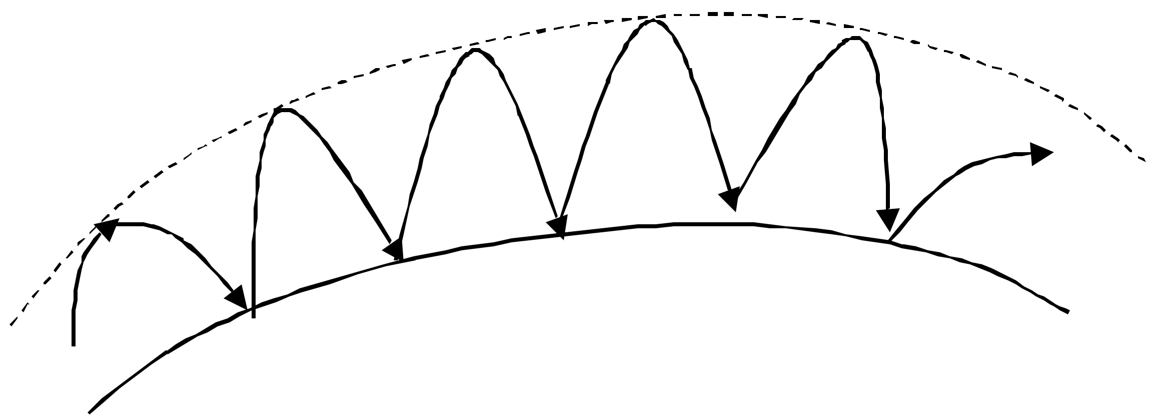
EC3630 Radiowave Propagation

OVERVIEW OF ELECTROMAGNETIC WAVE PROPAGATION

by Professor David Jenn



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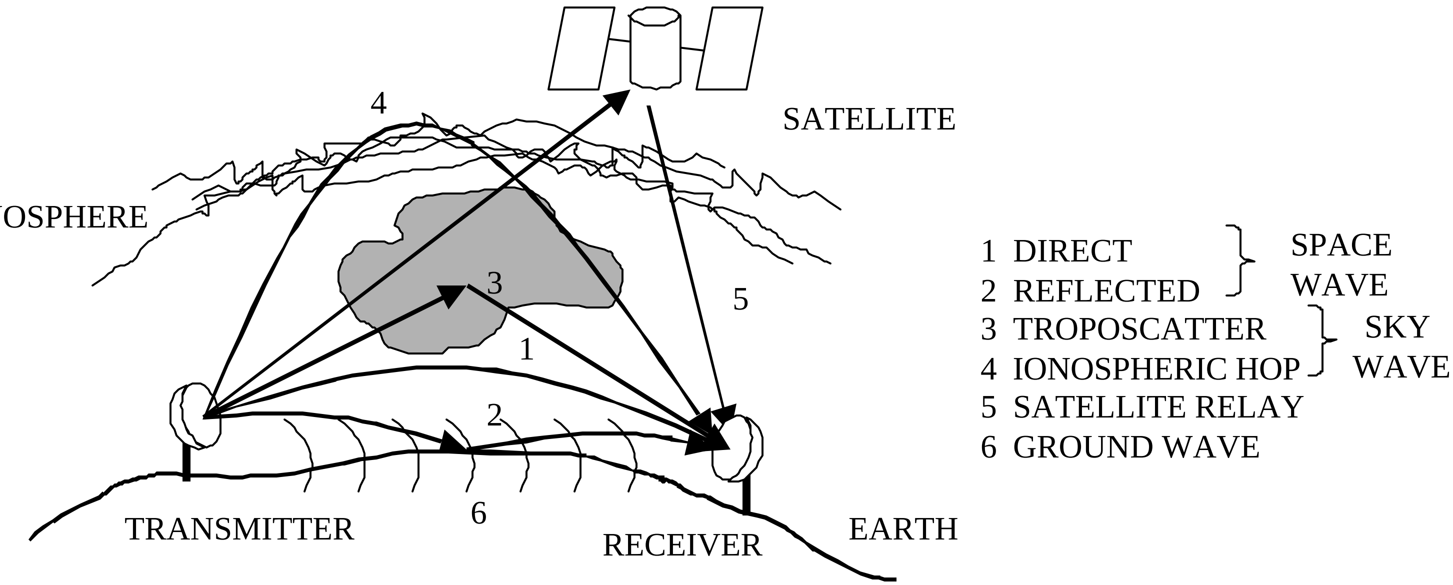
Propagation of Electromagnetic Waves

Radiating systems must operate in a complex changing environment that interacts with propagating electromagnetic waves. Commonly observed propagation effects are depicted below.



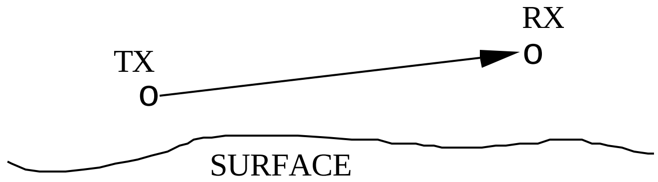
<u>Troposphere</u>: lower regions of the atmosphere (less than 10 km)
<u>Ionosphere</u>: upper regions of the atmosphere (50 km to 1000 km)

Effects on waves: reflection, refraction, diffraction, attenuation, scattering, and depolarization.

