Febuary 25, 2003

Radio propagation studies
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Doppler Effect in Auroral Backscatter

Volker Grassmann, DF5AI

Abstract. The Doppler effect in Aurora dx communication is calculated by analysing scatterers in motion in the geometry of bistatic scattering. The result is equivalent to the generally know Doppler formula if the relative velocity is interpreted the velocity component along the bisector of the triangle transmitter-scatterer-receiver. This velocity component may change considerably in Aurora QSOs even if the scatterers' velocity is constant. Practical implications are discussed in a model calculation by using a modified version of the BeamFinder analysis software. The signal distortion in Aurora dx communication is discussed in terms of velocity pertubations which broadens the spectrum of the scattered radiowave. Multipath backscattering is also identified a possible source of signal distortion. In many cases, the Doppler effect isn't obvious to the radio operator because he generally lacks a frequency of reference. The radio operator may however notice dx stations answering his CQ call on the 'wrong' frequency. It is shown that the corresponding frequency offset is twice the Doppler shift. This effect may cause practical complications in UHF Aurora dx communication e.g. in the 432 MHz band.

1. Introduction

This paper discusses the nature of the Doppler effect in coherent backscatter from the Auroral ionospheric E region. The region of backscatter is considered a *scatterer* synonymous with a given scatter volume whose scattering properties may be described by overall macroscopic quantities, e.g. its drift velocity. The following analysis is motivated by actual discussions in the community of radio amateurs and because model calculations were not available in the author's previous paper [6].

2. Doppler shift calculation

2.1 General notes

The Doppler effect is associated with transmitters and receivers in motion. However, motion is a relative concept in that it must always be referred to a particular frame of reference, chosen by the observer. In the receiver's frame of reference, the Doppler shift is

$$\Delta\omega_{RX} = \mathbf{k}_{TX} \cdot \mathbf{v}_{TX} \qquad (1a)$$

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where $\Delta\omega_{RX} = 2\pi \cdot \Delta f_{RX}$ (Δf_{RX} is the corresponding frequency shift), $\mathbf{k}_{TX} = \frac{2\pi}{\lambda_0} \cdot \hat{\mathbf{e}}_{TX-RX}$ is the transmitter wavevector (λ_0 is the wavelength of the transmitted radiowave, $\hat{\mathbf{e}}_{TX-RX}$ is the unit vector which directs from the transmitter to the receiver) and $\mathbf{v}_{TX}$ is the transmitter's velocity vector. Please note, that $\Delta\omega_{RX} > 0$ if $\mathbf{v}_{TX}$ is parallel to $\mathbf{k}_{TX}$, i.e. if the transmitter moves towards the receiver, and $\Delta\omega_{RX} < 0$ if the transmitters moves away from the receiver.

Describing the same Doppler effect in the transmitter's frame of reference, we have

(1b) $$\Delta\omega_{RX} = -\mathbf{k}_{TX} \cdot \mathbf{v}_{RX}$$

because $\mathbf{v}_{TX} = -\mathbf{v}_{RX}$. In this case, $\Delta\omega_{RX} > 0$ if the receiver moves towards the transmitter (i.e. if $\mathbf{v}_{RX}$ is antiparallel to $\mathbf{k}_{TX}$) and $\Delta\omega_{RX} < 0$ if $\mathbf{v}_{RX}$ is parallel to $\mathbf{k}_{TX}$.

The reader is perhaps more familiar with the Doppler formula

$$\Delta f = f_0 \cdot \frac{v}{c}.$$

Please view the discussion in the appendix.

2.2 Aurora dx communication

2.2.1 Bistatic scattering

We may consider two Doppler components in Auroral backscatter, i.e. the Doppler shift along the uplink and the frequency shift along the downlink of the scatter path. On the uplink, station A is the transmitter and the scatterer S represents the receiver. The uplink Doppler shift in the transmitter's frame of reference, see eqn. (1b), is

(2a) $$\Delta\omega_S = -\mathbf{k}_{AS} \cdot \mathbf{v}_S,$$

where $\mathbf{v}_S$ is the velocity vector of the scatterer and $\mathbf{k}_{AS}$ is the wavevector directing from station A to the scatterer S, see figure 1.

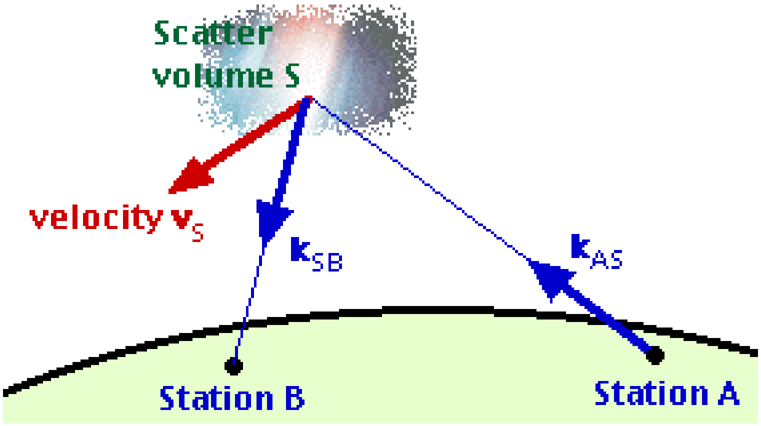

Figure 1. Vectors in the Doppler shift calculation.

On the downlink, the scatterer may be considered a transmitter located in the ionosphere. In station B's frame of reference, the Doppler shift is (see eqn. (1a)) :

(2b) $$\Delta\omega_{\mathrm{B}} = \mathbf{k}_{\mathrm{SB}} \cdot \mathbf{v}_{\mathrm{S}},$$

where $\mathbf{k}_{\mathrm{SB}}$ is the wavevector from the scatterer S to station B, see figure 1.

The radio wave along the downlink S-B is the Doppler-shifted radio wave of the uplink A-S which is already Doppler-shifted. As a consequence, the length of the vector $\mathbf{k}_{\mathrm{SB}}$ is not identical to the length of $\mathbf{k}_{\mathrm{AS}}$ (note that the length of the wavevector is 2π divided by the actual transmitter wavelength which is λ_0 on the uplink and $\lambda_0 + \Delta\lambda_{\mathrm{S}}$ on the downlink, respectively).

