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QST Issue: Mar 1990
Title: Practical Radio Aurora
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Practical Radio Aurora

Radio amateurs have known and used auroral propagation for more than fifty years. Here are some new suggestions—*practical* proposals—for making wider use of this most curious form of VHF and UHF propagation.

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Radio amateurs discovered auroral propagation in 1939, and have accumulated a great deal of practical knowledge about it over the intervening fifty years. Five previous *QST* articles have laid the foundations for understanding and using this most unusual form of radio propagation.[1] These fine contributions to the radio art make a most useful introduction to auroral propagation, and readers who are unfamiliar with radio aurora will want to review them. Although usually associated with the VHF and UHF bands from 50 to 432 MHz, aurora also provides useful propagation on 28 MHz. Aurora is not often exploited on 28 MHz, but it may be especially attractive during the solar minimum, when F-layer skip at 28 MHz all but disappears.[2]

This article builds on previous *QST* articles in three ways. First, it explains some characteristics of radio aurora that have received scant attention in the past. These include the relations of auroral activity to the solar cycle, considerations of geographic coverage, and implications of Doppler shift. Second, some practical hints are presented for making auroral contacts in the bands above 432 MHz—something amateurs have yet to accomplish. Finally, there's a short discussion of some recently discovered aurora-related phenomena that bear watching in the future. Understand from the outset that some analyses presented here simplify complex and incompletely understood physical mechanisms for the sake of focusing on useful principles. These simplifications are noted where appropriate.

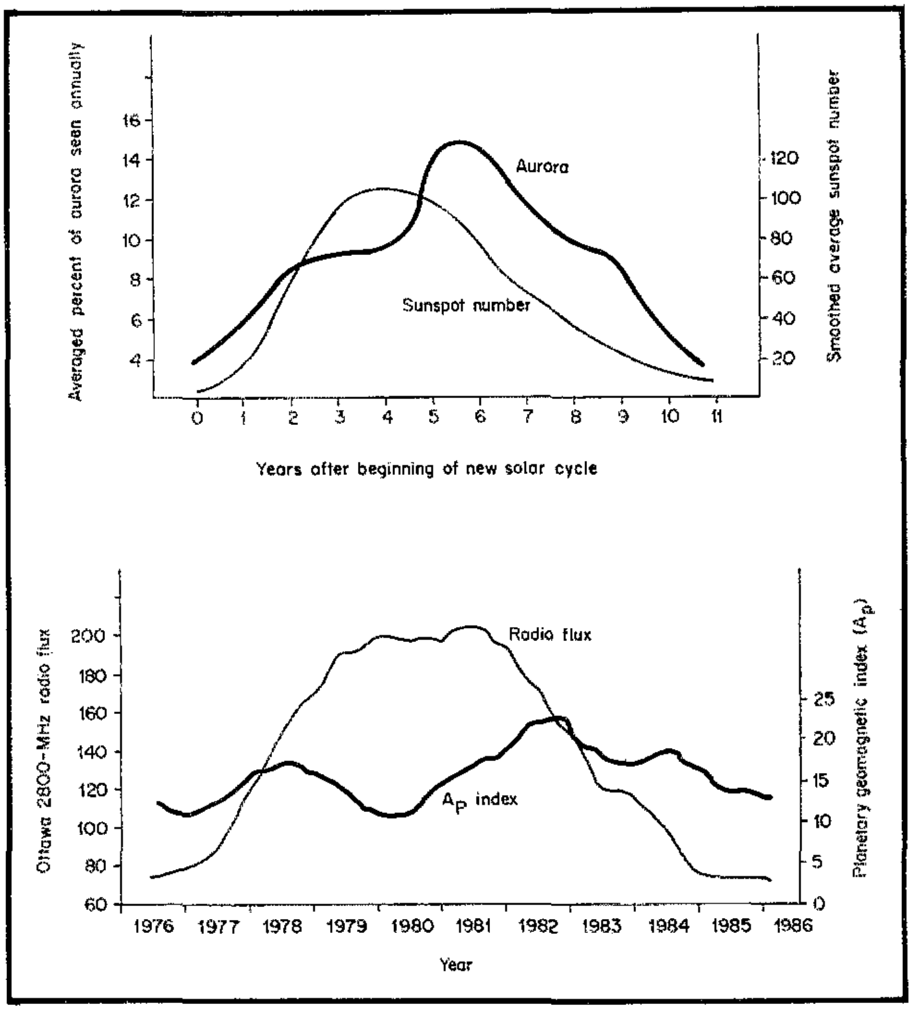

Fig 1—At A, occurrence of aurora compared with the sunspot cycle. The auroral curve shows the average percentage of the total number of auroras in the 11-year solar cycle seen each year across the cycle. Data points are four-year averaged annual observations during solar cycles 14 through 17 (1901-1945), made from the Yerkes Observatory, Wisconsin. The smoothed average sunspot numbers for cycles 8 through 20 provides a reference. Based on Chamberlain, pp 109-111. At B, planetary geomagnetic index (A_p) compared with the 2800-MHz solar flux during solar cycle 21. Source: NOAA-USAF Space Environment Services Center.