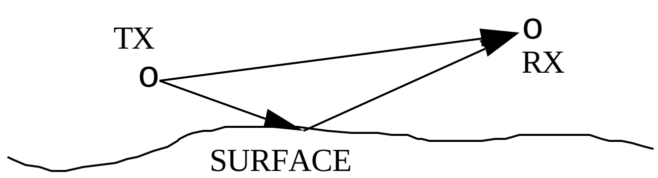
Survey of Propagation Mechanisms (1)

There are may propagation mechanisms by which signals can travel between the transmitter and receiver. Except for line-of-sight (LOS) paths, their effectiveness is generally a strong function of the frequency and transmitter-receiver geometry and frequency.

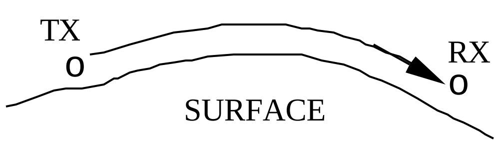
1. direct path or "line of sight" (most radars; SHF links from ground to satellites)



2. direct plus earth reflections or "multipath" (UHF broadcast; ground-to-air and air-to-air communications)

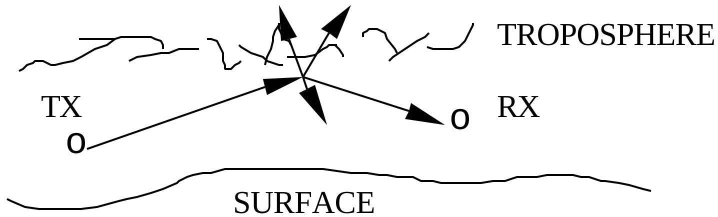


3. ground wave (AM broadcast; Loran C navigation at short ranges)

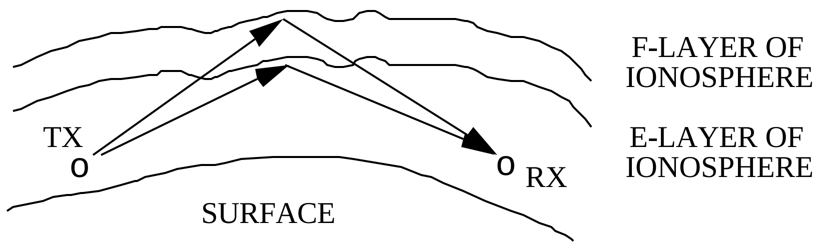


Survey of Propagation Mechanisms (2)

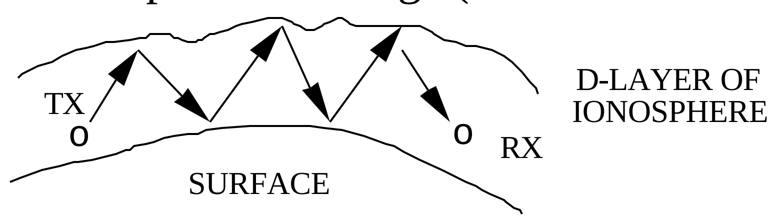
4. tropospheric paths or "troposcatter" (microwave links; over-the-horizon (OTH) radar and communications)



5. ionospheric hop (MF and HF broadcast and communications)



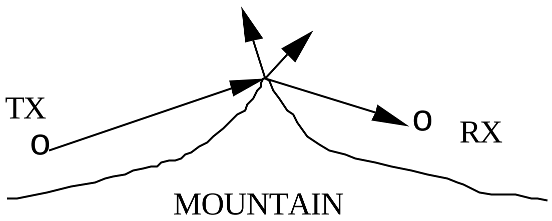
6. waveguide modes or "ionospheric ducting" (VLF and LF communications)



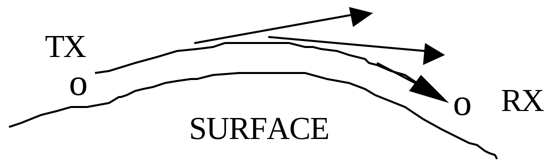
(Note: this is not the same as ionospheric hopping. In this case the ionosphere and earth's surface act like a parallel plate waveguide.)

Survey of Propagation Mechanisms (3)