The Doppler effect is proportional to the transmitter frequency, e.g. the Doppler shift on 432 MHz is three times the Doppler shift on 144 MHz. The Doppler shift on, say, 144.100 MHz is therefore 1.00007 times the Doppler shift on 144.099 MHz, i.e. the frequency offsets differ by a very small fraction of 1 Hz. In practice, that difference may be neglected corresponding to a linearised calculation of the Doppler effect in bistatic scattering in which terms proportional to $\mathbf{v}_{\mathrm{S}}^2/c^2$ may be omitted. Therefore, we can write

(3) $$\left|\mathbf{k}_{\mathrm{AS}}\right| = \left|\mathbf{k}_{\mathrm{SB}}\right|,$$

i.e. the length of the wavevectors may be considered identical and the total Doppler effect is the sum of the components in eqn. (2a) and (2b) (note that those terms are given in the same terrestrial frame of reference):

(4) $$\Delta\omega_{total} = (\mathbf{k}_{\mathrm{SB}} - \mathbf{k}_{\mathrm{AS}}) \cdot \mathbf{v}_{\mathrm{S}},$$

see also [6]. Using eqn. (3) and replacing angular frequencies by frequencies, we finally obtain

(5) $$\boxed{\Delta f_{total} = \frac{1}{c} \cdot f_0 \cdot (\hat{\mathbf{e}}_{\mathrm{SB}} - \hat{\mathbf{e}}_{\mathrm{AS}}) \cdot \mathbf{v}_{\mathrm{S}}}$$ (Doppler shift in bistatic scattering),

where $\hat{\mathbf{e}}_{\mathrm{AS}}$ and $\hat{\mathbf{e}}_{\mathrm{SB}}$ are unit vectors (i.e. $\left|\hat{\mathbf{e}}_{\mathrm{AS}}\right| = \left|\hat{\mathbf{e}}_{\mathrm{SB}}\right| = 1$) parallel to $\mathbf{k}_{\mathrm{AS}}$ and $\mathbf{k}_{\mathrm{SB}}$, respectively. The frequency shift Δf_{total} is the difference between the receiver frequency of station B and the transmitter frequency of station A. Note that eqn. (5) is not restricted to Auroral backscatter, i.e. it is applicable in all bistatic radar applications.

2.2.2 Geometrical interpretation

Introducing the abbreviation

(6) $$v_D = (\hat{\mathbf{e}}_{\mathrm{SB}} - \hat{\mathbf{e}}_{\mathrm{AS}}) \cdot \mathbf{v}_{\mathrm{S}}$$

in eqn. (5), we obtain $\Delta f = f_0 \dfrac{v_D}{c}$ which is the well known Doppler formula. Thus, using the Doppler formula in bistatic scattering, the relative velocity corresponds to a velocity component which considers the movement of the scatterer relative to the transmitter as well as the scatterer's motion relative to the receiver. Detecting a Doppler shift in an Aurora QSO, the observer cannot calculate the Aurora's velocity relative to his antenna system because the observed frequency shift includes two components which cannot be distinguished if the scatterer's and the dx station's position is unknown.

In figure 2, $\mathbf{v}_D$ is the velocity component along the line B which is the bisector in the parallelogram defined by the vectors $\hat{\mathbf{e}}_{SB}$ and $-\hat{\mathbf{e}}_{AS}$ (neglecting an additional factor in this graphical interpretation because $\hat{\mathbf{e}}_{SB} - \hat{\mathbf{e}}_{AS}$ does not represent a unit vector, in general).

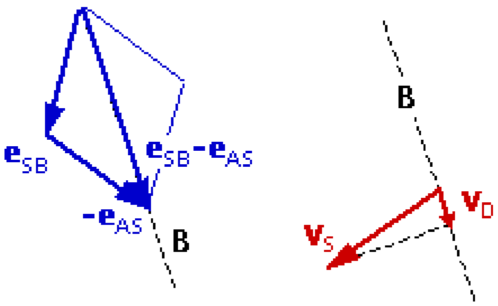

Figure 2. Interpretation of the velocity component $\mathbf{v}_D$.

Doppler measurements from three independent positions may reveal all components of the velocity vector $\mathbf{v}_S$. This type of measurement (tristatic backscattering) is conducted e.g. by the three 932 MHz EISCAT radars in Norway, Sweden and Finland to investigate ion motions in the ionosphere by incoherent scattering, see e.g. [5].[1]

2.2.3 Monostatic backscattering

Aurora dx communication corresponds to bistatic backscattering where two stations are available in independent positions. In monostatic backscattering, the receiving and transmitting antenna is identical, i.e. the vector $\hat{\mathbf{e}}_{SB}$ is antiparallel to $\hat{\mathbf{e}}_{AS}$. In this case, eqn. (5) becomes

$$\boxed{\Delta f_{mono} = \pm \frac{1}{c} \cdot f_0 \cdot 2 v_{rel}}, \qquad (7)$$

(Doppler shift in monostatic scattering)

where v_{rel} is the velocity of the reflecting target in the radar's frame of reference. Thus, the Doppler effect corresponds to twice the relative velocity between the radar and the target (e.g. Auroras, weather fronts, airplanes, cars etc.).

3. Interpretation

3.1 Zero Doppler shift

Using eqn. (5), we may identify conditions in which no Doppler shift is present, i.e.

$$\Delta f_{total} = \frac{1}{c} \cdot f_0 \cdot (\hat{\mathbf{e}}_{SB} - \hat{\mathbf{e}}_{AS}) \cdot \mathbf{v}_S = 0. \qquad (8)$$

Discussing the requirements of zero Doppler shift might appear surprising because we wish to understand the Doppler effect's impact on dx communication and there is none in the case of zero Doppler shift, obviously. However, it is believed that the following analyses may reveal the nature of the Doppler effect in bistatic scattering and may provide information which is indeed relevant to Aurora dx communication.

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[1] Remarkably, radio amateurs are also capable to conduct radar experiments in the ionosphere, see [4].

Evidently, the Doppler shift is zero in *all* Aurora QSOs if $\mathbf{v}_S = 0$, i.e. if the center of backscattering remains in the same position. However, we may identify situations in which the Doppler offset is zero with *some* Aurora QSOs even if the scatterer is in motion.

3.1.1 Identical wavevectors

The Doppler shift is zero if $\hat{\mathbf{e}}_{SB} - \hat{\mathbf{e}}_{AS} = 0$, i.e. if $\hat{\mathbf{e}}_{AS} = \hat{\mathbf{e}}_{SB}$. However, this case is impossible because that geometry corresponds to forward scattering rather than backscattering (see the discussion of Auroral backscatter e.g. in [2] and [7]). Furthermore, the receiver would represent a geostationary spacecraft in polar latitudes (which is again impossible) rather than a terrestrial radio station.