Aurora and the Daily, Annual, and Solar Cycles

More than five decades of radio-aurora observations and more than two centuries of systematic visual aurora observations have shown that auroras appear in certain daily, monthly, and annual cycles. As these have been discussed elsewhere in some detail, only the briefest review is necessary here.[3] Auroral activity has two distinct daily peaks. The most prominent occurs at about 1800 local time, followed by a gradual decline toward midnight. A secondary peak occurs at about 0200. Auroras are rarely observed at 1200 local time. There is a distinct tendency for aurora to reappear at 27-day intervals, because auroras are closely linked to general solar activity. Finally, auroras are two to three times as likely to occur near the spring and fall

[1]Notes appear on page 25.

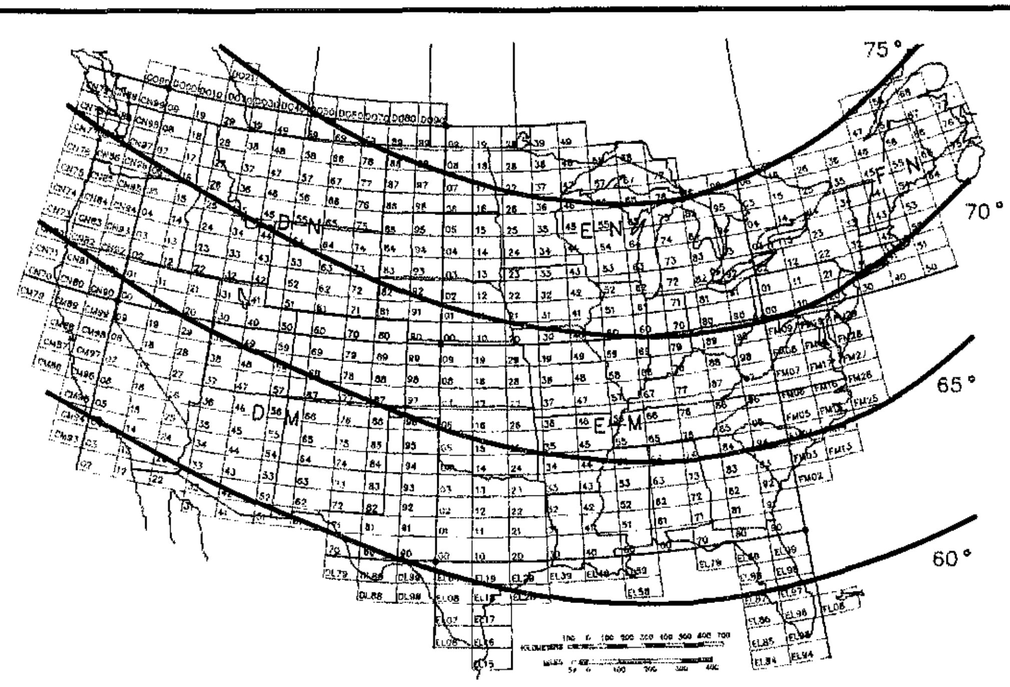

Fig 2—Geomagnetic latitude (measured as magnetic inclination) as of 1985. Geomagnetic latitude is centered on the geomagnetic pole, which is currently located in the Canadian arctic south of the geographic pole. Source: Forbes, p 58.

equinoxes, that is, in late March and late September, than during other times of the year.

A less well-known auroral cycle lags the 11-year cycle of solar activity by nearly two years. This is indicated in Fig 1A, which presents a summary of visual observations made from the Yerkes Observatory in Wisconsin between 1901 and 1945.[4] Aurora appearances do not form a smooth curve. There is a slight plateau between two and four years into the 11-year cycle, a main peak just after five years, and a small bump at about year eight.

It is difficult to account for the odd shape of this curve, but because auroral activity corresponds closely to geomagnetic activity, the ups and downs of the planetary A index (A_p) may provide the underlying pattern of auroral activity. Quite surprisingly, a plot of the A_p index during the most recent complete solar cycle (1975-1986) reveals a very similar curve with three peaks corresponding to the features noted in the curve of visual data from early in the century. Compare Fig 1A with Fig 1B. If these data do trace a predictable cycle of auroral activity, then auroral activity will probably peak during late 1991 or early 1992, one to two years after the currently predicted peak of solar cycle 22.