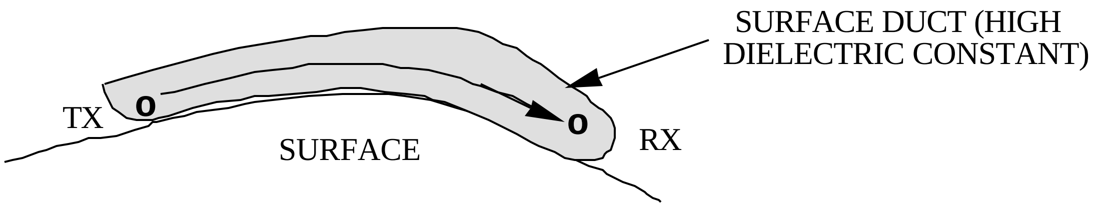
7. terrain diffraction



8. diffraction by the curved earth

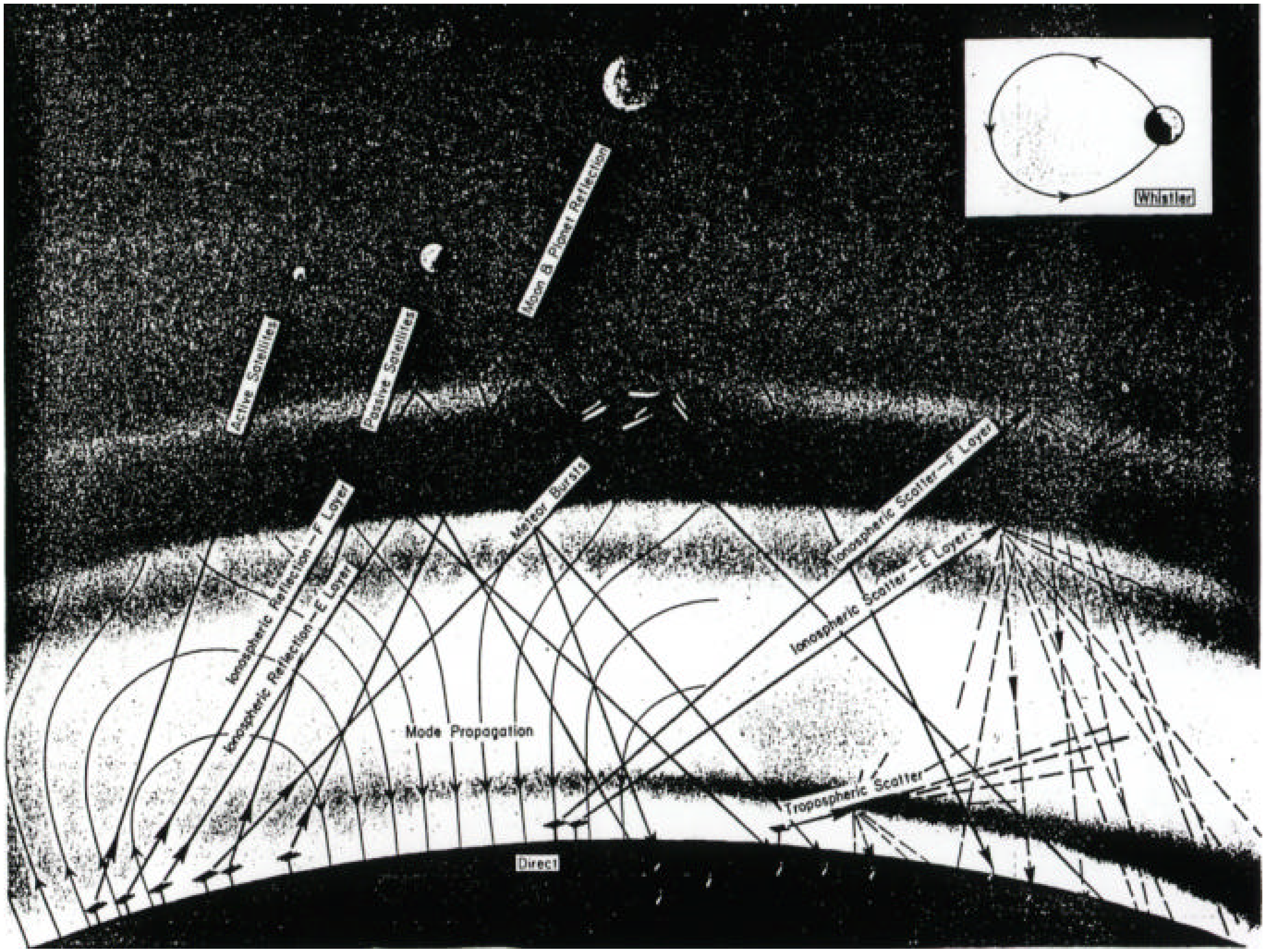


9. low altitude and surface ducts (radar frequencies)