3.1.2 Perpendicular aspect angle

The Doppler shift is zero if the product $(\hat{\mathbf{e}}_{SB} - \hat{\mathbf{e}}_{AS}) \cdot \mathbf{v}_S = 0$, i.e. if $\hat{\mathbf{e}}_{SB} \cdot \mathbf{v}_S = \hat{\mathbf{e}}_{AS} \cdot \mathbf{v}_S$. In this case, the uplink and the downlink Doppler effect is identical in magnitude, the direction is however opposite and, as a consequence, the uplink shift and the downlink shifts cancels each other.

Alternatively, the term $(\hat{\mathbf{e}}_{SB} - \hat{\mathbf{e}}_{AS}) \cdot \mathbf{v}_S = 0$ may be interpreted by orthogonal vectors $\hat{\mathbf{e}}_{SB} - \hat{\mathbf{e}}_{AS}$ and $\mathbf{v}_S$. Note that the vector $\hat{\mathbf{e}}_{SB} - \hat{\mathbf{e}}_{AS}$ plays another important role in Auroral backscatter because

$$\boxed{(\hat{\mathbf{e}}_{SB} - \hat{\mathbf{e}}_{AS}) \cdot \mathbf{B} = 0} \tag{9}$$

describes the geometry of Auroral backscatter (see e.g. [2] and [7] and figure 3), where $\mathbf{B}$ is the geomagnetic field line penetrating the scatter volume. Thus, eqn. (9) is fulfilled in Auroral backscatter at all times (except of the so-called *unusual Aurora QSOs*, see e.g. [1]).

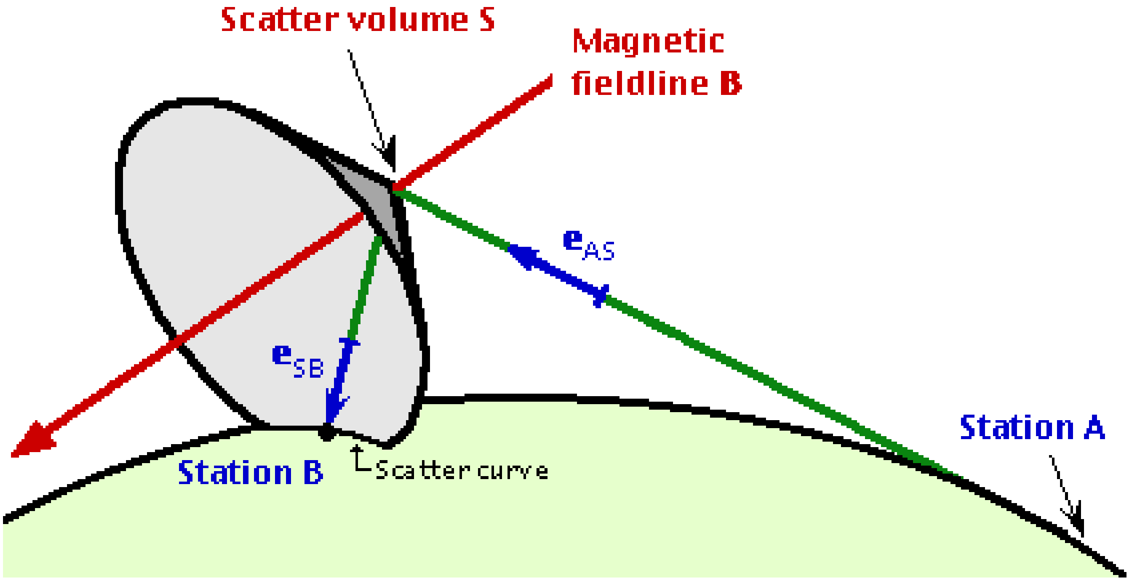

Figure 3. Scatter geometry in Aurora dx communication, adopted from [2].

We may conclude from eqn. (8) and eqn. (9) that field-parallel motion of the scatterers does not cause any Doppler shift. Note that field-parallel motion of the scatterers would however force the layer of backscattering to change height which is obviously not true because Auroral backscatter constantly originates around 105 km, in general. However, ionospheric dynamics need to be discussed in a separate paper because it would exceed the scope of this paper.

3.2 Maximum Doppler shift

The Doppler shift is maximum if the velocity vector $\mathbf{v}_S$ is parallel (or antiparallel) to $\hat{\mathbf{e}}_{SB} - \hat{\mathbf{e}}_{AS}$, see eqn. (5). However, the maximum upshift and downshift must be considered a theoretical maximum because there is no guarantee for parallel (or antiparallel) vectors in practice. Thus, we generally observe smaller maximum upshifts and downshifts in a real Aurora opening.

The maximum Doppler shift is also controlled by the direction of the vectors $\hat{\mathbf{e}}_{SB}$ and $\hat{\mathbf{e}}_{AS}$ because of the variable length of the vector $\hat{\mathbf{e}}_{SB} - \hat{\mathbf{e}}_{AS}$. The absolute maximum of the Doppler shift is therefore achieved if, in addition to the parallel/antiparallel vectors from above, $\hat{\mathbf{e}}_{SB}$ is antiparallel to $\hat{\mathbf{e}}_{AS}$. Antiparallel vectors $\hat{\mathbf{e}}_{SB}$ and $\hat{\mathbf{e}}_{AS}$ correspond to the monostatic radar case (see chapter 2.2.3), i.e. in Aurora dx communication we observe smaller Doppler shifts in comparison to scientific radars operating in the monostatic scatter mode.

4. Model calculation

4.1 Velocity vector field

The Aurora's velocity vector may vary considerably in magnitude and direction as a function of time and the scatterer's geographical position. In an approximation, the velocity vectors are assumed a zonal vector field from the east to the west, see figure 4. Note that there is no need to model the actual speed (vector length) because only the direction of the velocity vectors is significant in the following analyses. Introducing that vector field, we will focus on a particular type of Aurora opening, of course. On the other hand, this model may demonstrate the variable nature of the Doppler effect in Aurora dx communication and we may identify practical differences of minor and major Aurora openings from the radio operator's perspective.

