakes. As was typical of this sort of terrain, it was swept by wind and as a result had little or no snow cover, a few inches at the most. As a result the whole area would be frozen to a considerable depth, i.e. several feet. In fact, being in the permafrost zone, both gravel and lake would be frozen right down to the permanent frozen layers.

The muskeg areas too had little snow cover and as a result again all the water pans and the earth could be expected to be frozen down to the permafrost level also.

From Fort Churchill the aircraft flew across Canada to the North of Lake Athabaska and on to Whitehorse in the Yukon. This journey allowed measurements to be made over terrain which was heavily wooded and contained a large number of lakes. There was a complete cover of loose lightly compacted snow some three feet or more deep. This covered lake and land, and also, being different in texture from the hard fine granular snow as found at Fort Churchill, it thickly coated all the branches of the trees.

As a result of the deep snow cover the ground was thermally protected and would be less cold, and frozen to a smaller depth, than at Fort Churchill. The ice on the lakes was less thick than the Bay ice and also would be comparatively smooth on the surface.

Further checks on this type of terrain were made in flights on the return journey from Fort Nelson to Edmonton, and from Edmonton to Ottowa, using, in the latter case, open water of Lake Superior for a comparison.

4 Results

The figure for the reflection coefficient of sea water was accepted as 0.85. It was also known that over typical English moist terrain the reflection coefficient was down relative to sea water by about 4 to 6 db. There was, of course, a greater decrease over dry sandy soils after a long spell of dry weather.

Desert Sand Dunes

Over the dry shifting sands of Sinai the decrease, compared with a sea reflection, was approximately 15 db.

Barren Desert Rock

Measurements over the rocky desert of North Africa showed that the signals were not quite so weak as from the loose shifting sands and a comparative figure of 12 db would seem to be reasonable.

Frozen Sea

Reflections from the pack ice of Hudson Bay were 13 db less than from open sea. The reflection from the shore ice were of similar strength, the only difference being that from the pack ice the pulse was less steady and more ragged in shape. It is seen that this figure is considerably lower than the calculations indicated.

[redacted]

Muskeg and Barren Gravel

Both types of terrain seemed to give a reflection 10 - 13 db down on sea. The value was mostly 13 db down but occasionally the reflected wave seemed to increase in strength. This was probably due to a somewhat stronger specular reflection from smooth sheets of ice which were sometimes very extensive, instead of the customary mixture of gravel or muskeg and small ponds.

Inland Snow Covered Lakes

The reflection from the snow covered lakes was somewhat stronger than from the rough sea ice and was about 10 db down on sea reflections. This may partly be due to the fact that the inland lakes, being completely surrounded by tall trees, had smooth ice surfaces. The sharpness with which the reflection changed when flying from forest to lake indicated that the reflection was largely specular.

Snow Covered Forest

This provided the weakest signals so far recorded and the value was repeated each time flying was done over such ground. The value was consistently 20 db down on a sea reflection.

- The above results are collected together, assuming the reflection coefficient for water to be 0.85.

Terrain	Reflection Relative to Sea	Reflection Coefficient assuming 0.85 for Sea
Sea	0	0.85
Dry Desert Sand	-15 db	0.15
Barren Desert Rock	-12 db	0.21
Frozen Sea Ice	-13 db	0.19
Smooth Snow Covered Lakes	-10 db	0.27
Frozen Muskeg and Gravel	-10 db	0.27
	to -13 db	0.19
Frozen Snow Covered Forest	-20 db	0.08

5 Conclusions

The survey has covered all terrains which were expected to give very low values of reflection coefficient. Whilst it is expected that heavily wooded European terrain or tropical forests etc. may well cause a significant decrease in the coefficient of ordinary soil, it is not expected that values as low as for arctic forest will be obtained.

It should be stressed that these low coefficients refer specifically to terrain so cold that all moisture content has been frozen. Normal ground, snow and ice, even when apparently well frozen, can have small droplets of water distributed through them. This would tend to increase the coefficient, so that measurements of snow covered surfaces in U.K. and indeed in central Europe would, in general, have coefficients of quite a large value.