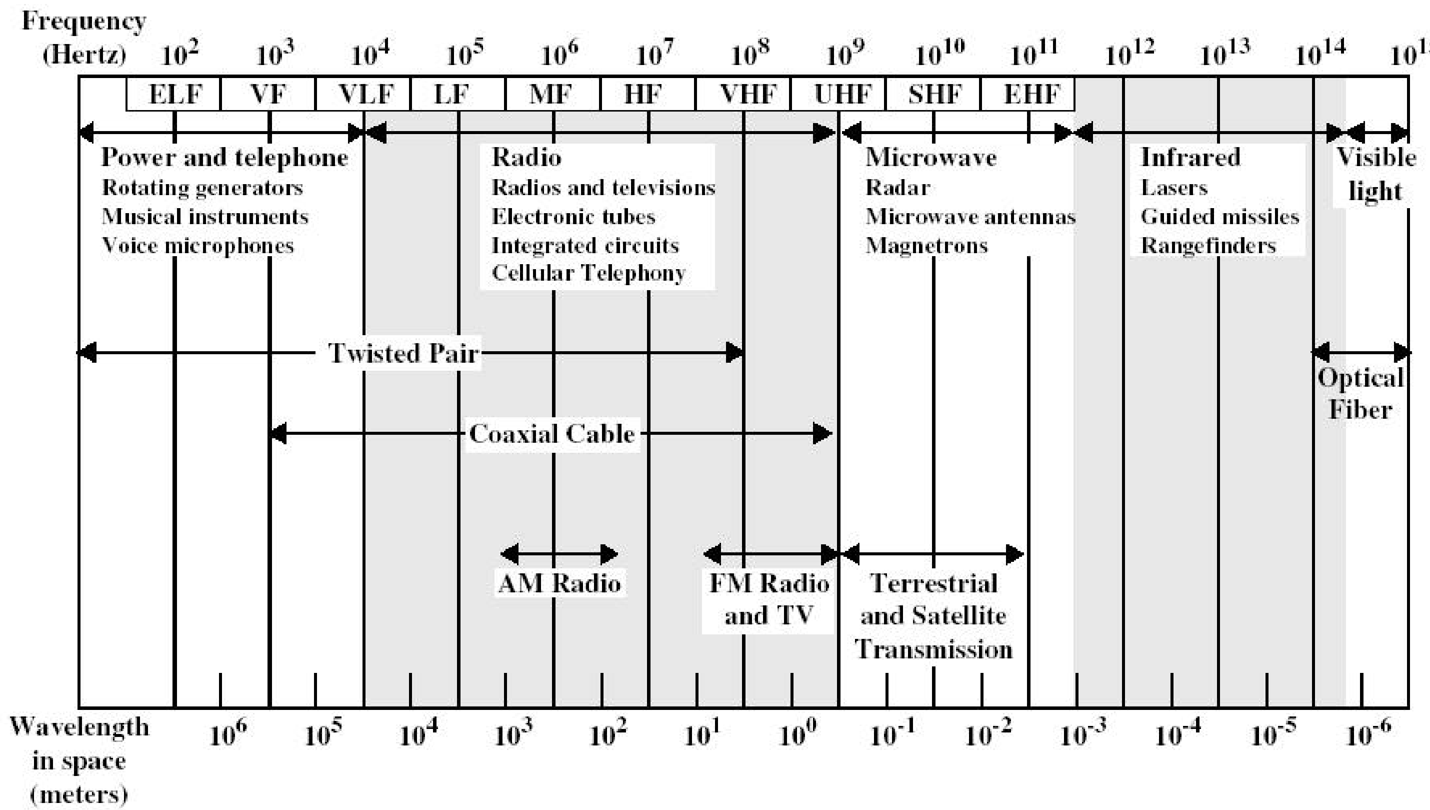
10. Other less significant mechanisms: meteor scatter, whistlers

Illustration of Propagation Phenomena



(From Prof. C. A. Levis, Ohio State University)

Electromagnetic Spectrum



ELF = Extremely low frequency
VF = Voice frequency
VLF = Very low frequency
LF = Low frequency
MF = Medium frequency
HF = High frequency
VHF = Very high frequency
UHF = Ultrahigh frequency
SHF = Superhigh frequency
EHF = Extremely high frequency

(From W. Stallings, *Wireless Communications and Networks*, Prentice Hall)

Propagation Mechanisms by Frequency Bands

VLF and LF (10 to 200 kHz)	Waveguide mode between Earth and D-layer; ground wave at short distances
LF to MF (200 kHz to 2 MHz)	Transition between ground wave and mode predominance and sky wave (ionospheric hops). Sky wave especially pronounced at night.
HF (2 MHz to 30 MHz)	Ionospheric hops. Very long distance communications with low power and simple antennas. The "short wave" band.
VHF (30 MHz to 100 MHz)	With low power and small antennas, primarily for local use using direct or direct-plus-Earth-reflected propagation; ducting can greatly increase this range. With large antennas and high power, ionospheric scatter communications.
UHF (80 MHz to 500 MHz)	Direct: early-warning radars, aircraft-to satellite and satellite-to-satellite communications. Direct-plus-Earth-reflected: air-to-ground communications, local television. Tropospheric scattering: when large highly directional antennas and high power are used.
SHF (500 MHz to 10 GHz)	Direct: most radars, satellite communications. Tropospheric refraction and terrain diffraction become important in microwave links and in satellite communication, at low altitudes.

Applications of Propagation Phenomena

Direct	Most radars; SHF links from ground to satellites
Direct plus Earth reflections	UHF broadcast TV with high antennas; ground-to-air and air-to-ground communications
Ground wave	Local Standard Broadcast (AM), Loran C navigation at relatively short ranges
Tropospheric paths	Microwave links
Waveguide modes	VLF and LF systems for long-range communication and navigation (Earth and D-layer form the waveguide)
Ionospheric hops (E- and F-layers)	MF and HF broadcast communications (including most long-distance amateur communications)
Tropospheric scatter	UHF medium distance communications
Ionospheric scatter	Medium distance communications in the lower VHF portion of the band
Meteor scatter	VHF long distance low data rate communications

Propagation of Electromagnetic Signals

by
Professors C. A. Levis[1] and D. C. Jenn

1. Definition of Propagation

Information can be transmitted in many ways. The use of electromagnetic energy for this purpose is attractive, in part, because often physical connections are not necessarily required This advantage gave rise to the terms *wireless telegraphy* and *wireless telephony* which were commonly used for radio in the early part of the 20th century. (The term *wireless* had become archaic to engineers, however, it had a rebirth with the proliferation of computer and information networks in the 1990s. Today it is these systems are associated with the term *wireless*.) The connectionless feature of electromagnetic propagation is utilized in many engineering systems: long distance point to point communications, radar, radio and television broadcasting, navigational aids, etc. The same considerations make electromagnetic energy useful in *sensors*, systems which obtain information from and about regions to which the energy is directed. Electromagnetic sensors are used for measuring the electron concentrations in the Earth's upper atmosphere (and now planetary atmospheres as well), the wave-state of the sea, the moisture content of the lower atmosphere, the moisture in soils and vegetation, the size distributions of particles in smoke, and many other parameters.