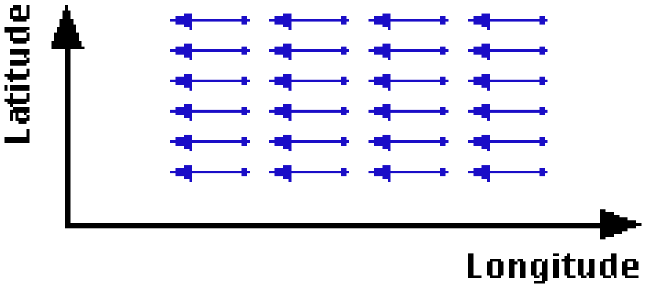

Figure 4. Velocity of Aurora scatterers used in the model calculation.

4.2 Minor Aurora openings

Using a modified version of the BeamFinder analysis software [8], the vector field was implemented in the program's Aurora dx range analysis. In the example of figure 5, the observer may access two Auroral scatterers in north-western and in north-eastern direction, respectively. The corresponding scatter curves 1 and 2 denote the intersection of the so-called scatter cone with the Earth's surface (compare to figure 3). Note that the observer can establish Aurora QSOs exclusively to dx stations located along the scatter curves. Figure 5 may be interpreted a minor Aurora opening because only two scatterers are available resulting in limited dx opportunities.

Figure 5. Variation of the Doppler shift along the scatter curve (blue: positive shift, red: negative shift).

The Doppler shift is displayed in colour code, i.e. the observer receives an up- and downshifted frequency if the dx station is located in the blue and red wing of the scatter curve, respectively. Note the change in colour, e.g. in the eastern part of scatter curve 2. Here, the Doppler shift reverses from upshift to downshift (or vice versa), i.e. dx stations located in this segment of the scatter curve show little or no Doppler effect corresponding to the discussion of zero Doppler shift in chapter 3.1.2.

In a minor Aurora opening, there seems to be a clear relationship between the actual antenna heading, the dx station's geographical position and its Doppler shift. In this example, the Doppler shift seems to be always negative when targeting the scatterer above central England (the observer will probably never notice the blue wing of scatter curve 1 because no dx station is generally available in the ocean). Targeting the scatterer above Poland, he will always notice negative Doppler shifts except of positive shifts in long-distance QSOs to the far eastern end of scatter curve 2 which he will consider extraordinary anyway.

4.3 Major Aurora openings

Note the intersection of the scatter curves indicated by the purple area just below the observer's position in figure 5. Dx stations from this area are associated with positive as well as negative Doppler shifts depending on the scatterer's position in the actual Aurora QSO. In a major Aurora opening, similiar areas may extend over a large geographical region. This phenomenon may cause some confusion to the radio operator because he may receive dx stations from the same geographical region with opposite Doppler shifts.

Increasing the number of scatterers in figure 5, we will finally obtain a maximum number which cannot be increased further. Figure 6 shows the maximum area in the E-region of the ionosphere (green) from where the observer may receive backscattered radiowaves. This area results from the specific geometry in Auroral backscatter (see e.g. [2] and [7]. In a major Aurora opening more scatterers may indeed exist, of course, but these scatterers cannot contribute to Auroral backscatter relevant to this observer. On the other hand, increasing the number of scatterers in figure 5 increases the number of the scatter curves as well and, as a consequence, we may no longer identify discrete scatter curves but a continuous geographical region which may be considered the *maximum dx target area* (see the area within the yellow border in figure 6).

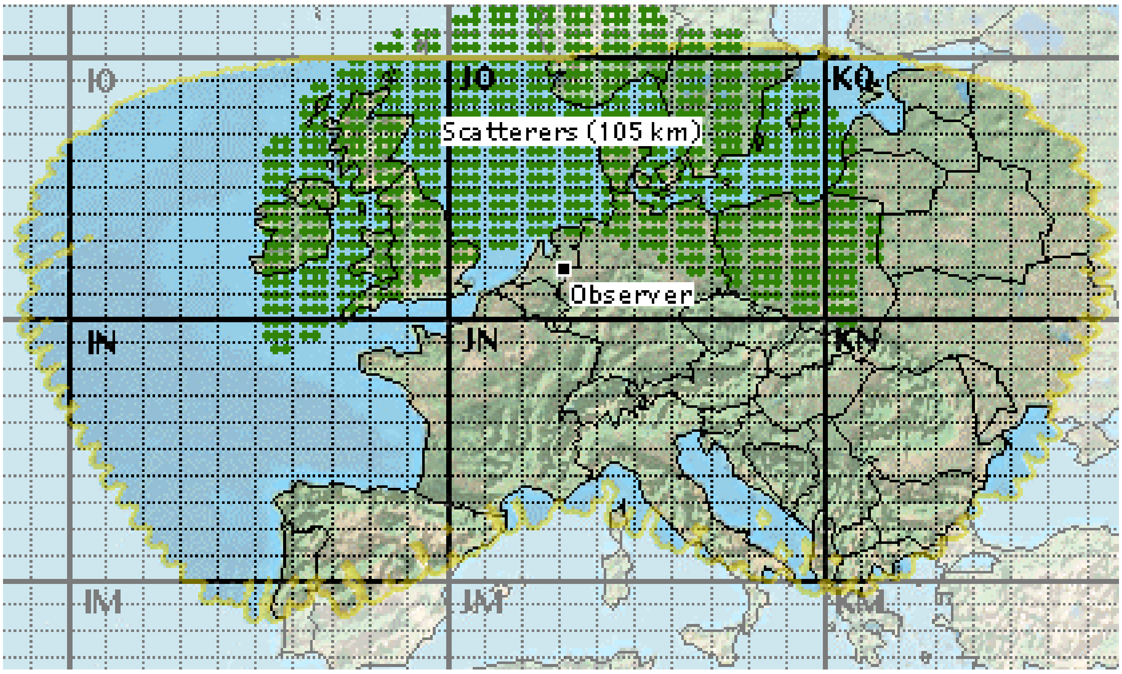

Figure 6. BeamFinder analysis of Auroral backscatter displaying all scatterers (green) which can support Aurora dx communication within the yellow border.

Applying the flow model of figure 4 in the example of figure 6, we may identify the geographical distribution of dx stations associated with positive Doppler shift. In the light blue area of figure 7, the positive Doppler shift varies between zero and 60 percent of the theoretical maximum (see chapter 3.2). In the dark blue area of figure 7, the upshift varies between 60 and 89 percent of the theoretical maximum. Note that the theoretical maximum corresponds to the monostatic radar case, i.e. a dx station close to the observer is generally associated with a larger Doppler shift in comparison to dx stations in long-distance QSOs.