Geographic Considerations

In the northern hemisphere, auroras appear in the northern sky; they are rarely seen in southerly geographic latitudes in the northern hemisphere. Although this is generally accurate, the appearance of auroras correlates more closely with geomagnetic latitude, measured as magnetic inclination.[5] See Fig 2. Between 20 and 80 auroras also may appear annually over the Great Lakes (75° geomagnetic latitude), to fewer than 5 per year south of Pennsylvania (70° geomagnetic latitude), but authorities do not agree on these numbers.[6] Stations in the American West are likely to experience fewer auroras than stations at the same geographic latitude in the East because, as Fig 2 shows, the geomagnetic latitude dips considerably to the southeast in North America. The southerly extent of any particular aurora also correlates closely with the intensity of a geomagnetic disturbance. The higher the K index, the farther south, by geomagnetic latitude, an aurora is likely to appear.[7] Table 1 compares approximate K-index values and visual occurrences of aurora with geomagnetic latitudes. The strong association of aurora with geomagnetic activity has made close monitoring of the K and A indexes one popular technique for predicting radio aurora.[8]

Given the geographic distribution of aurora, it is often assumed that auroras spread southward from some more northerly origin. On-the-air observations seem to confirm the gradual expansion of radio-aurora activity over time, but this may be deceiving. This impression may simply be the result of how quickly operators became aware of auroral conditions, as on-the-air activity may lag considerably behind actual conditions, especially in more southerly latitudes where auroras are rare.[9] Aurora may actually form quite suddenly over a wide area. Reports in Amateur Radio journals over the years are scattered with references to aurora beginning and ending as if a great ionospheric switch were thrown; other anecdotal evidence suggests that the intensity of radio-aurora activity peaks very soon after aurora appears. What can we make of these sometimes contradictory observations?

A detailed study of 144-MHz contacts during the great February 1986 aurora seems to show that the aurora appeared and disappeared simultaneously over a

Table 1

Distribution of Aurora with Geomagnetic Latitude

Geomagnetic Latitude	*Average Annual Number of Overhead Auroras*	*Average K Index Required for Aurora*
75°	20-40	5
70°	10	7
65°	1-2	9

Sources: See Chamberlain and Forbes.

Table 2

Claimed North American Distance Records via Aurora

Frequency (MHz)	*Distance (km)*	*Stations*	*Date*
144	2169	WBØDRL — KA1ZE	Feb 8, 1986
220	1842	WB5LUA — W3IY/4	Jul 14, 1982
432	1901	WB5LUA — W3IP	Feb 8, 1986

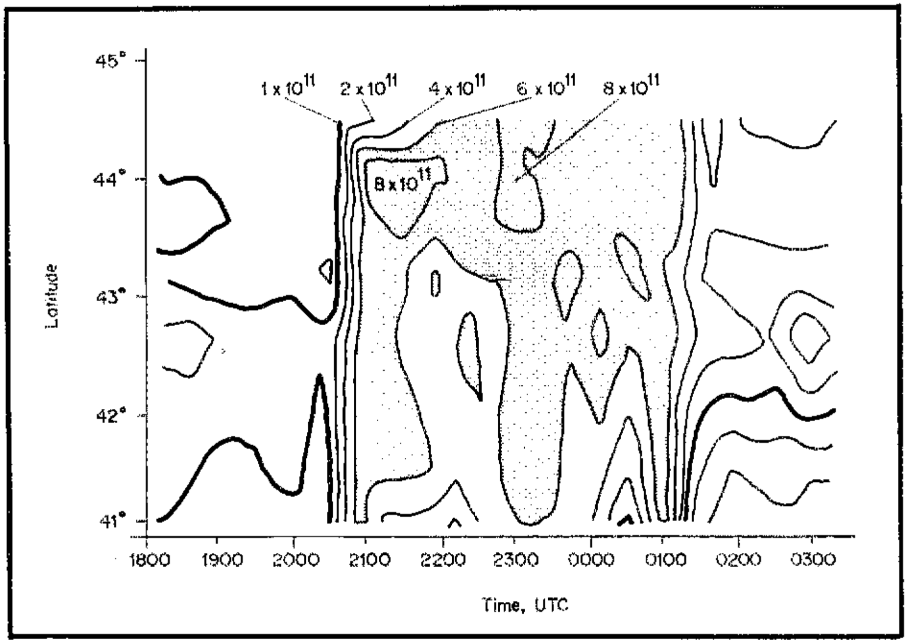

Fig 3—Electron density in the E layer at about 110 km altitude north and south of the Millstone Hill radar site in the Haystack Observatory, Massachusetts (42° latitude), on Feb 8-9, 1986. Density is measured in electrons per cubic meter (e/m³). Note the sudden intensification over a wide north-south belt at about 2030 UTC. The shaded portion represents a density in excess of 6 × 10^{11} e/m³. Source: Massachusetts Institute of Technology, Haystack Observatory.

broad geographic band, thus no real expansion took place.[10] A radar scan of the ionosphere made from the Haystack Observatory in Massachusetts during the same period supports this view. Fig 3 shows isograms of equivalent electron density in the E layer at about 110 km altitude over time during that aurora. Electron density increased nearly tenfold, from less than 10^{11} to nearly 10^{12} electrons per cubic meter (e/m³), within a twenty-minute period. This rapid ionization did not expand slowly southward, but appeared over a very broad north-south region all at once. Although the radar did not scan farther south than 41° latitude, satellite observations made at the same time indicate that these conditions extended as far as South Carolina at 34° latitude.