In most or all of these applications it is possible to divide active systems[2], at least conceptually, into three parts. The first is the transmitter; it generates the electromagnetic energy in an appropriate frequency range with the desired time waveform, superimposes on it whatever information is to be sent, and launches the resulting signal toward the receiver or the region to be sensed. The last is the receiver; it accepts some fraction of the energy which has been transmitted and extracts from it the desired information. Propagation is the link between the transmitter and receiver, i.e., the process whereby the information bearing energy or signal, is conveyed from the transmitter in the receiver.

2. Propagation and Systems Design

Propagation considerations can, and usually do, have a profound influence on systems design. They are therefore of great importance to the systems engineer as well as to the propagation specialist. For example, consider the *White Alice* system, a communication system implemented in Alaska and northern Canada during the late 1950s. It was designed partly for general communications needs and partly to convey information from the Distant Early Warning (DEW) line to Command Centers of the US Defense forces. Note that this was before the advent of satellites, so a terrestrial radio communication link was the only possible solution at the time.

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[1] Based on unpublished notes by C. A. Levis, Ohio State University, modified and expanded by D. C. Jenn, Naval Postgraduate School

[2] An active system is one that has its own source of radiation (i.e., a transmitter) as opposed to a passive system that only receives electromagnetic radiation. Passive systems can receive radiation that is transmitted by other active systems, or radiation that is emitted naturally by objects and the environment. Infrared night viewers are an example of the latter that operate in the infrared regions. Passive sensors that operate in the microwave and millimeter wave regions are called *radiometers*.

The establishment and maintenance of telecommunications centers in the inhospitable environment of the Arctic is a difficult and expensive matter. In the high-frequency (HF) band it is possible to transmit signals for very great distances with very modest equipment and antennas – a fact well know to radio amateurs (ham operators). Thus HF systems might seem to be the cheapest solution for this application. There are however several drawbacks to this approach. The ready propagation of the HF signals would make an HF system very susceptible to interference from signals arriving from other parts of the Earth. Also, HF propagation depends on the ionosphere, an ionized atmospheric region which is strongly influenced by the Sun. At times the Sun ejects huge streams of charged particles which severely upset the ionosphere and make HF communication in the Arctic and sub-Arctic region quite impossible. Thus and HF systems might be cheap, but it would be unreliable, and unreliability was unacceptable for this application.

The method that was chosen utilizes tropospheric scatter propagation, the reflection of signals by minor irregularities that are always present in the lower atmosphere. In contrast with HF, the ranges that can be achieved by this means are only on the order of 200 miles, necessitating intermediate communications stations between the DEW Line and the more populated areas. Also, very large antennas and high-powered transmitters are required. Figure 1 shows a *White Alice* site. It should be apparent that its establishment and maintenance was neither easy nor cheap. Nevertheless, the high reliability and relative freedom from interference associated with the troposcatter propagation outweighed the cost and other considerations, and so for this system was implemented. This illustrates how propagation considerations often play a dominant role in systems design when information must be communicated over substantial distances.

3. Historical Background

The idea that electromagnetic signals might propagate over considerable distances with the velocity of light was first proposed in 1865 by James Clerk Maxwell. Having added the displacement current term to the set of equations governing electromagnetic events (now called *Maxwell's equations*) he deduced that among their possible solutions rectilinear wave motion would be included. Thus an electromagnetic disturbance should be capable of being propagated over substantial distances. This prediction was verified experimentally by Heinrich Hertz in a series of experiments conducted in the late 1880s. Many of his experiments utilized waves of approximately one meter wavelength, in what is now termed the ultra-high frequency (UHF) range, and transmission distances were generally on the order of a few feet.

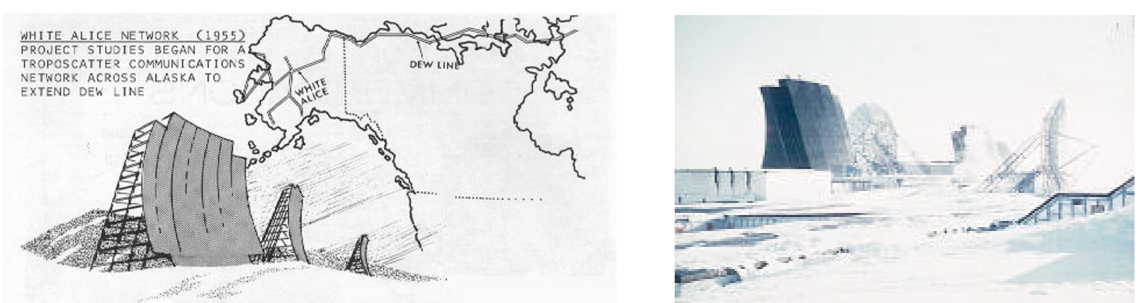

Figure 1: The White Alice troposcatter communication system.

