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Reply

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Introduction

Greenwald [this issue] has asserted that the loss of 21 dB of coherent integration gain as a result of the Doppler shifts which are caused by target velocity, target rotation, target structure, and spacecraft motion will remove any possibility of imaging the magnetopause with a radio sounder. Greenwald's main points are as follows: (1) A decrease in the signal-to-noise ratio by 21 dB will decrease the angular precision of a radio sounder by "a factor of more than 100," thereby eliminating "any possibility of imaging the magnetopause with a radio sounder" (paragraphs 2 and 14). (2) For the reported velocities at the magnetopause, coherent integration "will be totally ineffective" (paragraphs 3, 5, and 6). (3) Small rotations of the magnetopause will cause large additional phase shifts which will "nullify any benefits of phase-coded transmission" (paragraphs 4, 7, 9, and 10). (4) Multiple random echoes from a rough surface "will render unacceptable any form of phase-coherent detection" (paragraphs 8 and 11). And (5) Spacecraft motion parallel to a structured surface will "make it unlikely that any form of coherent processing gain will be achieved" (paragraph 12).

Coherent integration, phase-coded transmission, and phase-coherent detection refer to the pulse compression and spectral integration techniques which were discussed on pages 1587 and 1588 of *Calvert et al.* [1995]. The purpose of coherent integration is to improve the signal-to-noise ratio as described by our equation (33) in order to improve the angular resolution of a radio sounder as specified by our equation (35).

The relevant issue is whether coherent integration will work for radio sounding at the magnetopause, and if not, whether useful images of the magnetopause can be produced without coherent integration. This is of critical importance to magnetospheric research, since the proposed sounder is now scheduled for flight on the IMAGE spacecraft in January 2000 [see *Reiff et al.*, 1994].

How Often Will Coherent Integration Work?

As pointed out by Greenwald, pulse compression requires a Doppler shift which causes no more than about one quarter of a wavelength phase shift during an echo pulse. At 30 kHz, for the sounding parameters which were specified in our paper, this corresponds to a velocity of about 25 km/s, and according to the ISEE 1 and ISEE 2 observations of *Berchem and Russell* [1982], the magnetopause velocity exceeds this value about three quarters of the time. On the other hand, using a pulse with eight phase-coded intervals instead of the 16 which were originally suggested in our article, the maximum velocity at which pulse compression should work increases to about 50 km/s, at the expense of only 3 dB in the coherent integration gain. As a consequence, it then becomes possible to use phase-coherent detection approximately half of the time, since about half of the 30 velocities which were measured by *Berchem and Russell* [1982, Figure 7(a)] were less than 40 km/s.

For the coherent detection which was discussed in our paper, the coherent integration processing gain using both pulse compression and spectral integration was about 21 dB, corresponding to a factor of 11.3 in the signal-to-noise ratio. At 50 kHz, as shown in our Figure 16, this then increases the signal-to-noise ratio by about a factor of ten, corresponding to an improvement in the angular uncertainty of the echo direction measurements of a radio sounder from about ±4° without coherent integration, to approximately ±0.4° using 16 phase-coded intervals in the transmitted pulse, and ±0.6° using eight phase-coded intervals in the transmitted pulse. It is therefore expected that high-

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resolution measurements of the position and shape of the magnetopause are feasible for approximately half of the velocities which were measured by *Berchem and Russell* [1982].

Angular Precision Without Coherent Integration

The relevant point raised by Greenwald is that coherent integration may not work for the highest velocities which have been detected at the magnetopause. This, however, is not expected to compromise the usefulness of radio sounding for magnetospheric research, since useful images of the magnetopause with roughly ±4° angular resolution would still be possible virtually all of the time without having to rely upon coherent integration.

Apparently confusing the signal-to-noise voltage ratio with a power ratio, Greenwald has asserted that 21 dB corresponds to a factor of more than 100 in the angular precision of our echo direction measurements. This error has therefore led him to underestimate the angular precision of a sounder by an order of magnitude in his paragraphs 2 and 14, and therefore conclude that the angular precision without coherent integration would be about ±50°, instead of the ±4° which was actually predicted by our Figure 16. We are also in the process of devising other coherent integration techniques in order to measure the direction and velocity of the magnetopause over a wider range of velocities, and Greenwald is also wrong to assume that the simple coherent integration scheme which was discussed in our article was the only method for measuring the magnetopause with a radio sounder.