In figure 8, a similiar analysis is shown for dx stations associated with negative Doppler shift. The maximum downshift is 93 percent of the theoretical maximum in this example. Comparing figure 7 to figure 8, the area of positive Doppler shift extends, more or less, from the north-west to the south-east, and the area of the negative Doppler shift is directed from the south-west to the north-east. Hence, we may identify a geographical region centered to the observer's location in which the positive and negative Doppler shift overlap, see figure 9. Evidently, this pattern results from the flow model which was initially introduced, see figure 4. In a real Aurora opening the pattern may therefore look different in comparison to this results.

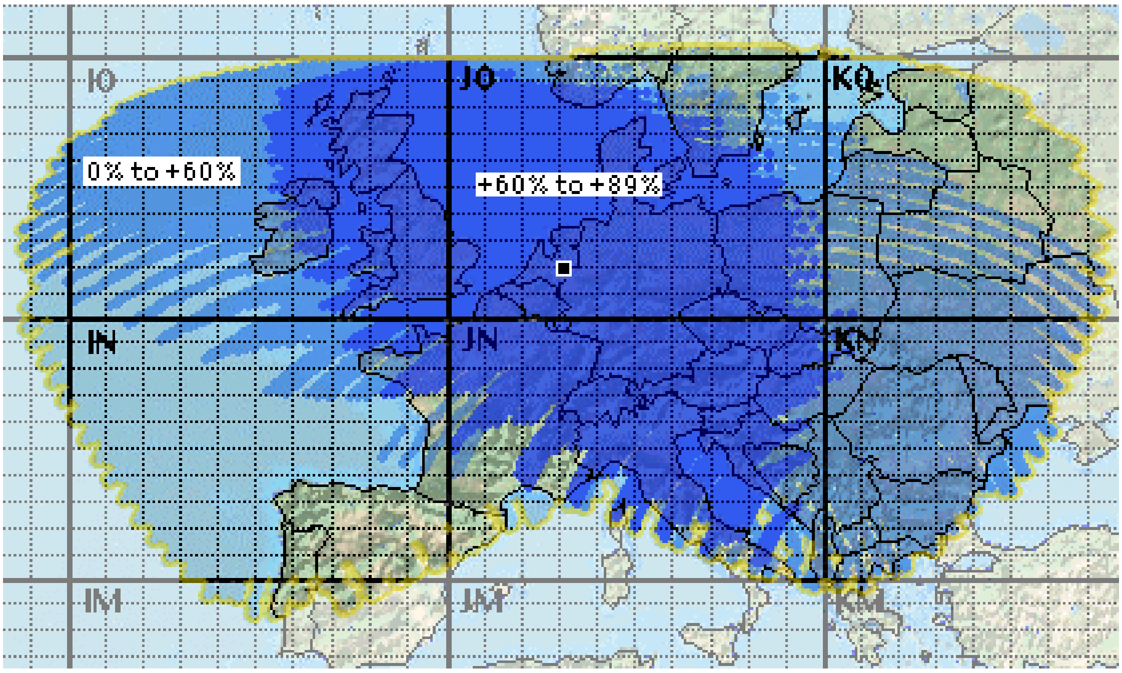

Figure 7. Geographical distribution of dx stations associated with positive Doppler shift. The Doppler upshift corresponds to 0 % to 89 % of the theoretical maximum. The traces in the peripherials (see for example the blue stripes in the south-west of Ireland) result from limited resolution in the model calculation.

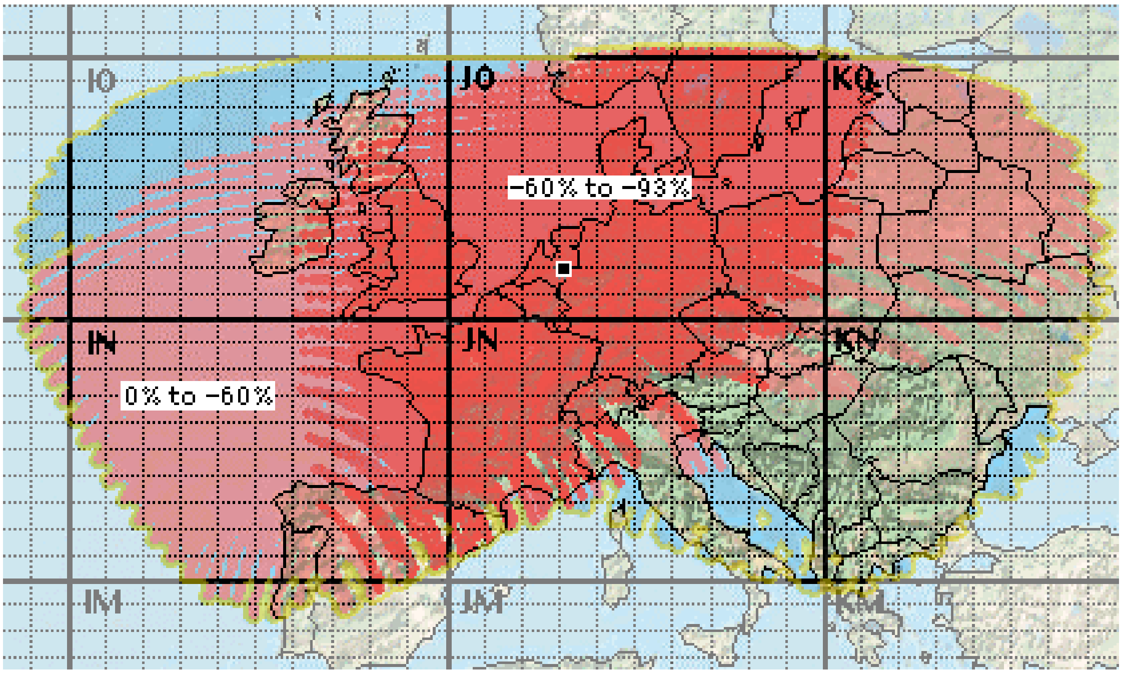

Figure 8. Geographical distribution of dx stations associated with negative Doppler shift (between 0 % to 93 % of the theoretical maximum).

