Propagation in the LF-Band

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This abstract intends to give an overview to the relevant mechanism of propagation of RF waves in the LF range, which according to ITU addresses frequencies from 30kHz to 300kHz. As usual a lot of simplifications are necessary to describe natural effects. This is called modelling. The following explanations are based on simplified, but scientifically accepted models to ease assumptions and predictions on propagation properties.

Some of the basic simplifications are:

The earth is a sphere.
The earth's surface is smooth and homogen.
The earth's electrical properties are (at least in certain regions) homogen and constant.
The ionosphere consists of tiny layers of distinct height above the earth's surface having constant reflectivity (at least for portions of a day, season, solar cycle).

There are essentially two modes of propagation relevant in the LF range. Ground Wave Propagation and Sky Wave Propagation.

Ground Wave Propagation

Ground Wave Propagation concerns electromagnetic fields traveling along the earth’s surface, while inducing and being induced by currents flowing on and slightly below the earth’s surface. Sometimes those fields are referred to as the surface wave.

If the electrical properties of the earth’s soil were ideal, i.e. infinite conductivity, unity permittivity, unity permeability, then the field strength of the ground wave would strictly follow the "rule of inverse distance". If at a distance of 1km the field strength is 1mV/m, then at a distance of 10km it is 100uV/m and at 1000km 1uV/m. This is not the case, because the conductor "earth" is in no way perfect. Conducting RF currents in it cause energy from the RF field being converted into heat.

CCIR Rec.368-6

For the practical prediction of the ground waves fieldstrength, CCIR has issued Recommendation 368-6, which consist of a set of diagrams for typical ground properties. Each diagram contains graphs showing available fieldstrength for 25 frequencies from 10kHz to 30MHz in dependance of the distance. This method was compiled from a mathematical model and verified to provide accurate data by practical measurements.

Ground Wave Example for 137 kHz

For use in our LF-Band (CEPT/ERC Rec. 62-01 E) band I pick the 150kHz-graph for "average ground" (sigma=3mS/m, epsilon=22) and compile the values for a standardized ERP = 1 W. To adapt to other values of ERP use the equation E(ERP) = E(1W) + 10*log(ERP/1W)

100 km	37 dBuV/m
200 km	28 dBuV/m
300 km	23 dBuV/m
400 km	18 dBuV/m
500 km	13 dBuV/m
600 km	9 dBuV/m
700 km	5 dBuV/m
800 km	1 dBuV/m
900 km	-2 dBuV/m
1000 km	-6 dBuV/m
1100 km	-9 dBuV/m
1200 km	-13 dBuV/m
1300 km	-17 dBuV/m
1400 km	-20 dBuV/m
1500 km	-23 dBuV/m
1600 km	-27 dBuV/m
1700 km	-30 dBuV/m
1800 km	-34 dBuV/m
1900 km	-37 dBuV/m
2000 km	-40 dBuV/m
2100 km	-43 dBuV/m
2200 km	-47 dBuV/m

Practical Ground Wave Coverage on 137 kHz

The practical ground wave coverage range would depend on the lowest fieldstrength discernable from external noise in a given receiver IF Bandwidth (signal equals noise). Assuming an IF-BW=500Hz an equivalent external noise level expressed as vertical field strength of -9dBuV/m would classify a "very quiet site" (Recommendation ITU-R PI.372-6) for natural, atmospheric as well as artifical, man-made noise.

A radiated power of 1 W then yields a boundary of useful ground wave coverage (wanted signal equals external noise) in dependence of the ground properties (assumed homogeneous) over a selected ground path as follows:

range	ground type	conductivity	permitivity
1600 km	sea water	5 S/m	70
1600 km	marsh land	30 mS/m	40
1450 km	wet ground	10 mS/m	30
1080 km	fresh water	3 mS/m	80
1100 km	average ground	3 mS/m	22
700 km	medium dry ground	1 mS/m	15
430 km	dry ground	300 uS/m	7
290 km	very dry ground	100 uS/m	3
200 km	fresh w. ice - 1Cels.	30 uS/m	3
180 km	fresh w. ice -10Cels.	10 uS/m	3

Sky Wave Propagation

Sky Wave Propagation concerns electromagnetic fields leaving the antenna in two ways. One traveling in a straight line which encloses a positive angle (take-off angle = TOA) with the ground level, the other one in a straight line which encloses a negative angle with the ground level. The latter line bounces the ground level at a certain distance, to be reflected and finally travelling in parallel (with a phase delay) with the former line. Some refer the first skywave portion as the direct wave, the second skywave portion as the ground reflected wave.

