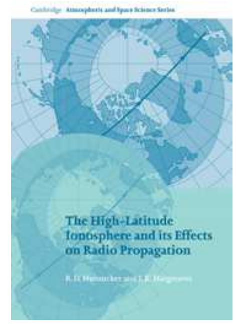

Title: ***The High-Latitude Ionosphere and Its Effects on Radio Propagation***
Author: R. Hunsucker and J. Hargreaves
Publisher: Cambridge University Press
ISBN: 978-0-521-04136-2
Date published: 2007
Length: 617 pages, 5 page index
Status: In print
Availability: 160 USD (softcover)
Reviewer: Whitham D. Reeve

The High-Latitude Ionosphere and Its Effects on Radio Propagation is a book in the *Cambridge Atmospheric and Space Science Series*. I was especially glad to obtain a copy – the author taught two graduate level advanced communications courses for the University of Alaska Fairbanks that I attended in Anchorage in 1973 and 1974 (Dr. Hunsucker flew each week to Anchorage from Fairbanks to teach the classes). To my knowledge there are no other books that discuss high-latitude radio propagation phenomena in any detail despite the many important problems associated with them. I previously reviewed another CASSS book ***The Solar-Terrestrial Environment*** by J. Hargreaves, a co-author of the book reviewed here [Hargreaves]. That review may be found at {Reeve20}.

It has been understood for many years that terrestrial radio propagation as well as Earth's magnetic field responses to disturbances in the Sun and solar wind are significantly different at high latitudes than at low and middle latitudes. For reference, *high latitudes* generally are considered those above 60° north or south of the equator. These sometimes are called *auroral latitudes* or *polar latitudes*. Low latitudes are 0° to 20° or 30° either side of the geomagnetic equator and middle latitudes are approximately 30° to 60° north and south of the geomagnetic equator.

The book may be used as a text by undergraduate and graduate students in an academic study of radio propagation at higher latitudes, but it has a much wider audience and also is usable for lower latitude radio propagation as well. The authors state in the *Preface* that "Advanced radio amateur operators and shortwave listeners should also find useful information in this monograph."

The High-Latitude Ionosphere and Its Effects on Radio Propagation is highly usable but I did note some minor deficiencies. On the positive side, like many technical books, a list of references and bibliography is included at the end of each chapter. This book breaks down the reference lists by chapter section. The bibliography includes general reading on the topics covered in the chapter as well as a list of relevant conference reports. These add value for readers who plan further study. The publisher's Resources webpage for the book includes errata with a couple dozen entries. A buyer should download these errata to avoid very time-consuming paths to misery when trying to use an unknowingly faulty equation. I did note that the errata is not complete – I spotted a few more-or-less obvious errors not listed.

On the negative side, the book does not have a glossary. Unfamiliar parameters and terms required some hunting around to clarify. For example, I had forgotten just what *invariant latitude* is – this describes the point on Earth where a particular magnetic field line touches the surface according to the dipole model of the geomagnetic field. On Earth's surface, the invariant latitude is the same as the magnetic latitude. It is easy to calculate for locations above the surface.

The index in any technical book is very important yet the index in this book is pretty sparse. Terms such as *gyro frequency* and invariant latitude appear several times in the text but are not found in the index. Also, some of the many radiation absorption plots are too small and unusable even though they are key to understanding a particular phenomenon described in the text. My book, which is a “digitally printed” version of the original 2003 edition, has black-white illustrations exclusively but there is some reference to colored traces in the text. Overall, the deficiencies are very minor compared to the many positive aspects of the book.

The first four chapters of ***The High-Latitude Ionosphere and Its Effects on Radio Propagation*** introduce the ionosphere in general (chapter 1), the influence of the magnetosphere (chapter 2), principles of radio propagation (chapter 3) and techniques in ionospheric observations (chapter 4). These chapters total over 200 pages and constitute an informative book in themselves. ***The Solar-Terrestrial Environment*** noted above at 415 pages contains in-depth treatments of the subjects in chapters 1, 2 and 4, so a reader who already has read that book may decide to skip those three chapters here. However, since ***The High-Latitude Ionosphere and Its Effects on Radio Propagation*** is almost 15 years newer, it includes more current information gained about the magnetosphere and ionosphere and about the techniques used to study them.