6 Acknowledgements

The author wishes to thank the Ministry of Defence for the valuable assistance given by the Joint Intelligence Bureau in locating the most suitable desert and arctic terrains, thus allowing advance planning to be made.

The Canadian Defence Research Board co-operated in the carrying out of the flights in Northern Canada by providing much information and assistance in organising the programme. By arranging for Sq/Ldr. K.R. Greenaway, R.C.A.F., of their Arctic Research Division to join the expedition throughout the flying programme, they provided us with expert advice on arctic terrains and conditions. Without this assistance it would have been impossible to identify the various types of terrain under the difficult flying conditions encountered.

The flights were carried out in a York aircraft from the Royal Aircraft Establishment. Whilst in Canada the aircraft was attached to the Ministry of Supply, Climatic Detachment C.E.P.E., Edmonton, Alberta.

The work was carried out under the guidance of Mr. W.L. Horwood of the Radio Dept. at the Royal Aircraft Establishment. Mr. W.G. Candle accompanied the author on all the flights and assisted in the experimental programme as well as being responsible for maintaining the equipment and installation.

LIST OF SYMBOLS

P_t	=	Transmitter power
P_a	=	The power in the matched load of a receiver aerial at O
P_u	=	The part of P_a useful in building up the peak of the received pulse
G	=	Power gain of transmitter aerial, relative to an isotropic source, in a direction normal to the plane of the aerial
$f_1(\alpha)$	=	The power distribution pattern of the transmitter aerial at an angle α to the normal to the aerial
δa	=	An element of area of the ground
h	=	The height of the aircraft above the earth
d	=	The slant distance from the aircraft to a point on the earth
σ	=	The ratio of power re-radiated from an area δa to the power incident upon it
$f_2(\alpha)$	=	The distribution pattern of the power re-radiated from the area δa.
g	=	The power gain normal to the area δa relative to the value for isotropic re-radiation
A	=	The equivalent absorbing area of the receiving aerial
p	=	The polarisation factor of the power, re-radiated from the area δa
r	=	The distance on the ground between the vertical from the plane and the slant distance at an angle α
s	=	The distance equivalent to one pulse length

LIST OF SYMBOLS (Contd.)

R	=	The voltage ratio of reflected to incident fields, i.e. the reflection coefficient
K	=	The complex relative permittivity of a medium
λ	=	Transmitter wavelength

LIST OF REFERENCES

No.	Author	Title, etc.
1	H. Schönfeld	Die Elektrischen Höhenmesser für Flugzeuge Deutsche Akademie fur Luftfahrtforschung, 1943.
2	J.E. Clegg	The Back Scattering of 3 cm Radio Waves from The Earth's Surface. TRE Technical Note T2132 June 1951.
3	J.A. Saxton	Reflection Coefficient of Snow and Ice at V.H.F. Wireless Engineer. Vol.27, Pages 17-25, 1950.

Attached:

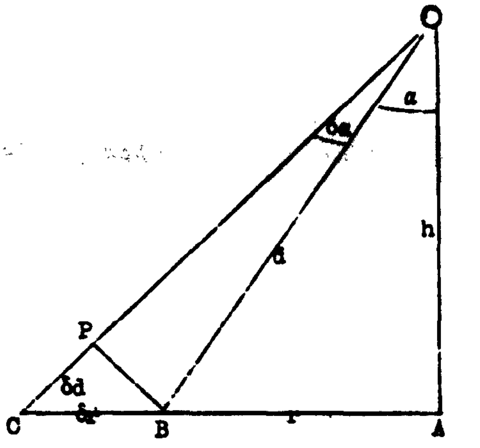
Appendices I and II
Detachable Abstract Cards

APPENDIX I

Calculation of the Law of Attenuation with Height of the Useful Signal received by a Pulse Altimeter from a Surface rough compared with the Wavelength

A transmitter at O radiates power P_t.