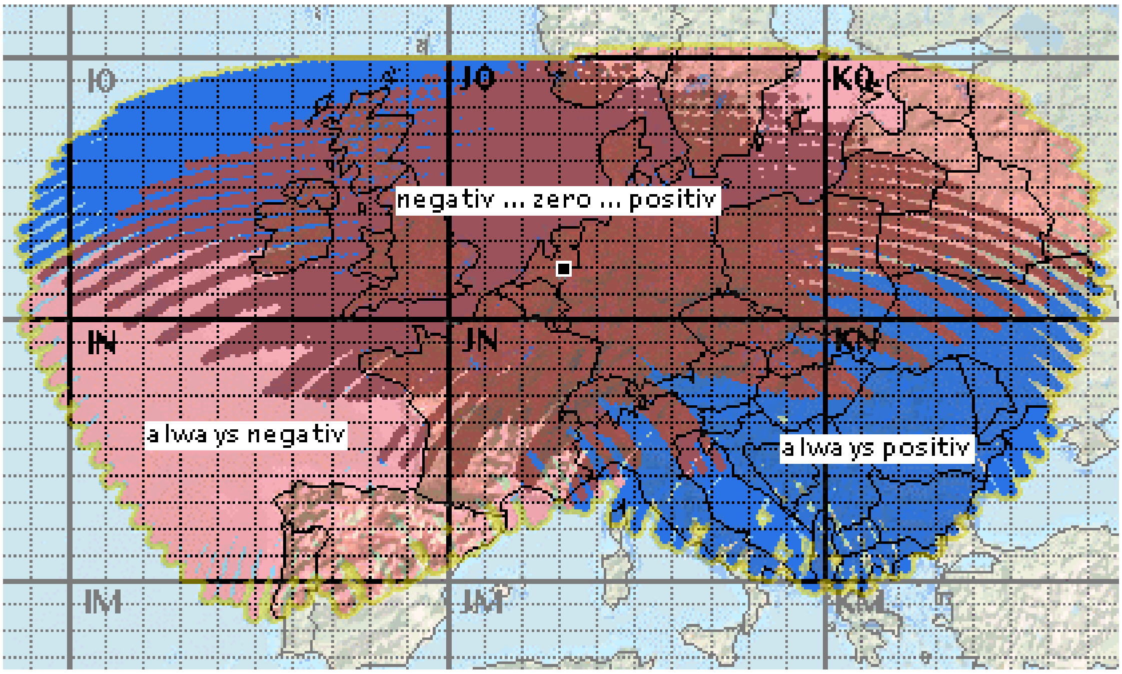

Figure 9. Summary of positive and negative Doppler shifts.

In the overlap region, the observer may receive the same dx station with positive or negative Doppler shift depending on the scatterer's actual geographical position. This explains a phenomenon reported by many radio operators, i.e. the change of the dx signal's audio pitch when changing the antenna heading. In this case, the dx station illuminates Auroral scatterers in a wide geographical area which the observer's antenna scans segment by segment by rotating the antenna beam. Changing the scatterer also changes the scatter geometry which finally affects the Doppler effect resulting in a azimuthal variation of the frequency shift, see also chapter 5.2. We may conclude that this phenomenon does not exist in long-distance Aurora communication because the corresponding scatterers are located, more or less, in a small geographical area which excludes significant changes in Doppler shift.

It is worth to mention, that conditions of zero Doppler effect (see chapter 3.1.2) are restricted to the overlap area because in all other regions, the Doppler effect is always positive or always negative, see figure 9.

5. Signal distortion

5.1 Doppler broading of the radio spectrum

It is generally known, that Aurora signals are distorted (see figure 10) making voice communication impossible in many cases. Auroral backscatter is often described by columns of irregularities aligned to the Earth's magnetic field which may scatter the incident radio wave. The same subject, by the way, is dicussed in terms of plasma waves and plasma instabilities by scientists. However, using the picture we are familiar with, i.e. columns of irregularities, the signal distortion may be interpreted by the pulsating and “wobbling” nature of those columns.

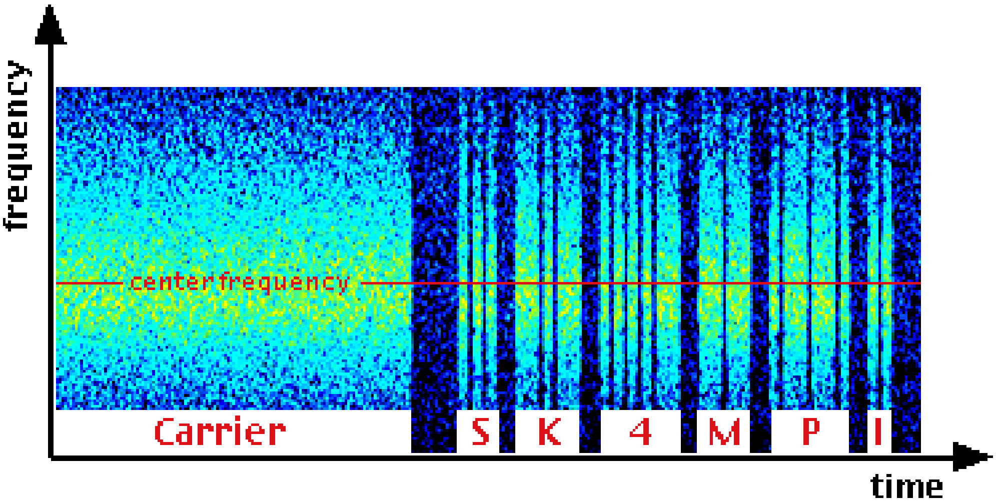

Figure 10. Time/frequency audio spectrum of the Aurora beacon SK4MPI from November 14, 1997 by OH5IY. In the vertical bars (dark blue), the radio channel was silent. The signal distortion is represented by the vertical spread (light blue, green and yellow) above and below the center frequency corresponding to a total audio bandwidth of about 3 to 4 kHz. Adopted from [3].