Such an orderly progression from theory to experimental verifications has by no means been characteristic of the field of radio-wave propagation in general, however. When Marconi attempted his first trans-Atlantic transmissions in 1901, using waves of approximately 300 meters length, in what is now called the medium frequency (MF) band, there was no clear theoretical understanding of whether signal transmissions over such great distances might be possible. After the experiment was a success, there remained considerable controversy about the propagation mechanism until the now known explanation, ionospheric propagation, was sufficiently understood to be generally accepted. Such a lag of theory behind experiment has been quite characteristic of the field of radio propagation, and even now there are many phenomena which are not well understood or predicted by theory. As more powerful transmitters and more sensitive receivers became available over increasing frequency ranges, the body of knowledge regarding electromagnetic signal propagation has grown enormously and become increasingly complex.

4. The Influence of Signal Frequency and of Environment

In part this complexity is due to the extra ordinary range of frequencies (or wavelengths) which are useful for signal propagation. The lowest of these are in the vicinity of 10 kHz (30 km), although lower frequencies (longer wavelengths) are useful for observing geomagnetic phenomena. With the advent of lasers, the highest frequencies of interest for communicating information over considerable distances have shifted to the order of 10^{15} Hertz, corresponding to a wavelength of a few tenths of a micron (millionths of a meter). Thus a frequency range of eleven decades is spanned. A corresponding range in the case of structures would span from the lengths of the largest bridges to those of some viruses. A description of mechanical structures of over such a range of dimensions would also be complex.

The variety and complexity of the observed electromagnetic signal propagation phenomena are further increased by the diversity of the environment. For example, the conductivity of sea water varies by the factor of more than 10,000 over the frequency range 100 kHz to 200 MHz, so that its characteristics change from that of an excellent conductor to those of a lossy dielectric. The dielectric constant also changes, though to a lesser extent. There are also geographic variations, since salinity varies geographically. At VLF, all wave structures in the ocean are small compared to the wavelength of the signals. The ocean can then be approximated by a smooth conducting surface. At higher frequencies, the signal wavelength decreases until it may be of the same order of magnitude as the large ocean swells. The ocean thus behaves as a rough lossy dielectric in the VHF range, but in this frequency range the small capillary wavelets due to wind can still be ignored. As the frequency is increased further, so that the signal wavelength becomes a few millimeters or less, the swells represent randomly tilted flat plates; it is now the capillary wavelets that represent the roughness. Of course in all of these cases the roughness statistics vary with time and with location. Clearly the sea surface is a complicated propagation medium boundary. Land exhibits similar variations except that there are no important temporal changes. The atmosphere, like the sea is highly variable both temporally and geographically since its lower levels are strongly influenced by weather, and its upper ones by solar activity.

It is not surprising, then, that various propagation calculation techniques are appropriate to the various frequency and environmental regimes, and that in many cases resulting predictions are of an approximate and statistical nature. This course does not attempt to develop any of these techniques exhaustively, but rather to give a survey of the most common calculations and phenomena, which should be of value for the systems designer.

Since signal frequency is such a very important parameter, a rough indication of which range is being considered of often necessary. Standard frequency bands have been defined by the IEEE, and are used for this purpose. These are frequently used in the literature as well, and are generally not meant to be taken too literally, for propagation phenomena do not fall so neatly into decade frequency regions. Nevertheless the bands are useful for giving a quick, rough indication of the frequency range under discussion.

The wide frequency range employed and diversity of the environment give rise to a surprising number of propagation mechanisms for EM signals. A *propagation mechanism* is a physically distinct process by which the signal may travel from the transmitter to the receiver. Fortunately, depending both on the frequency and on the environmental conditions, one mechanism (or perhaps a few) usually produces much higher signal strengths than the others. These are said to be the dominant mechanisms for the particular conditions (sometimes referred to as *propagation modes*) and the others can often be neglected.

As an example, consider ordinary ionospheric reflection. Under many conditions, the ionosphere is extraordinarily effective in guiding signals in the range of VLF to HF. Signals propagated by this mechanism are likely to be very much stronger than those received in any other way over the same path, and other mechanisms may be neglected when this is true. For one, the ionospheric reflection process is not useful when the distances between the transmitter and receiver are relatively short. In that case, the signals arriving at the ionosphere at steep angles pass right through it, while those going up at a shallow angle end up at too great a distance; the ionosphreic signals are then said to "skip" over the receiver. Also, in the LF range in the daytime, certain regions of the ionosphere absorb signals very effectively. The same is true of HF at medium and high latitudes when the Sun is highly disturbed. Under any of these conditions, other propagation mechanisms may become dominant – or else no efficient propagation mechanism may exist, so that communication in certain frequency ranges becomes difficult or impossible under these conditions.

One example of this variability of propagation mechanisms has probably been observed by everyone, and that is the daytime/nighttime effect in the standard broadcast (AM) band, which falls in to the MF frequency band. During the daytime, only stations with a two or three-hundred mile radius are received and the reception is likely to be interference free. At sunset the situation changes, sometimes with dramatic abruptness. Now distant stations can be received with ease. Unfortunately, of those frequencies which are shared by several stations, many are likely to be received simultaneously, much to the frustration of the listener. The nighttime propagation mechanism is dominated by ionospheric reflection, but since the ionosphere absorbs signals well in this frequency range in the daytime, as noted previously, the daytime mechanism is a different one: the ground wave. Thus a change in the dominant propagation mechanism is responsible for the difference in reception conditions. Note that the ground wave is present also at night, but its effect is not noticed at that time at reasonably large distances from the transmitter because the much higher signal strength of the ionospherically propagated signal, when it propagates, effectively swamps the ground wave signal so that its effect is negligible.