Depending on the ground properties at the TX antenna site, depending on the polarization of the antenna (vertical in this sense) and the value of the TOA, the combined skywave traveling upwards to the ionosphere has differing energy content for the same ERP.

The combined skywave traveling upwards reaches the boundary of the ionosphere at a certain ground-distance from the TX site. It’s direction of travel encloses an angle with the line perpendicular to the boundary’s area (angle of ionospheric incidence = AOI). The skywave then penetrates the ionospheric region, exchanges energy with the molecules and ions present there, while being continuously refracted. Refraction occurs due to the fact that in the conductive ionospheric region the speed of propagation increases with the rate of ionization. The higher rays of the travelling wave penetrating into the ionospheric region become higher speed than the lower rays. This is similar to the effect observeable on a light beam traveling through a prisma of glas.

Assuming the ionospheric refraction coefficient were high enough to aim the direction of travel back towards ground, the refracted skywave then will leave the ionospheric region with quite the same AOI and will arrive ground level at twice the former mentioned ground-distance with an angle equal to the former TOA.

Assuming the ionospheric refraction coefficient were too low, the incoming skywave would fully pass the first ionospheric region under a now modified direction of travel to reach the next ionospheric region. While passing the first region, the energy content of the skywave would have decreased (inversely proportional to the frequency squared).

As the boundaries of the ionosphere constitute shells of spherical shape, they tend to focus the arriving skywave (analogy to spherical mirrors). Assuming the arriving wave consists of parallel rays, the departing rays then become convergent.

CCIR Rep.265-7

CCIR has issued Report 265-7 which provides a simplified model of ionospheric refraction and attenuation, incorporating most of the former mentioned effects using tailored diagrams derived from practical measurements and normalization thereof for frequencies from 30 kHz to 500 kHz.

The method is based on reducing the "true" ionosphere into a tiny layer of zero thickness, having a constant height of 70km during daytime and 90km during night-time. The geometric path of the skywave is approximated by straight lines (ray method), the actual, continuous refraction is replaced with distinct reflection (mirror analogy).

Effects of ground dependent vertical antenna pattern is accounted for by introducing a factor "Ft" for the TX antenna, "Fr" for the RX antenna in dependence of the ground properties in the first fresnel zone arround the antennas site, the actual TOA and the actual operating frequency.

Effects of ionospheric focusing is accounted for by a factor "D" in dependence of the TX-RX ground distance, actual operating frequency and time of day (daytime, night-time).

The energy exchange with the refracting ionosphere is accounted for by a factor "RC" (reflection coefficient) in dependence of the normalized frequency, time of day, season of year and epoch of solar activity. The basic data are for an typical minimum epoch of the solar activity, showing three graphs (day-time in winter, day-time in summer and night-time). The normalized frequency is the product of the cosine of AOI and the actual operation frequency.

It is a time consuming job to combine all the highly empiric diagrams for Fr, Ft, D, RC together into the final equation to derive skywave fieldstrengths "Es" for a given ERP in Watts, operating frequency "f" in kHz, variable TX-RX ground distance "d" in km - even for a single time of day, season of year and epoch of solar activity.