The dynamical behaviour of the scattering columns may be interpreted by variations of the velocity vector, e.g.

$$\mathbf{v}_{\mathrm{S}} = \mathbf{v}_{\mathrm{S0}} + \Delta\mathbf{v}_{\mathrm{per}}(\mathrm{t}), \tag{10}$$

where $\mathbf{v}_{\mathrm{S0}}$ denotes the steady state background velocity and $\Delta\mathbf{v}_{\mathrm{per}}(\mathrm{t})$ denotes the highly variable pertubation in speed and direction (“velocity noise”). Introducing eqn. (10) in eqn. (5), we obtain

$$\begin{aligned} \Delta f_{total} &= \frac{1}{c}\cdot f_0 \cdot (\hat{\mathbf{e}}_{\mathrm{AS}} - \hat{\mathbf{e}}_{\mathrm{SB}})\cdot \mathbf{v}_{\mathrm{S0}} + \frac{1}{c}\cdot f_0 \cdot (\hat{\mathbf{e}}_{\mathrm{AS}} - \hat{\mathbf{e}}_{\mathrm{SB}})\cdot \Delta\mathbf{v}_{\mathrm{per}}(\mathrm{t}) \\ &= \Delta f_0 + \Delta f_{per}(\mathrm{t}) \end{aligned} , \tag{11}$$

Similiar to eqn. (5), the scattered radio wave is Doppler-shifted by a constant Δf_0 but it is also affected by the variable Doppler spectrum $\Delta f_{per}(\mathrm{t})$. This spectrum broadens the dx signal which may cause considerable signal distortions depending on the nature of the spectrum $\Delta\mathbf{v}_{\mathrm{per}}(\mathrm{t})$. On the other hand, scientific radars may examine dynamical processes in the ionosphere by measuring the spectrum $\Delta f_{per}(\mathrm{t})$.

5.2 Doppler broadening by multipath backscattering

The region of backscattering is generally not spot-like in nature but is, more or less, an extended geographical region. Figure 11 displays the beams of the transmitting and receiving antenna overlapping in the blue area as well the scatter curve (green) which comprises all scatterer positions in the E-layer of the ionosphere which can support Auroral backscatter from station A to B and vice versa (see e.g. [2]).

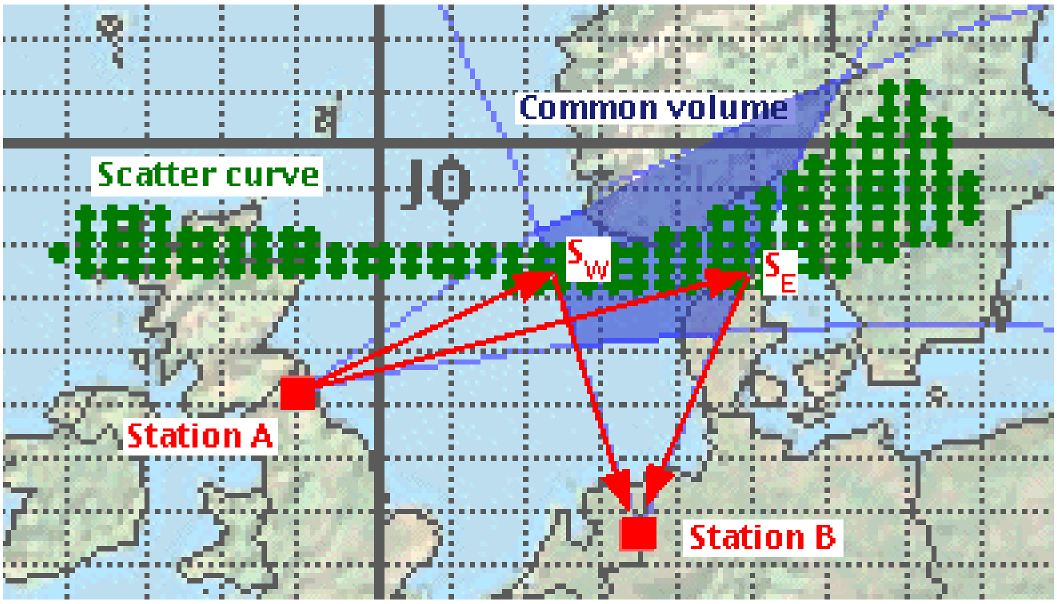

Figure 11. Auroras extending in a large geographical area (green) may cause backscattering from various regions within the common scatter volume (blue).

Major geomagnetic disturbances may result in Auroral backscatter originating from all positions along the scatter curve. Two examples are shown in figure 11, i.e. the most eastern and western scatterer (S_E and S_W) but all scatterers located between S_E and S_W may also contribute to Aurora dx communication between station A and B, of course.

Thus, eqn. (5) must be considered separately for each of the scatterers. Even if the Aurora velocity vector $\mathbf{v}_S$ is constant in all cases, the relative motion of the actual scatterer may vary considerably relative to station A and B. Therefore, the term $\hat{\mathbf{e}}_{SB} - \hat{\mathbf{e}}_{AS}$, see eqn. (5), is variable and, as a consequence, the Doppler effect varies along the scatter curve. Station B therefore receives a mixture of various Doppler shifts resulting in another type of Doppler broading which may also cause signal distortion.

Note that this effect is independent from the geophysical nature of backscattering, i.e. this is a geometrical effect resulting from large antenna beamwidths in combination with Auroras extending over a large geographical region. Unfortunately, measurements focusing on this effect are not yet available. However, radio amateurs are familiar with a similiar phenomenon because many dx operators report Aurora events in which the audio pitch of the received signal varies when changing the antenna direction, see also chapter 4.3.

6. Doppler effect in practice

6.1 Observing scatterers in motion

Identifying the motion of the scatterers is difficult using amateur radio antennas. The half power beamwidth of amateur radio arrays is typically 20° to 40° in azimuth, i.e. the radio operator cannot recognise even larger displacements of the scatterer within the antenna beam, in general. Actually, the antenna doesn't track a particular scatterer but illuminates a scatter volume where scatterers moving through. Watching a train with binoculars in fixed position, you may spot the train's engine in the first moment. Then the trailers are moving through the range of vision, one after the other. Thus, the antenna beam may scan a region of moving scatterers similiar to the binoculars scanning the cars of the train. Thus, we can hardly identify neither fast moving scatterers nor scatterers in fixed position when using the azimuth information of the antenna system.

6.2 Observing the Doppler effect

Only the Doppler effect can provide information on the scatterer's motion. However, the effect isn't obvious to the radio operator because he generally lacks a frequency of reference, i.e. the frequency he observes in the absence of the Doppler effect. Therefore, it is a rare but impressive phenomenon to receive dx stations on the backscatter path and, at the same time, on the direct path. On the other hand, the radio operator may compare his transmitting frequency to the frequency on which the dx station answers his call. This scenario is discussed in detail in the following paragraph.