5. Overview of Propagation Mechanisms

A brief overview of the propagation mechanisms follows in order to provide a frame of reference for the detailed theories to be discussed later in the course.

1. Direct Path

The simplest mechanism is *direct propagation*, involving the travel of the signal directly from the transmitter to the receiver quite unaffected by any medium. It has the form of a spherical wave, which generally can be approximated as a plane wave. Direct propagation may seem to be a highly idealized situation, and indeed it is, but it has important applications. For frequencies in the UHF and higher bands, the ionosphere has little influence, essentially because the electrons responsible for its conductivity at the slower frequencies are unable to follow the rapid variations at such higher frequencies. Also, at these higher frequencies it is possible to build very directive antennas, so that the signal beam may be kept from the ground (except perhaps at the endpoint of it intended path, if this is on the ground). Under these conditions, the signal propagates unaffected by ground or sky; propagation is essentially direct. Since most radars operate in this fashion, because a narrow beam is also advantageous for separating a particular radar target from its surroundings, direct propagation is the dominant mechanism, and the only one to be considered for most microwave radar calculations.

The frequency region for the *direct* mechanism is not open-ended at the higher end, however, for there is a band of frequencies (the upper SHF range and above) in which atmospheric constituents are able to absorb energy efficiently. In this range the direct propagation theory must be modified to account for this absorption by the inclusion of an additional attenuation term. As frequency is increased further, the wavelength decreases until it is of the order of magnitude of atmospheric dust and water droplets, which then can scatter the signal with some efficiency, and this requires further modifications. In short, direct propagation is the appropriate mechanism to consider only when all other mechanisms are inoperative, a situation most frequently encountered in the atmosphere at UHF to SHF with systems utilizing highly directive antennas and only when the transmitter and receiver are in plain view with respect to one another.

2. Tropospheric Refraction

The effect of gravity causes the atmosphere to be generally more dense and moist at lower altitudes than at higher ones. Though the effect is small, it causes a significant bending of the propagated signal path under many conditions. For example, in the design of microwave links used by telephone companies for long-distance telephone and television program distribution, care must be taken that the link will perform adequately for a variety of atmospheric conditions which may cause the beam to end upwards or downwards. This effect is known as *tropospheric refraction.*

3. Ducting

The bending effect of the tropospheric refraction may be strong enough to cause signals to follow closely along the curvature of the earth so that they are in effect guided along the earth. Such behavior is called *ducting*. A wave can propagate in a duct very efficiently, because the energy is mainly confined to the duct. Ducts are most frequently observed at VHF and UHF; they exist also at higher frequencies but the more directive antennas employed at these frequencies are less likely to couple effectively into the duct. Ducting is much more common at some locations than at other since it is closely related to meteorological phenomena. In most areas of the world is a source of potential interference rather than a means of reliable communication.

4. Ground Reflections

If the antennas used are not very directional, signals may travel from the transmitter to the receiver by reflection from the ground. In this case the directly propagated signal and the *ground-reflected* signal must both be considered in evaluating the total propagation performance of a system. A typical case is ground-to-air and air-to air communication at UHF. The size limitation of aircraft antennas makes it impossible to use highly directive antennas in this frequency regime, so that it is not possible to keep signals from reaching the ground. The ground reflected signals add to or subtract from the direct path signal, and both mechanisms must be considered.

5. Ground Wave

When antennas operate near or on the ground, it is found that the direct and reflected wave cancel almost completely. In this case, however, one also finds that a wave can be excited which travels along the ground surface, one of several types of waves included in the term *surface wave.* Since efficient transmitting antennas at MF and lower frequencies are necessarily large structures, because the wavelength is long, they are generally close to the ground, and ground wave propagation is important at these lower frequencies. It is the dominant mechanism for local standard broadcast (AM) transmissions in the United States.

6. Terrain Diffraction

When the receiver and transmitter are within line-of-sight, signals propagation at VHF and above is reasonably well described by the propagation concepts discussed so far. The theories of these mechanisms are derived form the concept of rays, i.e., of energy traveling along straight or nearly straight lines. Therefore these propagation mechanisms would allow no signal transmission when the endpoints are not within the line of sight (LOS). But such transmission is possible, and the reason becomes apparent when *diffraction* is considered. Diffraction by the Earth’s curvature itself is important, but even more pronounced is the effect of sharper obstacles, such as mountains. These obstacles scatter energy out of the incident beam, some of it toward the receiver, as shown in the charts.

7. Tropospheric Scatter

The troposphere is never truly homogeneous, as common experience with wind gusts and other meteorological phenomena indicates. The irregularities may be used to advantage when communications are needed over a path of several hundred miles, so that the two terminals are not within the LOS of each other. If very strong signals are beamed at a region of the atmosphere which is within the LOS of both stations, the relatively small signal scattered out of the beam may be sufficient to allow significant information transfer between the terminals. This is the mechanism employed by the White Alice system described earlier. Conversely, the diffraction mechanism (and indeed the propagation mechanism under appropriate conditions) may be the source of undesirable interference.

