Coordinate Registration of Super Dual Auroral Radar Network (SuperDARN) Radar Backscatter Using Three-Dimensional (3D) Ray Tracing

Alex T. Chartier

Abstract – Artificially induced backscatter from High-Frequency Active Auroral Research Program (HAARP)-generated irregularities serves as a useful reference point in assessing the accuracy of Super Dual Auroral Radar Network (SuperDARN) radar backscatter coordinate registration algorithms. The Kodiak (KOD) and Christmas Valley West (CVW) radars observed HAARP backscatter on April 23, 2014. The standard SuperDARN coordinate registration overestimated HAARP's great circle range (658 km and 2666 km) by 169 km and 345 km, respectively. Ray tracing, constrained by the observed signal elevation and bearing, and by ionosonde data, was effective in correcting these biases down to 61 km and –2 km, respectively.

1. Introduction

Backscattered ionospheric echoes of HF over-the-horizon transmissions are the basic scientific product of the Super Dual Auroral Radar Network (SuperDARN). To interpret these observations physically, it is necessary to register the coordinates accurately, both to identify the true locations of the scattering targets and to correctly interpret the lines of sight relevant to their Doppler velocities. This problem has parallels with coordinate registration of military skywave over-the-horizon radar targets, which can also be affected by variations in the ionospheric plasma density distribution. The high-latitude ionosphere presents unique challenges for HF propagation, due to the frequent presence of density irregularities created by particle precipitation and plasma convection. This study uses artificial irregularities generated by the High-Frequency Active Auroral Research Program (HAARP) at a known location (above Gakona, Alaska) to test the accuracy of SuperDARN coordinate registration. The April 23, 2014, case first analyzed by [1] is chosen, as HAARP-generated irregularities were observed in both Kodiak (hereafter KOD) and Christmas Valley West (hereafter CVW) radars. Clyde River (hereafter CLY) radar data were also examined, but no conclusive HAARP signature was found. Generation of F-region irregularities by HAARP is described in [2]. The Australian provision of high-frequency ray-tracing laboratory for propagation studies (PHaRLaP) 3D magnetoionic code [3] is used to interpret the SuperDARN data to improve on the standard coordinate registration. Ionosonde data from Digisondes [4] at Eielson Air Force Base, Gakona, and Idaho National Laboratory are used to constrain the International Reference Ionosphere (IRI-2016) electron density model [5] used by PHaRLaP with its default options. SuperDARN-observed elevation angle data are combined with PHaRLaP output to select the appropriate rays. Site locations and relevant SuperDARN range time Doppler data are shown in Figure 1. Note that KOD was operating around 13.5 MHz, while CVW was operating around 10 MHz during the relevant interval (around 8 Universal Time). The fitACF (https://github.com/SuperDARN/rst) version used here was 2.5.

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Alex T. Chartier is with the Space Exploration Sector, Johns Hopkins University Applied Physics Laboratory, 11100 John Hopkins Road, Laurel, Maryland 20723, USA; e-mail: alex.chartier@jhuapl.edu.

2. Case Study

HAARP-generated irregularities are clearly visible in KOD from ∼0 UT to 8 UT and in CVW ∼8 UT. The on–off signature of these echoes is unmistakeably artificial. In both cases, the HAARP backscatter is spread over >200 km of virtual range, which is much larger than expected, given HAARP is believed to generate irregularity clouds at most a few kilometers in diameter. The virtual range is estimated only from signal time of flight, so returns from multiple elevations could cause this apparent spreading.

The standard SuperDARN coordinate registration algorithm is applied to the data, and a sequence of HAARP on–off plots is shown in Figure 2, with spurious range gates removed. The geolocated SuperDARN data clearly show the HAARP on–off sequence. Two sources of error are apparent in the plots. The range of HAARP irregularities is overestimated, especially in the CVW data, and the irregularities are greatly spread in azimuth. The range overestimation is due to crude approximations of the signal propagation, while the azimuthal spreading is caused by improper treatment of sidelobes in beamforming. A technique to address beamforming issues has already been presented in [4], so the present analysis instead focuses on the problem of correcting range errors.