6.3 Dx stations answering on the 'wrong' frequency

Assuming, station A launches a CQ call on the frequency $f_{A(TX)}$. The call is received by station B and because of the Doppler effect, station B tunes his receiver to the frequency

$$f_B = f_{A(TX)} + \frac{1}{c} \cdot f_{A(TX)} \cdot (\hat{\mathbf{e}}_{\mathrm{SB}} - \hat{\mathbf{e}}_{\mathrm{AS}}) \cdot \mathbf{v}_{\mathrm{S}} . \tag{12}$$

Radio operator B is not aware of the Doppler effect because he cannot identify the transmitter's true frequency, i.e. $f_{A(TX)}$. When radio operator B answers the call, he will certainly starts transmitting on the frequency on which he has received the call, i.e. f_B. Note that there is no other logical frequency he may use even if he speculates a Doppler shift is present.

Station B's frequency is again Doppler-shifted, i.e. station A receives station B on the frequency

$$f_{A(RX)} = f_B + \frac{1}{c} \cdot f_B \cdot (\hat{\mathbf{e}}_{\mathrm{SA}} - \hat{\mathbf{e}}_{\mathrm{BS}}) \cdot \mathbf{v}_{\mathrm{S}} . \tag{13}$$

Introducing eqn. (12) in eqn. (13) and considering the linearisation which was already used in eqn. (3), we obtain

$$f_{A(RX)} = f_{A(TX)} + \frac{1}{c} \cdot f_{A(TX)} \cdot 2\,(\hat{\mathbf{e}}_{\mathrm{SB}} - \hat{\mathbf{e}}_{\mathrm{AS}}) \cdot \mathbf{v}_{\mathrm{S}} . \tag{14}$$

Thus, the frequency offset between station A's transmitter and station A's receiver is twice the Doppler shift of eqn. (12). If, for example, station A transmits on 144.050 MHz and the dx station returns on, say, 144.052 MHz then the dx station's true transmitter frequency is 144.051 MHz. The Aurora QSO therefore involves two stations operating on three frequencies, i.e. $f_{A(TX)}$, f_B and $f_{A(RX)}$, respectively.

Eqn. (14) has a more general meaning as it appears in the first moment. Interpreting station B a reflecting device (station B, so to say, reflects the CQ call received from station A), eqn. (14) is equivalent to the monostatic radar case if v_{rel} is replaced by v_D, see eqn. (7) and eqn. (6), respectively. Thus, eqn. (14) denotes the Doppler effect in monostatic radar applications in which the radar target is illuminated indirectly because the line-of-sight between the radar and its target is not available. This type of 'radar round the corner' really exists. A prominent example is *Woodpecker*, the Russian HF over-the-horizon radar which raised public interest in the 1980s, see e.g. [9].

6.4 Recommendations in Aurora dx communication

This above findings and results may motivate the following recommendations in Aurora dx communication:

- Do not abandon your CQ frequency too early due to QRM from adjacent frequencies because the QRM might reflect dx stations answering your call. Note that you experience twice the Doppler shift of the dx stations answering the CQ call
- Do not tune your transmitter to the frequency on which the dx station answers your call because your QSO may fail. Changing your transmitter's frequency creates a hop in frequency on the dx station's end of the scatter path and if the dx station is doing the same, nothing is achieved except of shifting the dx station by four times the actual Doppler shift in comparison to your original transmitter frequency. Evidently, the radio operators run the risk of loosing the actual frequency in this procedure which may cause failure of the QSO.
- Cancel the receiver independent tuning (RIT) before calling a dx station you have spotted. Any RIT offset may add to the Doppler effect creating a large frequency offset from the dx station's perspective.
- On the other hand, invoke the transceiver's RIT control by, say, 2 kHz in both directions when expecting dx stations answering your CQ call in the 2m band.
- Do not expect constant Doppler shifts in an Aurora opening. The Doppler shift may vary considerably even with dx stations located in the same geographical area. It is perhaps a clever idea to compensate the Doppler shift in a given Aurora QSO by considering the RIT adjustment of a previous QSO. However, there is actually no guarantee that the same adjustment is appropriate in the actual QSO.
- Aurora dx QSOs in the 222 MHz and 432 MHz band may fail if the radio operator is not prepared to large Doppler shifts which may exceed the receiver's audio bandwidth. If, for example, the Doppler shift is 500 Hz in the 144 MHz band, then it is 1.5 kHz in the 432 MHz band. Thus, dx stations answering your CQ call may be shifted by 3 kHz which is indeed a large offset in dx communication. Is this the reason, 1296 MHz Aurora dx communication is a true rarity? In the above example, the dx station's frequency offset may reach 9 kHz and, even worth, the direction of the Doppler shift isn't obvious, in general. Thus, the radio operator must search a segment of 18 kHz width for dx stations answering his CQ call. If the Doppler shift is 1 kHz in the 144 MHz band, then the radio operator must search a segment of 36 kHz in the 1296 MHz band. This effect raises another complication in UHF and SHF Aurora dxing because the dx station probably stops calling after a period of time insufficient to scan the frequencies in that segment.

7. References

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Appendix

A.1 Notes on eqn. (1a) and (1b)

The equations

$$\Delta f = f_0 \cdot \frac{v}{c} \qquad \text{(A.1)}$$

and

$$\Delta\omega = k \cdot v \qquad \text{(A.2)}$$

are identical except of a factor 2π which is introduced in eqn. (A.2). Multiplying both sides of eqn. (A.1) with 2π, we obtain

$$2\pi \cdot \Delta f = 2\pi \cdot f_0 \cdot \frac{v}{c},$$

$\Delta\omega = 2\pi \cdot \frac{v}{\lambda_0}$, because $\Delta\omega = 2\pi \cdot \Delta f$ by definition and $f_0 \cdot \lambda_0 = c$

$\Delta\omega = k \cdot v$ because $k = \frac{2\pi}{\lambda_0}$ by definition.

Finally, we may easily change to vector notation, i.e.

$$\Delta\omega = \mathbf{k} \cdot \mathbf{v}. \qquad \text{(A.3)}$$

In eqn. (A.1), the symbol v denotes the relative motion of the transmitter in respect to the receiver (or vice versa), i.e. v represents only a particular velocity component in three-dimensional space. Analysing Auroral backscatte by using eqn. (A.1) therefore requires further geometrical considerations. This limitation does not exist with eqn. (A.3) which considers the Doppler shift calculation a three-dimensional problem by using the vectors $\mathbf{v}$ and $\mathbf{k}$.