Chapter 3, *Fundamentals of Terrestrial Radio Propagation*, at 67 pages is an excellent overview of the physics of radio propagation and the terminology used to describe it. Any technical explanation of ionospheric propagation involves a heavy dose of magnetoionic theory. The concepts are not simple but are explained well in the book. Propagation depends on the ionosphere’s refractive index, n, which is expressed by *Appleton’s equation* and shown just for fun below.

$$n = \left[\frac{X}{1 - jZ - \dfrac{Y_T^2}{2(1 - X - jZ)} \pm \left(\dfrac{Y_T^4}{4(1 - X - jZ)^2} + Y_L^2 \right)^{1/2}} \right]^{1/2}$$

where + denotes the *ordinary* and – the *extraordinary* waves that result from electromagnetic propagation through a magnetized plasma. *X*, *Y* and *Z* are dimensionless quantities based on a ratio of the radio wave frequency and the frequency characteristics of the ionospheric medium. The three frequency characteristics are the *plasma frequency* for *X,* which depends on the electron density, *gyro frequency* for *Y*, which depends on the magnetic field, and *collision frequency* for *Z*, which depends on the rate of collision between a given electron and other particles in the ionosphere. Since *Y* depends on the magnetic field vector, it is convenient to divide it into two components, a transverse component Y_T and a longitudinal component Y_L. These are at a right-angle and parallel to the geomagnetic field, respectively.

It should be noted that the above equation also is called *Appleton-Hartree equation* and *Appleton-Lassen equation*. These recognize other scientists who independently developed the same equation in the same time frame. To add to the overall naming confusion, *Appleton’s formula* is another name often seen in the literature. Appleton’s equation is not derived in this book, but readers wishing to torture themselves can find derivations in [Ratcliffe] and [Davies].

Now, it is obvious that even a superficial understanding of the Appleton equation requires far more than a casual glance. Therefore, several simplifications are often made. These involve ignoring collisions and the magnetic field, including the effects of collisions alone, including the effects of the magnetic field without collisions, and so on. Although these are special cases, the complexity of many real propagation problems can be reduced using them. The authors walk through several simplifications, making it easy for a reader to understand the basics. I noticed that the book does not include plots of Appleton's equation for the various conditions – this is just as well as they require herculean concentration to interpret anyway.

Chapter 3 is not just about Appleton's equation. It also recognizes the role of computers in predicting terrain effects on radio propagation, such as diffraction over mountains and obstructions, and line-of-sight radio link performance. A table is provided that lists eight computer programs for this purpose and their source. Some of the sources undoubtedly have changed since the book originally was published in 2003, but I suspect most (if not all) still are available in one form or another. I started using these kinds of programs in the 1980s but they were somewhat limited and cumbersome and it was questionable how much they actually improved engineering efficiency. However, that changed over time with incremental and reliability improvements of the graphical user interfaces and computing hardware.

Another necessary improvement – needed for my work – was in the geodetic models used for the terrain. Because of its vastness and relatively sparse population, high resolution data for Alaska lagged the rest of the United States. The US Geological Survey eventually produced data that greatly improved the accuracy of my propagation studies.

Throughout the 1990s and first decade of the 2000s, I regularly used several of the programs listed and depended on them to reduce the engineering time needed to design VHF and UHF mobile radio, cellular and trunked radio system coverage areas and 2 GHz and higher frequency point-to-point line-of-site microwave radio relay paths. After construction, I almost always field verified the designs and always was pleased by their accuracy and usability.

Another table provided in chapter 3 is a list of PC-based HF propagation prediction programs. Generally, HF propagation is more complex than at higher frequencies because Earth's ionosphere and magnetic field have more effect. This is another area that has evolved over time and some of the programs listed actually include some effects of the high-latitude ionosphere. Without taking these effects into account (and, in many cases, even with them), the prediction of radio propagation at high latitudes is little more than a roll of the dice. The authors return to the subject of HF link prediction in chapter 9 and point out the gross limitations at high latitudes.