3. Ray-Tracing Analysis

A ray-tracing analysis is applied to correct range errors in the geolocation of HAARP backscatter. The propagation of signals from KOD and CVW is simulated by using PHaRLaP. Using this approach, SuperDARN scatter from a known bearing, elevation,

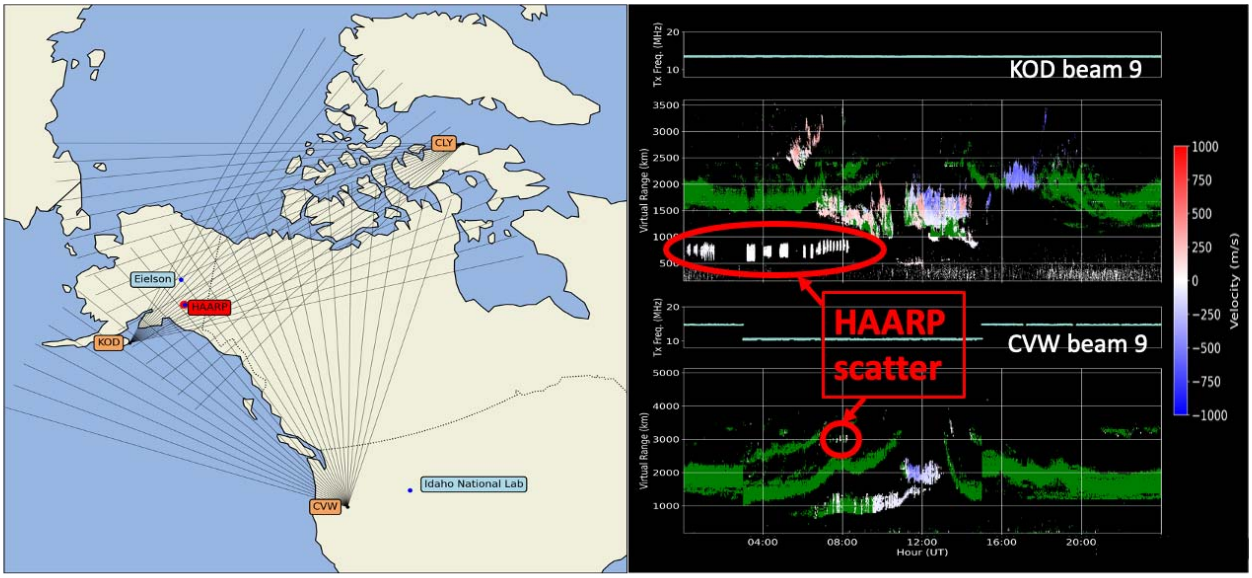

Figure 1. Left panel shows the locations of the HAARP heater (red), Eielson and Idaho National Lab Digisondes (blue), and KOD, CVW, and CLY SuperDARN radars (amber). Right panel shows SuperDARN range time Doppler data containing HAARP backscatter on April 23, 2014. Likely ground scatter is colored green. HAARP scatter is identified by its rapid on–off signature matching the known heater schedule.

and range can be geolocated unambiguously, though note that ordinary mode propagation is being assumed here.

The background ionosphere used in the simulations is based on IRI-2016, with first-order modifications applied to improve agreement with ionosonde data obtained from the Global Ionospheric Radio Observatory [4]. The modifications applied to IRI-2016 are a 30% increase in the electron density, and a 54 km reduction of the ionospheric layer height. These modifications result in good agreement between the observed and simulated ground scatter locations, and indicate that HAARP scatter from KOD occurs at 1/2 hop, while HAARP scatter from CVW occurs at 1 1/2 hop. Figure 3 shows an example of KOD–HAARP ray tracing through the modified IRI-2016 ionosphere and indicates potential field perpendicular scattering locations at multiple heights through the E and F layers. Note we have ignored magnetoionic mode splitting in this simulation because the underlying data do not indicate which mode was received.