Over the following few hours, electron density receded and expanded twice, perhaps giving some credence to the notion that auroral activity may expand over time. The auroral session ended much as it had begun, that is, suddenly and simultaneously over a wide area—as if a great switch had been thrown once again. Although these data refer to just one period of a very intense aurora, they are typical of most auroras at middle latitudes.[11]

Maximum Distances

Auroral propagation is basically an E-layer phenomenon. Therefore, the maximum great-circle distance over which two stations could make contact, regardless of frequency, is about 2000 to 2200 km. This is the normal maximum range for single-hop sporadic-E and meteor-scatter contacts, for example, both of which are also E-layer phenomena. Current American distance records for auroral propagation, listed in Table 2, bear out this approximate figure, but there is still room to stretch those records. Contacts beyond 2200 km may be aided by enhancement due to favorable tropospheric conditions, or by high station elevations.

The three record contacts and many other recorded VHF and UHF aurora contacts in excess of 1500 km have predominantly east-west orientations.[12] The reason for this is not difficult to deduce. In order to make an aurora contact, both stations must be within 1100 km of the auroral front (the southern edge of auroral ionization in the northern hemisphere), otherwise the aurora will be below the radio horizon. Both signal paths intercept the auroral front at approximately equal angles of incidence, although in practice there is a great deal of leeway because the auroral front is not a precisely defined scattering medium. A typical two-dimensional geometry is shown in Fig 4. Stations A and B lie within 1100 km of the auroral front and have a common scattering region. Station C, north of the auroral front, would generally be shut out from auroral propagation; station D is too far south to use the aurora.

By extending this two-dimensional geometric analysis,[13] it can be seen from Fig 5A that the maximum distance that could be spanned perpendicular to the auroral front, that is generally north-south, is less than 1100 km, as shown by stations A and B. The very longest contacts are on paths just tangent to the auroral front, such as that made by stations A and C. Usually directional antennas are pointed considerably east or west of north when long-distance contacts are made. Paths significantly longer than 2200 km are probably not possible, except under the conditions noted earlier, because auroral ionization of sufficient density to scatter VHF radio signals has not been observed higher than the E layer. Stringent geometrical requirements make double-hop auroral propagation unlikely.

The Aurora Boundary Ellipse

The maximum distances a station could expect to work in intermediate directions, somewhere between 1000 and 2000 km, are shown as open points in Fig 5A. One quarter of an ellipse is formed when these points are connected. A complete ellipse appears when this process is duplicated for the west side of A and continued for various positions of the auroral front to the north of station A. The resulting aurora boundary ellipse, shown in Fig 5B, measures 2000 km along its minor (perpendicular) axis and 4000 km along its major (horizontal) axis.[14] The edge of this ellipse represents the maximum distance a station at the ellipse's center could expect to span via any aurora.[15]

A single boundary ellipse neatly defines the approximate limits of auroral contacts in many practical tests, but some cases require slight adjustment of the ellipse orientation.[16] Fig 6 shows the contacts made by Bill Maxson, N4AR, on 144 MHz over a five-hour period during the March 1989 aurora. In this case, the ellipse had to be

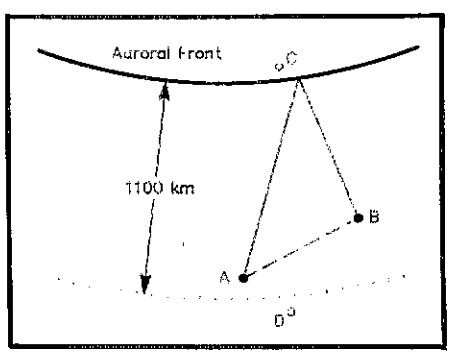

Fig 4—Two-dimensional geometry of a typical auroral contact. The solid lines show the actual signal path between stations A and B. The dashed line shows the great-circle path; the dotted line is the southern edge of the region in which stations can make auroral contacts. Station C lies north of the auroral front, and is usually unable to make auroral-scatter contacts. Station D is too far south of the auroral front to participate.