Chapter 4, *Radio Techniques for Probing the Ionosphere*, discusses the many methods that have been and are used to study how the ionosphere works. One of the authors has written a complete book on the subject [Hunsucker], so only a brief overview (45 pages) is given in the current book. The chapter has several sections covering ground-based and space-based measurement systems as well as methods for measuring the D-region absorption at high latitudes and the various types of ionospheric sounders that have helped gather data.

This review so far has covered 225 pages or a little more than one-third of the book. There are six more chapters, starting with chapter 5, *The High-Latitude F Region and the Trough*. Chapter 5 contains 57 pages and is where it is explained what makes the high latitude ionosphere different than lower latitudes. In particular, the high latitude F-region is exposed to the solar wind and interplanetary magnetic field (IMF) via Earth's magnetic field, thus, any solar disturbances are coupled to it either directly or through the magnetosphere. At lower latitudes Earth's ionosphere is shielded from the solar wind by the geomagnetic field. Although the Sun's radiation is important to production of the high latitude F-region, as it is at lower latitudes, the magnetic coupling to the solar wind make the F-region much more complex.

Another important factor is the area in which aurora occurs. A simple representation of the aurora shows that it occurs in a zone centered about 23° from the geomagnetic pole, or about 67° latitude, and is about 10° wide in latitude. However, the auroral region actually is oval shaped. On the equatorward side of the oval, the ionization is depleted, leading to a *trough* in the electron density in the F-region. Troughs are correlated with the planetary K_p-index and primarily are a night-time phenomenon. The K_p-index is based on geomagnetic activity in 3-hour synoptic periods as measured by observatories around the world.

Overall, the high-latitude ionosphere's F-region is quite irregular and is characterized by enhancements in the plasma (ion and electron) densities called *patches* and *blobs* and depletions called *holes*. Patches and blobs can range from tens of kilometers to 1000 km across and have high plasma densities on the order of those seen on the day-side ionosphere at low latitudes. Another remarkable characteristic is the speeds at which they move, 2000 to 5000 km h^{-1}. Holes are depleted regions similar to troughs except they are not elongated. The sources of these phenomena are not well understood despite intense study.

The magnetosphere operates on the edge of stability. It intermittently becomes unstable and suddenly releases a large amount of energy stored from the solar wind into the polar upper atmosphere. One manifestation of this energy release is the aurora. Chapter 6, *The Aurora, The Substorm and the E Region*, defines the many types of aurora including the visible kind (luminous aurora) and radar aurora, which is the reflection of radio waves (not just radio waves from radars) from ionization in the auroral region. Radio amateurs call this *radio aurora*.

Other aurora types include magnetic disturbances from the enhanced electric currents flowing in the auroral ionization and electromagnetic emissions in the very low and ultralow frequency bands (VLF and ULF). These emissions are due to wave-particle interactions and propagate to the ground where they are detected. Of particular concern to radio propagation is auroral absorption, which is the attenuation of radio waves as they pass through the auroral ionization. There are other types of aurora as well, and all of the various types may or may not be observed during any particular event.

Aurora of all types occur in what is called the *auroral oval*, which marks the instantaneous location of the aurora. It is where Earth's magnetic field divides between *opened* and *closed* field line configurations. Closed field lines wrap around and reenter Earth in the opposite hemisphere and the other pole of the magnetic dipole, whereas open field lines reach out into space where they interact directly with the IMF and are influenced by the solar wind (all magnetic field lines are continuous but open field lines have no clear path to the opposite pole). The auroral oval is widest at midnight and narrowest at noon and is fixed with respect to the Sun. Earth rotates underneath the auroral oval. The *auroral zone* is that part of the oval in the midnight sector.

All auroral phenomena are associated with energetic electrons that are coupled into the upper atmosphere along high-latitude geomagnetic field lines (electron precipitation). These may come with the solar wind or come out of the magnetosphere as the result of a solar disturbance. The luminous aurora is a manifestation of ionization by these energetic particles and subsequent recombination processes. The increased ionization occurs in the ionosphere's E- and D-regions with the more energetic particles penetrating into the D-region. Increased ionization in the D-region leads to absorption of radio waves that attempt to penetrate it on their way to higher refraction levels in the E- and F-regions.