8. Ionospheric Reflections

In the MF and HF bands, signals give the appearance of traveling in rays which are reflected by the ionosphere above and the ground below. Actually the rays are bent, rather than sharply reflected, in the ionosphere, but the net effect is essentially the same. Signal transmission by this means can be very efficient, and great distances can be spanned with modest power and equipment. For this reason the short-wave bands, as they are often called popularly, are utilized for broadcasting, point-to-point communications, and amateur use, and they have become exceedingly crowded. Depending on the signal frequency, the reflection can occur in various regions (sometimes called layers) of the ionosphere.

9. Waveguide Modes

In the VLF and LF part of the spectrum, the ionosphere and the earth may be considered, respectively, the top and bottom of a waveguide which propagates energy around the earth. This point of view is particularly useful at the lowest of these frequencies, because then the wavelength is so long that the spacing of the "waveguide walls," the earth's surface and the ionosphere, is on the order of a wavelength, so that the mode structure becomes relatively simple and amenable to calculation. Perhaps it is not quite correct to distinguish between ionospheric reflections and waveguide modes as different physical mechanisms: in both cases the signal is guided between the earth and the ionosphere. If the wavelength is short compared to the earth-ionosphere spacing, ray theory is more convenient, and one treats the problem as a series of reflections. In between, in the LF region, computations by either technique become difficult. Thus the distinction between ionospheric hops and waveguide modes is based more on the mathematical models than on physical processes.

10. Ionospheric Scatter

Signals of a frequency too high to be reflected coherently from the ionosphere may nevertheless still be slightly affected by it. One of these effects is the scattering out of the beam of a small amount of energy by ionospheric irregularities, quite analogously to the scattering by tropospheric irregularities discussed above. The ionospheric scattering is most noticeable in the frequency regime immediately above the endpoint of ionospheric coherent reflection. Ionospheric scatter communications systems have been operated successfully in the VHF band.

11. Meteor Scatter

Many persons think of meteors as rare phenomena, perhaps because our daytime habits and increasingly urbanized environment leads us to see them rarely. Actually, visually observable meteors are not rare by any means; however, those too small to be observed visually are even vastly more abundant. As they enter the atmosphere, trails of ionized gas are formed, and these ionized trails are capable of reflecting electromagnetic signals. Since the ionization is more intense than that in the ionosphere, signals of a high enough frequency to be relatively unaffected by the ionosphere may be returned from meteor tails. Systems in the VHF band have been built and operated successfully.

12. Whistlers

Signals in the audio range of frequencies can propagate through the ionosphere in a peculiar mode, in which they follow closely the lines of the Earth's magnetic field. It is not easy to launch man-made waves of such very long lengths, but lightning strokes generate and launch energy in this frequency range quite effectively. The lightning-generated signals travel along the Earth's magnetic field lines, often going out a distance of several earth radii, and so are guided by the line to the point on the opposite hemisphere where the field line terminates. This point is called the antipode; at the antipode the signal may be detected. Part of the signal may be reflected a the antipode to travel back along the same magnetic field line to the point of origin, and so on, back and forth. The peculiar sound of the signals has lead to the name *whistlers*. This mode of propagation has not been utilized for information transmission, because of the very small bandwidth available at such low frequencies and the very restricted area of reception, but it has been a means of obtaining information about the upper ionosphere. The same basic propagation mode has been proposed as a means for propagating electromagnetic signals through the ion sheath around space vehicles as they re-enter the atmosphere, by creating a magnetic field around the vehicle.

13. Urban propagation

Urban propagation is a unique and relatively new area of study. It is important in the design of cellular and mobile communication systems that must operate reliably indoors and in built up city areas. Is not a unique propagation mechanism in itself, but rather a combination of direct, reflected, refracted, and diffracted components operating in an environment where all contribute significantly. Furthermore, the relative strengths of the individual components can add and subtract over short distances and times, leading to *fading* or dropouts.

For example, in an urban or suburban environment there is rarely a direct path between the transmitting and receiving antennas. However there usually are multiple reflection and diffraction paths between a transmitter and receiver. A complete theoretical treatment of propagation in an urban environment is practically intractable. This is not a result of any shortcoming in the electromagnetic theory, but rather the unpredictability of the environment on both large and small scales (relative to the wavelength). The details of the environment change from city to city and from block to block within a city. Statistical models are very effective in predicting propagation in this situation.

14. Non-atmospheric Propagation

The phenomena discussed so far have dealt with electromagnetic signal propagation through space or through the Earth's atmosphere over considerable distances. A totally different environment prevails when signals are to be propagated through the ocean, or the Earth's crust, or some planetary atmospheres. Two very important applications dealing with non-atmospheric propagation are (1) communication and sensing through the ocean, and (2) ground penetrating radar for land mine detection. These two applications will be discussed briefly, but in this course we will be concerned primarily with atmospheric propagation phenomena.

6. Summary

Propagation is the process whereby the signal is conveyed between the transmitter and receiver, and its consideration can have a profound influence on systems design. The signal frequency and the environment determine which propagation mechanisms are dominant. Although these mechanisms generally appear to involve distinct physical processes, it is found in some cases that what is different is not the processes, but the model used to represent it.

An advantage of electromagnetic signal transmission in many systems is that no physical link, such as wires, is required between the transmitter and receiver. This has obvious advantages for such systems as wireless local area networks (WLANs), where the flexibility to add new users or to accommodate the redistribution of users, gives the wireless approach a significant advantage over wired systems.