The ray-tracing simulations indicate that KOD rays at multiple elevations should pass over HAARP perpendicular to the geomagnetic field (B) at heights ranging from the E layer to the upper F layer. Therefore, it is not surprising that the HAARP-induced backscatter should be spread in virtual range. To correct this spreading, we apply the received elevation angle data to the problem to select the appropriate rays. Note that the SuperDARN elevation angle fitting process returns two values, *elv* and *elv_low*, and we select the higher of these two in each case (which is not always elv). This addresses what we believe is an error in the elevation angle reporting in the SuperDARN files (elv should be the best guess, and elv_low should always be lower than that, but this is not the case in practice). The results of this analysis are shown in Figure 4.

In both cases, ray tracing is effective in reducing biases and root-mean-square error (RMSE) present in the standard approach. For KOD, the bias is reduced from 169 km to 61 km, while the RMSE is reduced from 57 km to 48 km. For CVW, the bias is reduced from 345 km to –2 km, while the RMSE is reduced from 73 km to km. It is somewhat surprising that ray tracing provided a better correction of the long CVW–HAARP path than the much shorter KOD–HAARP path. This may be an indication of an underlying issue with the KOD elevation data during the chosen case study (April 23, 2014). To illustrate this point, the KOD test is repeated with 10° added to the elevation angle, as shown in Figure 5. The increased elevation angle is effective in correcting the bias to –3 km, and the RMSE is also reduced to 43 km.

4. Conclusions

HAARP-induced irregularities provide a useful *ground truth* against which to test SuperDARN coordinate registration techniques. The standard SuperDARN coordinate registration produces significant errors, both for range spreading (RMSE: 57 km to 73 km) and range overestimation (169 km to 345 km). There is also a major issue with azimuthal spreading, though a potential solution has been described in [6]. Ray tracing through an accurate ionosphere, combined with observed elevation angle data, is largely effective in correcting the observed range overestimation, with remaining errors at KOD likely due to underestimated received elevation angles.

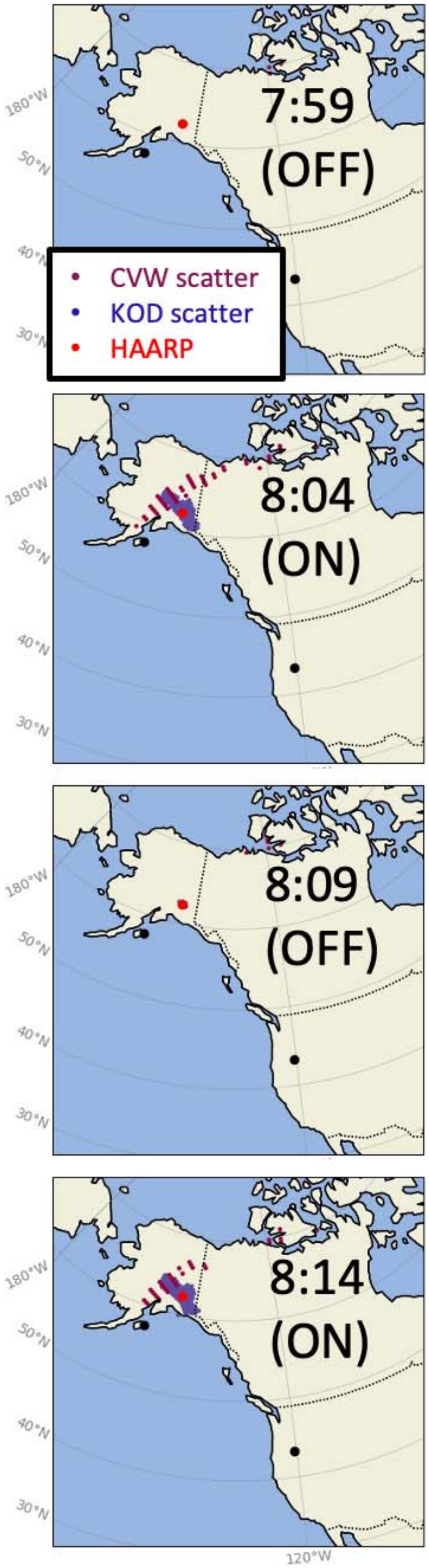

Figure 2. Geolocated SuperDARN backscatter from HAARP-induced artificial irregularities on April 23, 2014. HAARP heater operation is indicated on each panel (5 min on, 5 min off).