From "simple" geometric evaluation, values for ionospheric path length (IPL), TOA, AOI can be derived for a given ground distance "d" using the following constants:

h	daytime height hday=70km, or night-time height hnight=90km
U	earth’s circumference U=40074 km

deriving:

great circle angle in between TX and RX site		earth’s radius (km)	
c=d*2*pi/U	angle in radians	R = U/(2*pi)	angle in radians
c=d*360/U	angle in degrees	R = U/(360)	angle in degrees

half the IPL (km)	i = (R^2+(R+h)^2-2*R*(R+h)*cos(c/2))^0.5
angle of ionospheric incidence	AOI = asin((R*sin(c/2))/i)
take-off angle (radians)	TOA = pi/2-c/2-AOI angle in
take-off angle (degrees)	TOA = 90-c/2-AOI angle in
ionospheric path length (km)	IPL = 2*i

To read the reflection coefficient from the diagram we need the

effective frequency (kHz)	feff =f*cos(AOI)

and obtain "RC" for a season and a time of day during solar minimum.

skywave fieldstrength (result is uV/m), then becomes:

Es = 2*10^3*Eu*cos(TOA)*RC*D*Fr*Ft/IPL	when received with a magnetic antenna
Es = 2*10^3*Eu*(cos(TOA))^2*RC*D*Fr*Ft/IPL	when received with a short vertical antenna

Where Eu = (ERP*90/W)^0.5 is the "uncorrected" fieldstrength.

Parameters for 137 kHz

For those interested in doing yourself, the following frequency dependent parameters (representative only for 137 kHz) were "optically digitized" from the original graphs:

d TX-RX ground distance in km	D ionospheric focusing factor daytime / night-time	RC ionospher. reflection coefficient summer daytime / winter daytime / night-time	Fr & Ft RX/TX antenna ground pattern factor (sigma=2mS/m, epsilon=15)
100	1 / 1	0.00027 / 0.012 / 0.09	0.8
200	1.02 / 1.02	0.00045 / 0.017 / 0.1	0.8
300	1.05 / 1.05	0.0008 / 0.025 / 0.12	0.79
400	1.07 / 1.07	0.0014 / 0.035 / 0.14	0.78
500	1.1 / 1.08	0.0024 / 0.05 / 0.16	0.77
600	1.15 / 1.1	0.0036 / 0.07 / 0.18	0.76
700	1.18 / 1.14	0.005 / 0.08 / 0.195	0.75
800	1.22 / 1.18	0.0075 / 0.09 / 0.21	0.74
900	1.3 / 1.22	0.01 / 0.1 /0.225	0.73
1000	1.35 / 1.3	0.012 / 0.11 / 0.24	0.71
1100	1.45 / 1.35	0.014 / 0.12 / 0.25	0.69
1200	1.56 / 1.4	0.0155 / 0.13 / 0.26	0.67
1300	1.7 / 1.5	0.017 / 0.14 / 0.27	0.65
1400	1.83 / 1.6	0.019 / 0.15 / 0.28	0.6
1500	1.97 / 1.72	0.021 / 0.165 / 0.29	0.55
1600	2.1 / 1.9	0.023 / 0.18 / 0.3	0.48
1700	2.2 / 2.05	0.0237 / 0.19 / 0.31	0.44
1800	2.27 / 2.2	0.0242 / 0.2 / 0.318	0.4
1900	2.3 / 2.3	0.0245 / 0.21 / 0.323	0.35
2000	2.35 / 2.4	0.0247 / 0.215 / 0.326	0.33
2100	2.42 / 2.42	0.0249 / 0.218 / 0.328	0.31
2200	2.5 / 2.5	0.025 / 0.22 / 0.33	0.3

Skywave Example for 137 kHz

For your convenience I post the results from my last weekend "calculation marathon" which is only valid for:
solar minimum epoch, operating frequency = 137 kHz, ERP=1W, magnetic receiving antenna

