We investigated the role played by low-frequency turbulence in the determination of magnetic field overshoots in collisionless shock waves. The data set used in this study included magnetometer and solar wind data from the ISEE 1 and 2 spacecraft for ~65 quasi-perpendicular bow shocks. Overshoots were calculated from both high-resolution data and from data averaged to eliminate the effects of turbulence with frequencies greater than the ion cyclotron frequency. Overshoots determined by the two methods exhibited generally similar behavior, although those calculated from the high-resolution data were generally larger by a factor of ~2. Overshoot size correlated well with shock Mach number and electron beta in both cases. The size of overshoots calculated from the high-resolution data increased strongly with Mach number and beta, while those calculated from the averaged data showed less dramatic increases. The behavior of overshoots calculated from the average data was generally consistent with hybrid simulation results. The difference between overshoots measured using averaged and unaveraged data was generally consistent with the presence of a component of overshoot magnitude due to low-frequency turbulence. Measurable overshoots were observed for all shocks in the data set, although those associated with the weakest shocks were small. Neither set of overshoots showed any particular change in behavior at the first critical Mach number.

**OBSERVATIONS**

The primary data used in this study came from the ISEE 1 and 2 magnetometers [Russell, 1978]. Solar wind parameters were provided by the ISEE 1 solar wind experiment and ISEE 2 fast plasma experiment [Bame et al., 1978]. The data set contained ~65 quasi-perpendicular bow shock crossings which occurred under a variety of solar wind conditions. We calculated overshoots just as LKR did, defining the overshoot magnitude as $O = (B_m - B_D)/B_D$, where $B_m$ was the maximum magnetic field in the overshoot and $B_D$ was the average downstream field. The top of Figure 1 illustrates this calculation for a high-resolution magnetic field profile (see also Figure 2 of LKR). The LKR study used the highest
plasma betas and Mach numbers, and no dependence on

Overshoots calculated using the two methods were well
correlated ($r = +0.94$), but there were interesting patterns in
their differences. Comparison of results from the two meth-
ods is summarized in Table 2.

The variation between the data sets is parameterized by
both the difference ($H - L$) and the ratio ($H/L$) between
results from the two methods.

**DISCUSSION**

There were two questions which we sought to explore
using this dual data set. The first was whether or not
low-frequency turbulence was, in fact, confounding over-
shoot measurement, and, if so, the second was then what
were the characteristics of the overshoot which were re-
vealed once the turbulence had been removed. Our analysis
has, however, in addition to helping answer those questions,
raised another, concerning the first critical Mach number.
We will discuss each of these issues in turn. We also note at
this point that in this study we have focused on the effects of
turbulence with frequencies generally larger than the ion
cyclotron frequency, and inquired as to its effect on the
measurement of overshoot magnitude. We have not ad-
dressed the issue of the unsteadiness of the reflection proc-
ess itself, which appears to have a frequency on the order of
the ion cyclotron frequency.

**Presence of Turbulence**

Overshoots calculated from the averaged data sets were
certainly smaller than those calculated from the high-
resolution data and the differences between the two showed
interesting patterns. The ratio between the two values was
unrelated to upstream parameters, but the difference was
well-correlated with both Mach number and beta. This is
consistent with the hypothesis that the difference between
the two measurements results from the presence of tur-
bulence in the high-resolution data set. Note that neither the $B_m$
of the averaged data nor the downstream field should contain
turbulent contributions. The turbulence ($\delta B$) should con-
tribute only to the $B_m$ determination for the high resolution
data, and the difference between the two calculated overshoots
should be directly proportional to the amplitude of the turbu-
lence:

- high resolution $H$: $\varphi = \frac{[B_m + \delta B - B_d]}{B_d}$
- low resolution $L$: $\varphi = \frac{B_m - B_d}{B_d}$

The difference $H - L$ is thus $\delta B/B_d$. The ratio between the
two values is related to the magnitude of the turbulence in a
more complex fashion:

$$H/L - 1 = \frac{\delta B}{(B_m - B_d)}$$

In the best of all possible worlds the turbulence would
have clear parametric differences different from those of
the overshoot per se, which should then be reflected in the