Other Issues

In order to justify why radio sounding cannot be used to image the magnetopause, Greenwald has also raised a number of other issues, including the low power and large distances which are required for radio sounding in the magnetosphere and the effect of high target velocities on measuring the echo direction from the Doppler shift which is caused by spacecraft motion. The low power and large distances were dealt with in our paper, and Greenwald has not disputed our calculations of the signal-to-noise ratio for the echoes from the magnetopause. Greenwald also incorrectly asserts in paragraph 6 that measuring the Doppler shift which is caused by spacecraft motion is one of the techniques which we intend to use to measure the direction of the echoes in the magnetosphere. As pointed out on page 1589 of our paper, this method is clearly inadequate and the actual method is described in our Section 6.1.

Greenwald has also incorrectly implied that the typical velocities of about 10 m/s which have been detected for density irregularities in the ionosphere are representative of the highest velocities which can be measured by this technique. Velocities of up to about 1 km/s have been measured in the polar cap and auroral zone, and it has also been demonstrated that coherent integration can be successfully applied in this environment [see *Reinisch et al.*, 1995, and references therein]. The large distances in the magnetosphere relative to the wavelength are also not significantly different from those in the ionosphere, since in both cases the sounding distance is approximately 2500 wavelengths. As a consequence, there is no reason to assume that radio sounding cannot work in the magnetosphere because the environment in the ionosphere is much less dynamic and the geometry much more advantageous, as Greenwald has asserted in his paragraph 13.

Greenwald then asserts that the coherent integration gain for spectral integration cannot be realized as a result of unknown and unmeasured accelerations at the magnetopause. Although such accelerations cannot be ruled out, this would require a change in velocity of approximately 10 km/s in less than a minute, and it is simply unknown whether such accelerations are typical of the magnetopause.

Greenwald then turns his attention to target rotation, target structure, and spacecraft motion in paragraphs 7, 8, 9, 10, 11, and 12, in which he asserts that tiny rotations of the magnetopause will cause additional phase shifts which will nullify any benefits of phase-coded transmission, that multiple echoes from a rough surface will render unacceptable any form of coherent detection, and that spacecraft motion parallel to a structured surface will make it unlikely that any form of coherent processing gain will be achieved. Even though these three points are no longer relevant to Greenwald's argument as a result of his error in estimating the angular precision of a sounder without coherent integration, we will now discuss these three points as follows.

Coherent Detection

The word "coherent" refers to two different waves, or the same wave at a different time, having the same phase or a constant phase difference. The echoes from a stationary surface, for example, will be phase coherent in different directions, whereas those from a moving or fluctuating surface will undergo different Doppler shifts in different directions and thereby become spatially phase incoherent in these different directions.

In coherent integration, the signal which is being received at different times is summed in phase in order to improve the signal-to-noise ratio. In pulse compression this is accomplished by correlating different parts of a phase-coded pulse with the original modulation pattern, and in the case of spectral integration, by the Fourier analysis of a sequence of pulses. In both cases, the word coherent refers to the detection process and not to the spatial coherence of the echoes which are being received.

Coherent integration is also a linear process in which the echoes coming from different directions combine linearly to produce the composite echo which is detected by a radio sounder. In this composite echo, as depicted in Figure 20 of our paper, the individual echoes from a structured surface may or may not be coherent with one another. If these echoes are coherent and in phase, the echo is referred to as a specular reflection, but if they are not, it is generally referred to as scattering. This, however, has nothing to do with coherent integration, since as long as the individual echoes are coherent with themselves, coherent integration will yield the predicted coherent integration gain regardless of whether or not these individual echoes are coherent with one another.