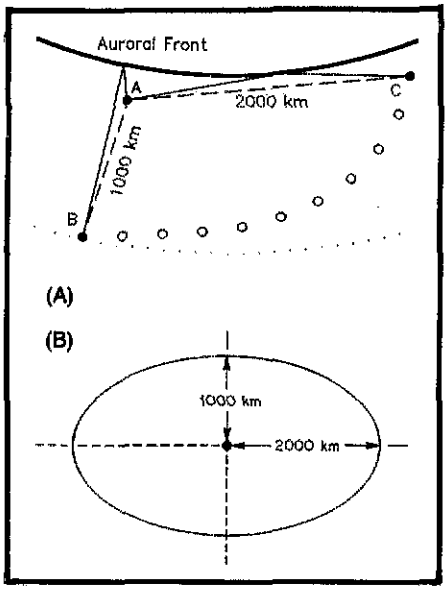

Fig 5—At A, extreme distances over which station A may communicate via auroral scatter perpendicular to and parallel to the auroral front are shown by points B and C. Extreme distances in intervening directions are shown by the open points. When connected, these points form one quarter of an ellipse. At B, the aurora boundary ellipse marks the limits to which a station at the center may communicate via aurora, assuming that all auroral fronts are parallel to the major axis.

tilted slightly with regard to geomagnetic latitude in order to fit all the stations he worked into the ellipse. The position of the auroral front probably changed substantially over the five-hour period, and for at least part of the time, the auroral front appeared at an angle with respect to N4AR's latitude. Also note that for any particular aurora, the distance between the station and the auroral front will impose additional restrictions within the limits of the boundary ellipse. For instance, as Figs 4 and 5A imply, aurora contacts in each extreme of the boundary ellipse cannot be made simultaneously. This is because vastly different auroral-front positions are needed to work into each extreme of the ellipse. In spite of these cautions and conditions, the boundary ellipse provides a good approximation of the limits of auroral propagation.[17]

Doppler Shift

VHF amateurs have long noticed and taken for granted the rough quality of aurora-propagated CW signals, variously described as a buzz, hiss, or raspy sound. SSB signals are usually so garbled that they are not useful for communications, especially on 144 MHz and above. Signals also seem much wider than normal, CW signals perhaps occupying 1 kHz or more at 144 MHz. In addition to the buzz and widening effect, VHF signals scattered by aurora are shifted in frequency by as much as several kilohertz. What causes these characteristics, and does understanding them have any practical application?

The frequency shift immediately suggests that some sort of Doppler effect operates on aurora-propagated signals. The Doppler effect is that familiar phenomenon that causes the pitch of a passing train whistle to increase as the train approaches a stationary observer and to decrease as it speeds away. The Doppler effect extends to radio, light, and other forms of radiating energy just as well as sound; the principle is the same. The problem of explaining the frequency shift in radio-aurora propagation is slightly more complicated, because neither the transmitting station (the train whistle in the classic analogy) nor the receiving station (the observer) is moving relative to one another. The relative motion is supplied by the aurora itself, for a moving reflector also induces Doppler shift. Indeed, both the frequency shift and the auroral buzz may be attributed to two separate sorts of apparent motion with the complexities of the aurora.

The shift in the center frequency of aurora-propagated signals can be explained by the mass movement of auroral E-layer electrons in the same direction relative to the earth. Such a motion exists as a result of powerful ionospheric currents that propel electrons (or at least electric charges) at velocities of 500 to 3000 meters per second (m/s) approximately parallel to the earth's geomagnetic latitudes within the auroral E layer. These velocities are sufficient to cause a frequency shift of up to 3 kHz for a 144-MHz signal and even greater shifts for higher signal frequencies.[18]

The magnitude of the Doppler shift caused by auroral propagation may be roughly calculated with an adaptation of the basic Doppler equation. For a moving reflector, the effect is doubled, and this is incorporated in the equation below.

$$\Delta f = \frac{2 f_s v}{c} \qquad \text{(Eq 1)}$$

where

Δf = change in frequency, Hz
f_s = signal frequency, Hz
v = apparent velocity of the reflector, m/s
c = speed of radio waves, 3×10^8 m/s