The gain in the direction OA with respect to an isotropic source is G, and the distribution pattern is $f_1(\alpha)$, where α is the angle between OA and the direction under discussion.



Then the power received on an element of area δa at A

$$= P_t \times \frac{\delta a}{4\pi h^2} \times G$$

The power on a unit of area δa at B—

$$= P_t \times \frac{\delta a \cos\alpha}{4\pi d^2} \times G \times f_1(\alpha)$$

It has been assumed that if energy from a dipole, or other plane polarised aerial is incident on a surface which is rough, then the scattered energy will have a random polarisation and will be scattered according to a suitable law.

Let the ratio of re-radiated to incident power at δa be σ and the radiation pattern be $gf_2(\alpha)$, where g is the gain normal to the surface. Then the power re-radiated from δa at B in the direction of O and available at a matched aerial of equivalent area A,

$$= P_t \times \frac{\delta a \cos\alpha}{4\pi d^2} \times Gf_1(\alpha) \times \sigma \times gf_2(\alpha) \times \frac{A}{4\pi d^2}$$

$$\text{But} \quad A = \frac{G\lambda^2}{4\pi} f_1(\alpha)$$

$\therefore$ Gain $= \frac{4A}{\lambda^2}$ and gain at angle α to OA is $Gf_1(\alpha)$.

Also a polarisation factor p must be added, since the power re-radiated from δa is randomly polarised and the aerial is polarised in one plane.

∴ Power available into a matched load

$$P_a = P_t \times \frac{\delta a \cos\alpha}{4\pi d^2} \times Gf_1(\alpha) \times \sigma g f_2(\alpha) \times \frac{G\lambda^2}{4\pi} f_1(\alpha) \times \frac{1}{4\pi d^2} \times p$$

$$= \frac{P_t \sigma p \lambda^2}{64\pi^3} \cdot G^2 g f_1^2(\alpha) f_2(\alpha) \times \frac{\cos\alpha\, \delta a}{d^4}$$

The power returned to an aerial at O from an annulus of radius AB and of width BC arrives approximately from one range d, if BC = δr.

Now $\delta a = 2\pi r\, \delta r$

But $r = h \tan\alpha$.

and $\delta r = h \sec^2\alpha\, \delta\alpha$

$$\therefore \quad \delta a = 2\pi h^2 \tan\alpha \sec^2\alpha\, \delta\alpha$$

$$\therefore \quad P_a = \frac{P_t \sigma p \lambda^2}{64\pi^3} G^2 g f_1^2(\alpha) f_2(\alpha) \frac{\cos\alpha}{d^4} 2\pi h^2 \tan\alpha \sec^2\alpha\, \delta\alpha$$

$$= \frac{P_t \sigma p \lambda^2}{32\pi^2} G^2 g f_1^2(\alpha) f_2(\alpha) \frac{h^2}{d^4} \tan\alpha \sec\alpha\, \delta\alpha$$

But $\cos\alpha = \frac{h}{d}$

$$\therefore \quad P_a = \frac{P_t \sigma p \lambda^2}{32\pi^2} G^2 g f_1^2(\alpha) f_2(\alpha) \frac{\sin\alpha}{d^2} \delta\alpha$$

---

or since $\cos\alpha = \frac{h}{d}$ and $\delta\alpha = \frac{h}{d^2 \sin\alpha} \delta d$

$$P_a = \frac{P_t \sigma p \lambda^2}{32\pi^2} G^2 g f_1^2(\alpha) f_2(\alpha) \frac{h}{d^4} \delta d$$

Putting $$K = \frac{P_t \sigma p \lambda^2}{32 \pi^2}$$

$$P_a = K\, G^2\, g\, f_1^{\,2}(\alpha)\, f_2(\alpha)\, \frac{h}{d^4}\, \delta d$$

The total power returned to the aerial at O

$$= K\, G^2 g \int_{d=h}^{d=\infty} f_1^{\,2}(\alpha)\, f_2(\alpha)\, \frac{h}{d^4}\, \delta d$$

Now if $f_1(\alpha)$ and $f_2(\alpha)$ are given as functions of $\cos \alpha$ certain facts are of interest. This is a reasonable approximation, for a dipole and reflector conform very closely to $f_1(\alpha) = \cos^2\alpha$(power). A single slot aerial behaves as $f_1(\alpha) = \cos \alpha$ approximately, whereas the radiation from a double slot aerial is not far from the law $f_1(\alpha) = \cos^2 \alpha$.