distance	summerday	winterday	night-time
100 km	-39 dBuV/m	-6 dBuV/m	8 dBuV/m
200 km	-35 dBuV/m	-3 dBuV/m	11 dBuV/m
300 km	-31 dBuV/m	-1 dBuV/m	11 dBuV/m
400 km	-28 dBuV/m	0 dBuV/m	11 dBuV/m
500 km	-25 dBuV/m	1 dBuV/m	11 dBuV/m
600 km	-23 dBuV/m	3 dBuV/m	10 dBuV/m
700 km	-21 dBuV/m	3 dBuV/m	10 dBuV/m
800 km	-19 dBuV/m	3 dBuV/m	10 dBuV/m
900 km	-17 dBuV/m	3 dBuV/m	9 dBuV/m
1000 km	-16 dBuV/m	3 dBuV/m	9 dBuV/m
1100 km	-16 dBuV/m	3 dBuV/m	9 dBuV/m
1200 km	-15 dBuV/m	3 dBuV/m	8 dBuV/m
1300 km	-15 dBuV/m	3 dBuV/m	8 dBuV/m
1400 km	-16 dBuV/m	2 dBuV/m	7 dBuV/m
1500 km	-16 dBuV/m	2 dBuV/m	6 dBuV/m
1600 km	-18 dBuV/m	0 dBuV/m	4 dBuV/m
1700 km	-19 dBuV/m	-1 dBuV/m	3 dBuV/m
1800 km	-21 dBuV/m	-2 dBuV/m	1 dBuV/m
1900 km	-23 dBuV/m	-5 dBuV/m	-1 dBuV/m
2000 km	-25 dBuV/m	-6 dBuV/m	-2 dBuV/m
2100 km	-26 dBuV/m	-7 dBuV/m	-3 dBuV/m
2200 km	-26 dBuV/m	-7 dBuV/m	-4 dBuV/m

Practical Sky Wave Coverage on 137 kHz

The practical skywave coverage range would depend on the lowest fieldstrength discernable from external noise in a given receiver IF Bandwidth (signal equals noise). Assuming an IF-BW=500Hz an equivalent external noise level expressed as vertical field strength of -9dBuV/m would classify a "very quiet site" (Recommendation ITU-R PI.372-6) for natural, atmospheric as well as artifical, man-made noise.

A radiated power of 1 W then yields a boundary of useful skywave coverage (wanted signal equals external noise) in dependence of the season and time of day as follows:

more than 2200 km	during night-time
more than 2200 km	during winter daytime
apparently none	during summer daytime

Solar Activity

As we are definitely no more in the minimum epoch of the solar activity cylce, nor at the maximum, the values derived so far may be utilized as a raw scale rather than exact figures. The original CCIR report provides a last diagram (dependent on the effective frequency, time of day, season of year) showing the "offsets" in between the values for minimum and maximum epoch of solar activity.

The differences pertaining the distances 100km through 2200km are:

The maximum epoch values for night-time are 2-4dB higher than those for the minimum epoch (May be appoximated by a constant 3dB offset for all these distances).

The maximum epoch values for winter daytime are 2-11dB higher than those for the minimum epoch. 2dB for 100km, 11dB for 300km, 5dB for 2200km (logarithmic interpolation in between).

The maximum epoch values for summer daytime are 3-9dB higher than those for the minimum epoch.
3dB for 100km, 9dB for 300km (logarithmic interpolation in between), no values for greater distances contained in the original graph.

By comparing the skywave values with groundwave values we see that both waves are of equal strength (under the constrains of ground property etc.) at:

550 km	during night-time
750 km	during winter daytime
1250 km	during summer daytime

Those distances mark the range center where ground wave and sky will vectorially sum to the total field. By calculating the travel time from TX to RX via ground distance and via ionospheric path length and the speed of light, we can derive the phase lag in between both waves, relate it to a wavelength and can assume the effect of interference, either constructively, or destructively.

Every change in propagation mode which cause variations in direction (virtual height of ionospheric region), amplitude (reflection coefficient of the ionospheric region, i.e. ionization) of the traveling waves will also vary the received total field. This is what is called interference fading.

Effect of ionospheric and magnetospheric disturbances

The previous mentioned CCIR report 265-7 exclusively relates to sky wave fieldstrengths under a typical, average solar (either minimum or maximum) activity profile. There are no values or estimates provided which are accounting for deviations from the average solar activity, such as solar flares, solar wind variations, geomagnetic storms.

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