One therefore has three different meanings for the word coherent: The spatial coherence of a wave in different directions, the temporal coherence of each of the individual echoes coming from different small areas of a reflecting surface, and also the phase coherence of these different echoes with one another. In radio sounding in which the waves are detected at a single point in space, spatial coherence has nothing to do with the problem, since the phase of an echo in different directions is unrelated to the temporal coherence of the waves which are being received at a single point in space. The phase coherence of the different echo components coming from different parts of a reflecting surface also has nothing to do with coherent integration, since coherent integration relies only upon the temporal coherence of the individual echo components with themselves. One can therefore coherently integrate a spatially incoherent signal, as is usually done in scatter radar or in the detection of distant planetary radio echoes, and the confusion arises simply from using the word coherent in two different ways.

Target Rotation

The echoes from the different parts of a rough surface, moreover, will come from the peaks and valleys of this surface where the incoming wave directions are perpendicular to the density contours at the point of reflection, as depicted in Figure 20 of our paper. As a consequence, the Doppler shift which is caused by small rotations at the reflection point always equals zero, since the reflection point occurs at a point of stationary phase for the total wave path between the sounder and the reflection point. The idea that small rotations cause large additional phase shifts is therefore incorrect. It is also not clear why Greenwald has assumed that the spot size at the magnetopause is determined by the receiver antenna length, nor is it clear what he had in mind for the structure of the magnetopause in his model, since he seems to have assumed that the phase shift for adjacent points are completely uncorrelated.

Target Structure

Since the individual echoes from a structured surface combine linearly to produce the composite echo which is detected by a radio sounder, there is no reason to assume that multiple random echoes from a rough surface will render unacceptable any form of phase-coherent detection. Moreover, if the velocities which were measured by *Berchem and Russell* [1982] correspond to waves or irregularities on the surface of the magnetopause, the high-velocity echo components will simply contribute to the background noise, leaving behind the low-velocity individual echoes which correspond to the average shape of the magnetopause.

In paragraph 11 it is also unclear why Greenwald divided one quarter of the wavelength by the sounder spatial resolution in order to determine the fraction of a transmitted pulse which would return to a sounder "in a phase coherent manner." We think he is assuming that two separate echoes from a stationary surface must be in phase in order to be detected by coherent integration, and that he is probably trying to say that we had ignored the fact that the individual echoes from the different parts of a structured surface would add incoherently to produce the composite echo which is detected by a radio sounder. The first of these is obviously incorrect for a stationary surface, and the second was analyzed in our Appendix A, in which we calculated the expected echo signal strength for the incoherent echoes from a rough surface.

Spacecraft Motion

For a stationary structured surface, each of the echo components coming from different locations on that surface will be Doppler shifted according to its own component of spacecraft velocity in the echo direction, without causing any significant problems for coherent integration. The problem once again appears to be not actually analyzing how the echoes are produced by a radio sounder, since Greenwald seems to have assumed for some reason that the echo path is always perpendicular to the satellite velocity.

Summary and Discussion

The only relevant point raised by Greenwald is that simple coherent integration may not always work for the highest velocities which have been detected at the magnetopause. This, however, will not prevent making useful images of the magnetopause with a radio sounder, since (1) useful images with approximately ±4° resolution should still be possible without having to rely upon coherent integration, and (2) coherent integration should still be feasible for roughly half of the velocities which have been measured by *Berchem and Russell* [1982]. Greenwald has simply overestimated the actual velocities which have been measured by *Berchem and Russell* [1982] and underestimated the actual angular precision of a sounder without coherent integration. He also seems to have confused spatial coherence with the temporal coherence which is necessary for coherent detection, and has not taken into account that the two techniques which were used to illustrate coherent signal detection in our paper are not the only methods which can be used to improve the signal-to-noise ratio of a sounder.

The critical error in his paper, moreover, is not any one of the many errors which we have pointed out, but instead is the tacit assumption that we should throw out the baby with the bathwater simply because this technique has certain limitations which are well known to anyone who works in this field. He is also incorrect to assume that we had ignored these issues in our previous study of the feasibility of radio sounding in the magnetosphere simply because we had decided to emphasize other topics which we considered more important in the published version of that study.

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