Actual Doppler shift will be considera-

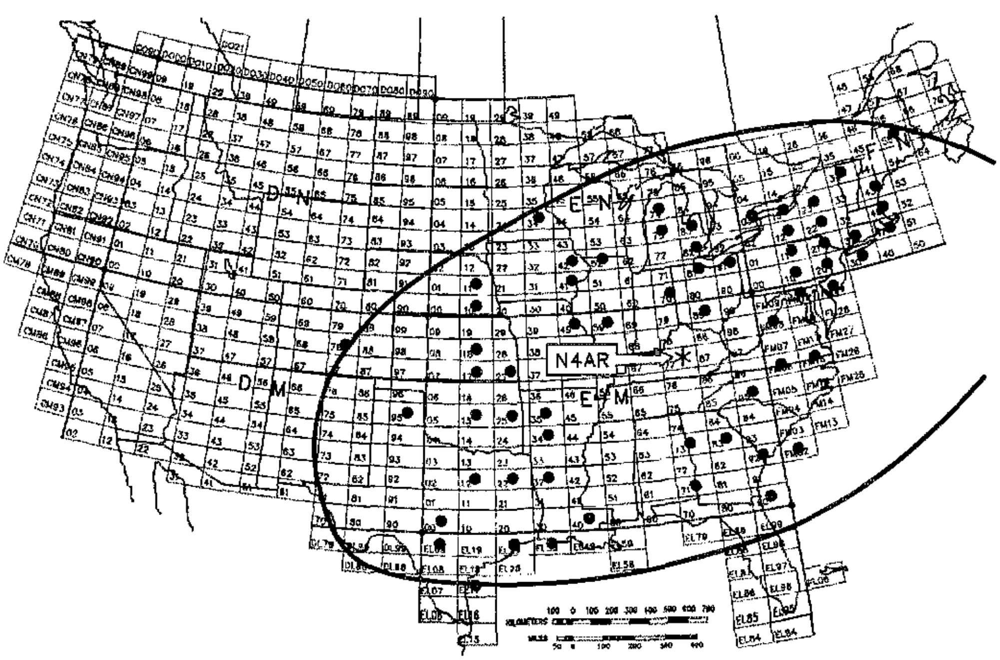

Fig 6—Contacts made by N4AR (located in grid EM77), 2217-0333 UTC, March 13-14, 1989, are shown by solid dots. Note that all contacts fall within the aurora boundary ellipse. N4AR probably worked to the very limit that auroral propagation allowed in several directions.

Table 3

Expected Doppler Shift (kHz) for Aurora-Propagated Signals at VHF and UHF

Equivalent velocity (m/s)	*Signal Frequency (MHz)* 50	144	220	432	903	1296
521	0.18	0.50	0.75	1.5	3.0	4.5
1042	0.35	1.00	1.50	3.0	6.0	9.0
2083	0.70	2.00	3.00	6.0	12.0	18.0
3125	1.00	3.00	4.50	9.0	18.0	27.0

Table 4

Expected Relative Strengths of Aurora-Propagated VHF and UHF Signals

Frequency (MHz)	*Relative Signal Strength (dB)*	*Approximate Signal Strength Comparison (S units)*
50	+32.2	9 + 52 dB
144	0.0	9 + 20 dB
220	−12.9	9 + 7 dB
432	−33.5	7
903	−55.8	3
1296	−66.8	1

An S unit is equivalent to 6 dB.

bly less than the calculations yield for electron currents of 500 to 3000 m/s velocity. Earthbound radio stations are nearly always at some distance perpendicular to the electron current, thus the relative velocity will be somewhat less, perhaps half the actual velocity. Even when equivalent velocities are used, the figures given in Table 3 still overestimate Doppler shift. The simplified equation does not take into account the index of refraction of the auroral ionosphere nor the scattering losses, both of which also reduce the Doppler effect.

The direction of Doppler shifts (higher or lower in frequency) depends on the direction of the electron flow and the relative positions of transmitting and receiving stations. Auroral electrons flow toward the sunlit side of the earth, that is, toward the east during daylight and toward the west during evening. The great reversal from east to west takes place at about 2200 local time.[19] It may be possible to detect the direction of the current flow and the timing of the great reversal by careful observations of Doppler shift. Calculation of effective velocity from Doppler shift may be more difficult, because the positions of transmitting and receiving stations in relation to the current flow may not be known with much precision. There may be some clever solutions to this problem that would make for some interesting experimental observations, but in most practical applications, it is not necessary to know the actual velocity.

Determining the Doppler shift from two-way contacts involves further difficulties, because two separate Doppler shifts take place. Consider this example. K9MRI sits down on his favorite aurora calling frequency of 144.190 MHz. Because of the Doppler effect, you hear him calling CQ on 144.188, and give him a call at that frequency. Doppler shift also affects your return signal, but it is likely to be in the opposite, and at least partially compensating, direction. K9MRI may hear you close to his own frequency, even though two Doppler shifts have taken place. It is also possible that your signal will be shifted in the same direction, thus magnifying the net Doppler effect. K9MRI is not likely to hear you on 144.190 in any case, but he cannot determine from your apparent frequency the actual Doppler shift on either signal.

In practice, it may be enough to take note of the net apparent Doppler shift, and use this figure in estimating where to listen for other stations or when moving from band to band. Once the net Doppler shift on a given frequency and path are determined, the Doppler shift on other bands can be estimated with some confidence. Such information might be very useful when moving a station from band to band, for example, especially when moving from 144 MHz to 432 MHz and higher. Doppler shift can be expected to be three times greater on 432 MHz than 144 MHz, and finding a station on a specific frequency might be tricky without taking this into consideration.

Auroral Buzz and Widening

The buzz and widening that are also familiar features of aurora-propagated signals result from a second Doppler phenomenon that can be attributed to a simultaneous raising and lowering of the signal frequency over a small range. If a physical reflector was responsible, it could be expected that it would be moving back and forth rapidly relative to transmitter and receiver. As the reflector moves forward with respect to the observer, the frequency of the reflected signal increases; as it moves back, the frequency decreases. The net effect would be to transform a single pure note into a complex of closely related higher and lower frequencies—a buzz.