It was found in the 1960s by a researcher at University of Alaska Fairbanks that luminous aurora tends to show repeating periods of activity lasting about 1 h with quiet periods lasting 2 to 3 h in between. These periods have a distinct beginning and end and are called *substorm*s. Sometimes and sometimes not, substorms develop into a full-blown geomagnetic storm. The consequences of substorms are most apparent in polar regions but their cause is in the magnetosphere. The trigger for substorms still is not understood.

The E-region is the last major topic in chapter 6. Here is what the authors say: "At middle latitudes the E region is easily the most boring part of the ionosphere. ... The same is true at high latitudes while geophysical conditions are quiet, but, when the Sun is active, the high-latitude E region becomes arguably one of the most exciting parts of the ionosphere." Precipitating particles (energetic electrons coupled in along magnetic field lines) are the main source of ionization during active conditions – these particles are the same ones that produce luminous aurora as discussed above.

The enhanced ionization in the high-latitude E-region has high conductivity and supports the auroral electrojet, which is a concentrated current system that flows westward along the auroral oval and is produced with luminous aurora. The effects on radio propagation vary wildly. It is interesting that poleward of the auroral oval, that is, the area over the polar cap, the E-region is considered *benign*. Here is it controlled by the Sun - it varies with the solar zenith angle and experiences seasonal effects similar to the mid-latitude E-region.

Now it is time to move down to the D-region. At lower latitudes, the D-region's effects on radio propagation are not as severe as at higher latitudes. At the lower latitudes the D-region may reduce the strength of an HF radio wave but it seldom prevents propagation for long periods. On the other hand, when the D-region at high latitudes becomes enhanced, radio propagation can be blacked out for long periods – days to a week or more. Chapter 7, *The High-Latitude D Region*, discusses two main phenomena – auroral radio absorption (AA, already mentioned above) and *polar cap absorption*, PCA.

Auroral absorption is due to energetic electron precipitation resulting in aurora activity whereas polar cap absorption is due to energetic protons emitted during a strong solar flare and hitting Earth within several minutes to a couple hours. It is interesting that, although AA occurs in a zone, it is not the same zone described by the auroral oval. AA activity occurs most frequently near midnight and shows wide variability among individual events. AA events are patchy, covering areas of tens to hundreds of kilometers and usually elongated in the east-west direction.

Auroral absorption's effects on propagation depend on radio circuit geometry, specifically the angle at which the radio wave passes through the D-region. For example, if a riometer (most of which have a broad vertical antenna pattern) detects 1 dB of absorption at 30 MHz, an oblique path will be attenuated by up to 20 dB. The level in dB of auroral absorption depends inversely on the square of the frequency. Therefore, AA greater than, say, 1 dB measured by a 30 MHz riometer can have a much larger effect on radio circuits throughout the lower HF band, leading to complete signal loss.

Auroral absorption is more frequent and more intense when geomagnetic activity is high (as is luminous aurora). The latitudes at which AA occurs decreases with increasing Kp-index and can go as low as 60° when the Kp-index is 6 or 7. Prediction of auroral absorption is based on statistics gathered from many riometers at high latitudes. The result of these predictions is the likelihood of a certain level of absorption at a certain site for a given level of magnetic disturbance. Not much more about it can be predicted.

Polar cap absorption events occur less frequently than auroral events but their effects cover a much wider geographical area and the absorption is more severe. A PCA that is recorded by a terrestrial cosmic ray detector is called a *ground level event* (GLE). The first GLE ever recorded, on 28 February 1942, was identified in retrospect because PCAs were not yet a known phenomenon. It coincided with a strong solar flare that also resulted in the first solar radio noise to be recorded. The radio noise was originally thought to be intentional jamming of British radars by the Germans during World War II. However, J. Hey, who was a radar troubleshooter during that time and received interference reports from several radar stations, correctly attributed it to the Sun after some research. He went on to become a well-known early radio astronomer and wrote about his experience in [Hey].