Moreover, re-radiation from a flat surface rough compared with the wavelength is given as $f_2(\alpha) = \cos \alpha$ (Lemberts Law).

$\therefore$ Total power available $P_a = KG^2 g \int_h^\infty \cos^n \alpha \, \frac{h}{d^4}\, \delta d$

where if the aerial polar diagram is $G \cos^m \alpha$ and the ground scattering is $g \cos^\ell \alpha$, $n = 2m + \ell$.

$$P_a = K\, G^2 g \int_h^\infty \frac{h^{n+1}}{d^{n+4}}\, \delta d$$

$$= K\, G^2 g \left[\frac{-h^{n+1}}{(n+3) d^{n+3}} \right]_h^\infty$$

$$= \frac{KG^2 g}{(n+3)\, h^2}$$

Thus the total power available is always proportional to $\frac{1}{h^2}$ as would be expected.

In the pulse altimeter only the power which arrives at the receiver within the pulse width time of the earliest return of energy is useful in building up the returned pulse.

Consider the last useful energy to be returned from an angle of α where $d = h + s$ where s is the extra path length equivalent to the pulse width delay, (for a $1/4$ μsec pulse $s \approx 130$ feet). Then the useful available power

$$P_u = K\,G^2 g \int_{d=h}^{d=h+s} \frac{h^{n+1}}{d^{n+4}}\,\delta d$$

$$= K\,G^2 g \left[\frac{h^{n+1}}{(n+3)h^{n+3}} - \frac{h^{n+1}}{(n+3)\,(h+s)^{n+3}} \right]$$

$$= K\,G^2 g \left[\frac{1}{(n+3)h^2} - \frac{1}{(n+3)\,\frac{(h+s)^{n+3}}{h^{n+1}}} \right]$$

$$= K G^2 g\ \frac{1}{(n+3)h^2} \left[1 - \frac{1}{\left(1+\frac{s}{h}\right)^{n+3}} \right]$$

Now expanding $\left(1+\frac{s}{h}\right)^{-(n+3)}$

$$= 1 - (n+3)\frac{s}{h} + \frac{(n+3)\,(n+4)}{2}\,\frac{s^2}{h^2} - \frac{(n+3)\,(n+4)\,(n+5)}{2 \times 3}\,\frac{s^3}{h^3} + \ldots$$

For values where $h \gg s$ and for small values of n, terms after the second are negligible and

$$\left(1+\frac{s}{h}\right)^{-(n+3)} \approx 1 - (n+3)\frac{s}{h}$$

Then

$$P_u = K\,G^2 g\,\frac{1}{(n+3)h^2}\left[1 - 1 + (n+3)\frac{s}{h}\right]$$

$$= \frac{K\,G^2 g\,s}{h^3}$$

$$= \frac{P_t\,\sigma p \lambda^2}{32\,\pi^2}\;\overline{G^2\,g\,s} \times \frac{1}{h^3}$$

So that for all heights where $h \gg s$ the attenuation with height follows a third power law.

APPENDIX II

Calculation of Reflection Coefficients for Various Terrains for Normal Incidence

The reflection coefficients of radio waves from snow or ice covered terrains have been calculated by Saxton[3] for all angles of incidence. In dealing with the general case, complex optical reflection formulae were used, and it was considered that for normal incidence, results could be obtained using impedance discontinuities.

The following data was extracted from the article by Saxton and was used as a basis for the calculations.