Scientific studies suggest that several possible movements of auroral electrons may cause the buzz effect. Random motion of electrons in the aurora may be responsible, especially as the aurora is not a single scattering plane, but exhibits features of depth. There may be many scattering regions, each contributing a slightly different sort of relative motion to the scattered radio signal. In addition, one of the primary movements of auroral electrons is downward in tight spirals from much higher in the ionosphere.[20] Spiraling electrons appear to both approach and recede relative to a stationary observer, and thus may contribute to the apparent forward and backward motion of the auroral scattering medium.

The apparent velocity of the relative back-and-forth motions of the auroral medium can also be calculated from Doppler shift. In this case, the width of the widened signal corresponds to the Doppler shift. One half the width of the signal can be attributed to the velocity of the medium in one direction, and this Doppler frequency shift can be applied to Eq 1 and Table 3 to estimate the comparative broadening on various bands. Typical 144-MHz CW signals may appear 1 kHz wide, suggesting a medium that appears to be moving at about 500 m/s. Under the same conditions, 432-MHz CW signals would be 3 kHz wide.

Signal Strength

Signal strengths of aurora-propagated VHF and UHF signals decrease rapidly with increasing frequency. Empirical studies indicate that strength varies with the seventh power of wavelength.[21] This can be written as a convenient equation in terms of frequency and decibels (dB) as:

$$S = 70 \log \left(\frac{f_1}{f_2}\right) \qquad \text{(Eq 2)}$$

where
S = comparative signal strength, dB
f_1 = first frequency, MHz
f_2 = second frequency, MHz

Table 4 provides the signal-strength relationship among the various VHF and UHF bands using 144 MHz as the point of comparison. The table assumes the same station gains across the various bands. The most striking feature of this relationship is the relatively weak signal strength likely above 432 MHz. Even during an intense aurora, when signals on 144 MHz may be 20 dB over S9, 1296-MHz signals may be barely out of the noise.

Aurora at 903 and 1296 MHz

Radar studies have shown that auroral echoes can be returned at frequencies as high as 3 GHz, suggesting that two-way amateur contacts ought to be possible above 432 MHz. No such contacts have been reported so far, but this achievement is within reach. How can it be done? Previous discussions of auroral characteristics provide some hints of what to expect. Extreme Doppler shift will undoubtedly make 903- and 1296-MHz auroral signals sound unfamiliar. They are likely to be shifted in frequency considerably, perhaps 4 kHz or more. Extreme Doppler broadening may make 903- and 1296-MHz auroral signals several kilohertz wide and sound like keyed noise. One 1295-MHz radar study of aurora produced consistent Doppler shifts of 4 kHz and broadening of 16 kHz.[22] Finally, signal strength is likely to be very weak by comparison to signals at 432 MHz, even during the the most intense auroras. At 1296 MHz, signals will be at least 6 S units (36 dB) weaker than those of comparable stations at 432 MHz. Thus, actual signal-strength differences may be greater, because 1296-MHz amateur installations rarely equal the station gain of typical 432-MHz stations.

A pair of well-equipped stations no more than 500 km apart may have better success in making a historic 903- or 1296-MHz auroral contact by first establishing themselves on 432 MHz. When signal strength on 432 MHz exceeds 6 S units above the noise, special attention should be paid to peaking antennas for maximum signal strength. If the auroral front is very close to stations attempting such contacts, there may be some advantage to elevating the antennas. Note the direction and magnitude of the Doppler shift on 432 MHz; it is likely to be twice as great on 903 MHz and three times as great on 1296 MHz. After all the preliminaries are noted, one or both stations should quickly change over to an agreed upon frequency on the 903- or 1296-MHz band, taking into account the estimated Doppler shift. Then listen for signals that sound like keyed noise—and good luck!

Auroral-E Propagation

An aurora-related propagation mode called *auroral E* has been used for at least thirty years, but some recent discoveries have considerably expanded the scope of aurora-related propagation phenomena.[23] There may be at least two distinct types of VHF auroral-E propagation. The more familiar type affects 50 MHz several hours after normal radio-auroral activity has ceased. In most cases, it appears only after midnight local time across the northern part of the US and southern Canada, although other paths have been spanned occasionally. East-west distances of 2000 to 5000 km are typical; signals are sometimes weak with a characteristic fluttery or watery sound, quite distinct from normal auroral signals. This type of auroral E has not been reported on 144 MHz or higher.