The occurrence of polar cap absorption events depends on the sunspot cycle, around ten or twelve per year near solar maximum down to zero or a few per year during solar minimum. The count depends on the absorption threshold setting. The median duration of events with absorption magnitudes greater than 1 dB is around 2.5 days but PCA events have been known to black out transpolar HF propagation for 10 days at a time (this probably is what happened in the 1951 film “The Thing from Another World”, which took place north of Alaska near the North Pole). The absorption usually appears first near the geomagnetic poles and then spreads to cover the polar cap some hours later. If a geomagnetic storm follows a flare, it usually causes the PCA to expand with the auroral oval.

The previous 400 or so pages have described the natural phenomena associated with the magnetosphere and ionosphere under both undisturbed and disturbed conditions and with emphasis on radio. Since scientific study must have practical applications, the final two chapters describe how these phenomena specifically relate to radio propagation: Chapter 8, *High Latitude Radio Propagation: Part 1 – Fundamentals and Early (Experimental) Results* and Chapter 9, *High Latitude Radio Propagation: Part 2 – Modeling, Prediction and Mitigation of Problem*. These chapters contain many examples, brief case studies and research summaries.

As already noted, propagation at higher latitudes can be quite different than lower latitudes. At higher latitudes Earth’s magnetic field lines allow solar wind particles and plasma to penetrate into the ionosphere, resulting in large magnitude irregularities aligned with the magnetic field in the ionosphere’s E- and F-regions and heavy absorption in the D-region. The effects cover a very wide frequency range – ELF (3 to 30 Hz) to UHF (300 to 3000 MHz).

Some propagation examples that are covered in chapter 8 are the submarine communications systems and navigation systems in the VLF and LF bands (3 to 300 kHz) (but not in great detail) and AM broadcast stations in the MF band (300 to 3000 kHz). E-region ionization in the auroral oval, called Auroral-E (AE), can strongly influence MF skywave propagation at night. At frequencies below the MF band, the primary propagation mechanism over very long distances (thousands of kilometers) is the Earth-ionosphere waveguide mode. The wavelengths involved are on the same order as the D-region height, so any change in this height caused by disturbances will affect the propagation modes (modes in the Earth-ionosphere waveguide are the configurations and orientations of the electric and magnetic fields between the D-region ionosphere and Earth's surface). The major cause of these effects at high latitudes are polar cap absorption.

The bulk of the discussions in the last two chapters has to do with HF propagation because that is the propagation most affected. The HF band primarily is a skywave band both day and night so any disturbances to the ionosphere have direct effects. In particular, the book describes tests carried out between Alaska and Scandinavia on fixed HF frequencies. I found some of these descriptions confusing (and possibly not complete).

Other tests included tangential HF propagation paths that skirted the auroral oval, paths that penetrated the oval from the equatorward side, paths from stations southward of the oval to stations close to its equatorward edge and transpolar paths that passed through the oval. There is a lot of data given here including ionograms, histograms of propagation conditions and plots of mode (hop) geometry. There is some discussion of ducted modes in the F-region. Some of these studies date back to the 1950s but many are near the book publication date. These all were basic research projects that established the state of our knowledge and still are relevant today.

Some interesting system design details emerge from the above-mentioned studies. For example, some of the studies showed that the signals propagated in relatively high-angle F2 modes and not low-angle modes as usually expected. This means that antennas designed for paths in the 5000 km range with low-angle radiation patterns will discriminate against such high-angle propagation and limit circuit reliability.

Another interesting phenomenon is called *auroral flutter*. It is the reception of multiple signal paths from auroral ionospheric irregularities. The flutter simply is fading that occurs at a high rate, say 20 Hz, and is observed most often during morning hours. I monitor WWV and WWVH and notice fading rates in the low Hz and sub-Hz ranges (most noticeable on Radio-SkyPipe charts) but I seldom hear fading at much faster rates. I am located on the southern edge of the northern auroral oval and the propagation paths from WWV and WWVH are not through the auroral oval on which flutter can occur. However, I suspect that during geomagnetically disturbed conditions, when the auroral oval has expanded overhead, it may be possible to detect the flutter.