Reflection Coefficient of Sea Water, normal incidence at 1600 Mc/s = 0.85

Complex permittivity of "average" land			11 - j2
"	"	" sea water	88 - j67
"	"	" ice	3.05
"	"	" snow	1.40

The intrinsic impedance of a medium of complex permittivity K is

$$\frac{377}{\sqrt{K}} \text{ ohms}$$

Thus we have

Medium	Impedance (ohms)
"Average" Land	112 + j10
Sea Water	34 + j11.5
Ice	216
Snow	320

The reflection coefficient R for normal incidence at the boundary of two media of impedances Z_1 and Z_2 is given by

$$R = \frac{Z_1 - Z_2}{Z_1 + Z_2}$$

The reflection coefficients for an air/land or an air/sea boundary can be obtained directly.

For the case where three media are involved, it is necessary to transform the impedance of the lowest medium through a distance equal to the depth of the intermediate layer.

Any layer depth can be allowed for in this way by the use of a circle diagram, and the resultant coefficient can be seen to be an oscillatory function with maxima and minima occurring at intervals of half wavelength of the thickness of the intermediate layer.

When considering the case of air, ice, land, or air, ice, sea, it is clear that, at the wavelength used, the layer thickness will at all times be rough compared with a wavelength, and therefore the resultant reflection coefficient will be an average value.

Consider various simple cases of one discontinuity

1. Air to Ice   Z air = 377 Z ice = 216

$$R = \frac{377 - 216}{377 + 216} = 0.27$$

2. Air to Snow   Z snow = 320 for well compacted snow

$$R = 0.08$$

The attenuation through deep ice is small, and through deep snow is negligible, so that it will be expected that in these cases the medium below the snow or ice must always be considered.

3. Air to Average Land   Z land = 112

$$R = 0.54$$

4. Air to Sea   Z sea = 36

$$R = 0.83$$

Cases of Three Media

5. Air - Snow - Land

The impedance of average land 112 + j10 will be transformed through various lossless depths of snow of impedance 320 ohms. The land impedance normalised to that of snow in 0.35 + j.031. The impedance at the upper snow surface will vary from 320 x 0.35 = 112 ohms when the depth is an odd number of λ/4 to 320 x 0.35 = 910 ohms when the depth is an even number of λ/4.

When these values are considered with the air impedance of 377

$$R = \frac{377 - 112}{377 + 112} = 0.54 \text{ as for the no snow case}$$

or

$$R = \frac{910 - 377}{910 + 377} = 0.42$$

6. Air - Ice - Sea

The impedance of sea water, 34 + j11.5 when normalised to ice of 216 becomes 0.16 + j.05. This value, when transformed as above through varying ice layers has extreme values of 34 and 1350 ohms.

The extreme values of R become 0.83 and 0.96.

In both cases the average value shows a decrease, but in neither case is it very much smaller.

7 Air - Snow - Land under arctic conditions

If land is intensely frozen to a considerable depth it is considered that, as all the moisture present in the soil is in the form of ice particles, the behaviour of the land will be comparable to that of desert where similarly no moisture is present as such. It is stressed, however, that it is imperative that no moisture, as such, must be present, either in the land or in the snow or ice cover.

Thus, if the reflection coefficient of frozen arctic terrain is assumed to be similar to that of desert sand, i.e. 0.17, the impedance is 257 ohms. When this is normalised to snow impedance it becomes 0.83.

The reflection coefficient when the transformed impedance is a maximum is 0.17 as for the simple case of air - sand.

But when the minimum impedance is calculated, it is seen to be 0.01. So that the average value can be quite low, of the order of 0.17/2 or 0.08. This condition will exist whenever the impedances of the snow or ice layer and the impedance of the land are such that the intermediate layer acts as a matching transformer i.e. whenever Z(ice or snow) = $\sqrt{377 \times Z \text{ land}}$.

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The reflection coefficient of desert sand agreed with a figure obtained earlier at 400 Mc/s. by other authorities. It had been considered to be the lowest reflection coefficient to be found from any natural terrain.

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Over terrain deeply frozen and covered by deep snow and vegetation however, appreciably smaller reflection coefficients were measured.

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