What may be a second auroral-E mode has been reported increasingly in recent years, most commonly on 50 MHz. This type appears during the height of exceptionally intense radio aurora sessions; signals are very strong and clear, nearly indistinguishable from familiar sporadic-E propagation. It has been possible to hear the transformation of Doppler-shifted aurora-propagated signals to the clear and strong signals that characterize auroral E over a period of less than a minute. Distances are typically limited to 2200 km, although some apparently double-hop contacts have been reported on 50 MHz. During the March 1989 aurora, as many as 100 auroral-E contacts were made on 144 MHz for the first time, and at least one other similar episode in the Pacific Northwest during August 1989 has been reported.[24]

There is some evidence that this second type of auroral E may affect signals at 220 MHz and even higher in frequency. Further experience with this newly discovered auroral phenomenon may reveal some of its mysteries.

Prospects

The next three years may provide exceedingly fruitful periods for radio-aurora operating and observation. The current solar cycle has already proven itself to be one of the most intense on record, and as appearance of aurora is closely related to solar activity, we might expect some spectacular conditions. The chances for aurora in the southern part of the US also appear excellent over the next several years. There is still room for distance records to be extended on various frequencies; no one has yet claimed an auroral contact on 903 or 1296 MHz. The causes of auroral-E propagation are still largely unknown, but these modes hold promise for transatlantic contacts on 50 MHz, more frequent occurrences on 144 MHz, and possibly a further breakthrough on 220 MHz. More reports are needed on 28-MHz auroral phenomena. Wherever you live in the middle latitudes, auroral propagation will undoubtedly provide considerable activity and excitement for you on the bands above 28 MHz over the next few years!

Acknowledgment

My thanks to Dr John C. Foster, Assistant Director, MIT Haystack Observatory, for providing data from the Millstone Hill 440-MHz radar, and for his accompanying explanations. The Millstone Hill incoherent-scatter radar is supported by the National Science Foundation.

Notes

[1] The first account of auroral propagation can be found in "56 and 112 Mcs.," *QST*, May 1939, p 78. Subsequent *QST* articles on aurora are listed in the first 5 references.

[2] Aurora and related geomagnetic storms usually disrupt all forms of propagation on the amateur bands below 28 MHz. Even mild auroras may absorb high-frequency signals, especially over polar and near-polar paths.

[3] See the *QST* articles cited in the first 5 references as well as Chamberlain, pp 110-112 and 222-223, and Lange-Hesse.

[4] See Chamberlain, pp 109-113. The Yerkes Observatory is at Williams Bay, Wisconsin, at 42° 30" north latitude.

[5] For more information, see Forbes, pp 52-64.

[6] See Harang, p 6; Chamberlain, p 106; and Moore, p 16 (reproduced in Miller, p 15). The geomagnetic latitude used in Moore's figure is apparently that of total magnetic intensity; it is not comparable to the magnetic inclination used in Fig 2. See Forbes for a more complete discussion.

[7] See Miller, p 16.

[8] This is discussed more fully in Miller and in C. L. Bixby and J. Morris, "The Art and Science of DXing," *QST*, Jan 1979, pp 11-14.

[9] This was the tentative conclusion of a study of reported 144-MHz auroral contacts in Pocock (*Proceedings*, 1989), pp 157 and 161.

[10] Compare this discussion with Pocock (1987), p 8.

[11] Letter from John C. Foster, Assistant Director, Haystack observatory, Jan 9, 1990.

[12] See Pocock (1987, and *Proceedings*, 1989).

[13] This simplifies the case considerably, because auroral path analysis is a three dimensional problem. See Miller and Lange-Hesse, pp 516-526 and 543-559.

[14] This also describes a 30° ellipse. Graphic analyses are easier with a template that contains many sizes of 30° ellipses; they are commonly available from stationers and drafting suppliers.

[15] A similar "aurora boundary fence" is described in Jessop, pp 2.21-2.23. A slightly different set of maximum-distance curves result from a three-dimensional analysis of the problem for very northern latitudes. See Lange-Hesse, pp 550-553.

[16] See Pocock (1986, and *Proceedings*, 1989).

[17] Several factors may explain these anomalies. The auroral front is not a single, smooth boundary. It may be wavy, discontinuous, or composed of partially separated ionized regions. Thus, exceptional contacts may be attributed to localized auroral features. Analysis of some of the cases suggest that the 4000- × 2000-km ellipse may be a bit conservative. A 4400- × 2200-km ellipse, which would still fall within theoretical limits, may be more appropriate, and may not require different tilts to account for all contacts.

[18] See Chamberlain, pp 224-226; Walt, pp 121-123; and Lange-Hesse, pp 534-36.

[19] See Leadbrand, pp 122-123; and Petrie, pp 68-69.

[20] See Chamberlain, p 226; and Lange-Hesse, pp 534-36. An especially graphic explanation of the spiraling of precipitating electrons within auroral storms is found in Akasofu.

[21] Miller, pp 17-18; and Chamberlain, pp 119-120.

[22] Abel and Newell, pp 235-238.

[23] Amateur experiences with auroral-E propagation are reviewed in Pocock (*QST*, 1989)..

[24] Thanks to Jerry Logan, NF7X, for bringing to my attention the August 1989 auroral-E event.

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