5. Acknowledgments

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6. References

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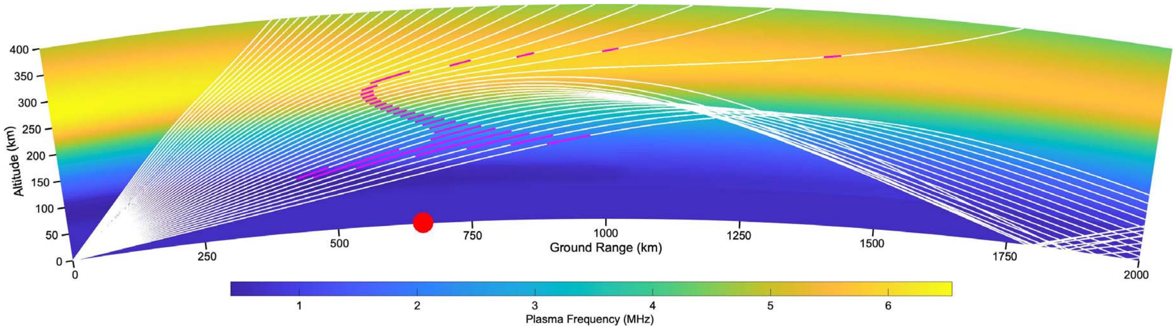

Figure 3. In white, 13.5 MHz rays propagated from KOD (at zero range) toward HAARP (658 km range, shown in red) through a modified IRI-2016 ionosphere. Ray tracing is performed by using the 3D PHaRLaP code. Ray path segments <0.5° of B-field perpendicularity are indicated in magenta.

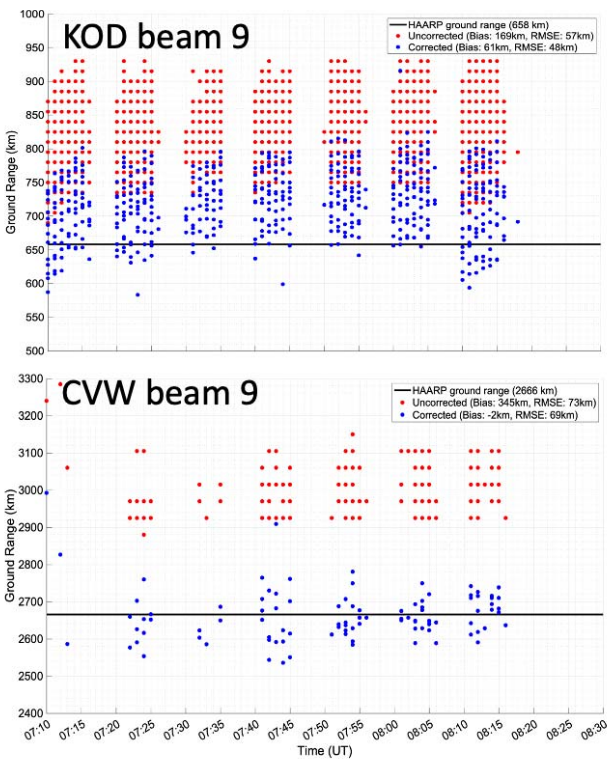

Figure 4. HAARP backscatter from SuperDARN radars with ray-tracing geolocation (blue) and with the standard coordinate registration algorithm (red). Note that the KOD range gate is 15 km, while the CVW range gate is 45 km.

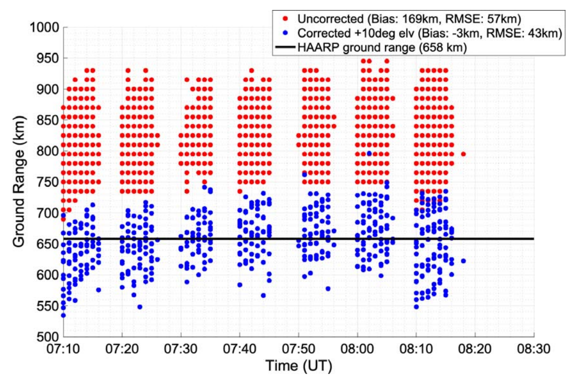

Figure 5. HAARP backscatter from KOD, with 10° added to the elevation angles. This is effective in correcting the geolocation range bias.