Chapter 9 focuses on propagation path prediction and ways to mitigate problems. I feel that readers without access to the original references used in this chapter will not be able to fully use the information presented; however, the chapter still is a good overview. There is a good description of how ray tracing is used in prediction models. Ray tracing depends on models of electron density profiles along the path. One of the problems has been the lack of accurate models for high latitudes. Even at lower latitudes, the authors point out, the models produce *climatology* and not *weather* outputs on a fairly sparse data grid. In other words, there is not enough specificity in the outputs to be useful here and now.

Any system that uses radio propagation requires a certain signal-to-noise (SNR) ratio for reliable operation. Therefore, any propagation model requires radio noise models to be incorporated. The authors mention CCIR

Report 322-3 as the *accepted* global radio noise model. This report is no longer available but the International Telecommunications Union – Radio Communications Sector (ITU-R), which replaced CCIR, does maintain a global radio noise database as well as numerous recommendations associated with radio propagation and noise. A reader wishing to pursue this aspect of radio propagation should start at the ITU-R Study Group 3 and their recommendations and reports [ITU-R SG3]. Specifically, the P.372 recommendations address radio noise.

The authors tabulate the applicability of fourteen ionospheric models to high latitudes. The table dates back to 1996 and a number of the entries refer to DEC/VAX computer platforms. Although the table indicates that many of the programs are available from the individual developers, it may be difficult now to track them down. The authors make it clear that one of the problems at the time the book was published was the gross inaccuracy of the data at high latitudes, but this most likely has been improved since then.

Another phenomenon at high latitudes discussed in chapter 9 has to do with propagation paths that do not follow the expected great circle path (GCP) but instead follow oblique (off to the side) paths. Bearing deviations as large as 100° from the GCP have been measured. These have been attributed to tangential interaction with the auroral oval and to drifting troughs, patches and blobs.

In conclusion, ***The High-Latitude Ionosphere and Its Effects on Radio Propagation*** is for serious study and not casual reading, but that does not mean it is hard to read. On the contrary, the authors have done a good job partitioning the interrelated subjects into individual chapters and reducing the very complex principles to levels understandable by almost anyone with an interest in the technical aspects of terrestrial radio propagation and how it is affected by the ionosphere. It covers a wide variety of subjects that apply to all latitudes but, of course, the emphasis is on high latitudes.

I have been a student of radio propagation in Alaska since the 1960s, and I have often wondered about the irregularities I have observed. In 2010 I installed a 3-axis magnetometer at my Anchorage station (geomagnetic latitude 61.7° N, on the southern edge of the auroral oval). The daily magnetograms led to questions about the northern magnetic field and why it reacts the way it does to solar activity. The connection of the magnetic field through the high-latitude ionosphere to the solar wind and interplanetary magnetic field very broadly explains a lot of what I observe.

I often see periodic structures in the magnetograms that correspond to the 1 h and 2-3 h geomagnetic substorm cadence discussed in chapter 6, which concern the aurora and auroral electrojet. The book has helped me understand the linkages and gave me ideas on what to look for and the possibilities of correlating my radio propagation and magnetic observations. Radio amateurs and other radio communication users at lower latitudes may wonder about communications to and from stations at higher latitudes, and this book very likely will help their understanding.

The High-Latitude Ionosphere and Its Effects on Radio Propagation was originally published in 2003 when the majority of research was based on ground instruments. That is no longer true today and most data now is from dedicated spacecraft that fly through the magnetosphere. To study more current results with respect to the magnetosphere, readers may wish to view the weekly Magnetosphere Online Seminar Series {MAG}. This series is not directly related to radio propagation but the underlying principles do apply. In any case, the book has not been superseded or invalidated by more current work.

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{Reeve20} Book review of The Solar-Terrestrial Environment is available at: http://www.reeve.com/Documents/Book%20Reviews/Reeve_BookReview_SolarTerrestrialEnv_Hargreaves.pdf

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