**Table 1. Correlation Between Overshoot Magnitude and Plasma Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Averaged Data</th>
<th>High Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron beta</td>
<td>+0.78</td>
<td>+0.79</td>
</tr>
<tr>
<td>Ion beta</td>
<td>+0.47</td>
<td>+0.47</td>
</tr>
<tr>
<td>Alfvén Mach number</td>
<td>+0.84</td>
<td>+0.91</td>
</tr>
<tr>
<td>Magnetosonic Mach number</td>
<td>+0.74</td>
<td>+0.75</td>
</tr>
<tr>
<td>Cos shock normal angle</td>
<td>−0.03</td>
<td>+0.03</td>
</tr>
</tbody>
</table>
values of $H - L$. What we found instead was that $H - L$ showed similar dependences to those of the overshoot: it was most strongly correlated with Alfvén Mach number and electron beta. These results are, however, consistent with studies of the low-frequency noise associated with shock crossings, which found that the magnetic component of the noise was positively correlated with Mach number and electron beta (M. M. Mellott and E. W. Greenstadt, unpublished manuscript, 1987). Thus the data were generally consistent with the presence of a component of overshoot magnitude due to low-frequency turbulence in addition to that due to ion dynamics per se.

**Effects of Turbulence**

The question then becomes does it make any real difference; i.e., does the presence of the turbulent component significantly alter the results of overshoot measurement? The correlations of overshoot size with Mach number and beta seen in the high-resolution data are, for instance, generally maintained in the averaged data. On the other hand, the dramatic increases in overshoot magnitude seen at high Mach numbers and large betas in the high-resolution data disappeared in the averaged data. This suggests to us that the strong growth in overshoot magnitude seen in the high-resolution data results from increasing levels of turbulence rather than from the ion dynamics.

Note that ion behavior has been studied in detail both through direct observations [Sckopke et al., 1983] and through simulations [Leroy et al., 1982; Quest, 1986]. The parameter ranges ($M_a$ and beta) over which the simulations were carried out were similar to those found in the data set, except that both sets of simulations were carried out only for exactly perpendicular shocks. The most important difference, however, between the simulations and the data seen here is that the simulation codes used did not include turbulent effects on electron scale lengths. Thus while we might expect the simulations to match the behavior of the averaged data set, we should not expect them to predict the full behavior seen in the high-resolution data. This is, in fact, what happens, as can be seen in Figure 3, where overshoots computed from high resolution and averaged field data are compared with those found in simulation studies. In the top panel median overshoots from both data sets are compared with results from the simulations of Leroy et al. [1982], and in the bottom panel results from the averaged data set are plotted along with those of the Quest [1986] simulations. The maximum rms deviation of overshoot magnitude in the Leroy et al. study was $\sim 20\%$, and the greater magnitude of the overshoots measured by the spacecraft is thus clearly significant, although the difference is much less in the case of the averaged data. The leveling off of overshoot magnitude seen at high Mach numbers in the averaged data is clearly more consistent with the simulation predictions than the strong growth seen in the high-resolution data. This turnover is due to the fact that the fraction of reflected ions saturates at $M_a \sim 8-10$.

Interest in the behavior of high Mach number shocks has

**TABLE 2. Variation Between $H$ and $L$ Resolution Overshoots and Its Relationship to Shock Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$H - L$</th>
<th>$H/L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfvén Mach number</td>
<td>+0.89</td>
<td>+0.09</td>
</tr>
<tr>
<td>Magnetosonic Mach number</td>
<td>+0.67</td>
<td>+0.17</td>
</tr>
<tr>
<td>Electron beta</td>
<td>+0.70</td>
<td>+0.22</td>
</tr>
<tr>
<td>Ion beta</td>
<td>+0.42</td>
<td>+0.05</td>
</tr>
</tbody>
</table>
increased as data have become available from the very strong bow shocks at the outer planets, and it is increasingly important, and possible, to check theoretical predictions against observations. Our results suggest that turbulence can play an important part in high Mach number shocks, and that the large overshoots seen at the outer planets [Russell et al., 1982] likely result from a combination of ion structure and turbulence.

Critical Mach Number

There was an additional unexpected difference between our work and the results of LKR, which appears in the overshoot behavior as a function of critical Mach number. It is illustrated in Figure 4 where overshoot magnitudes are plotted versus $M_f/M_c$. The three panels show the original LKR plot, our high-resolution data, and the averaged data. Note that the sharp jump in overshoot magnitude seen in the LKR plot did not appear in either our high resolution or averaged data. There are two reasons for this difference.

1. It was, of course, possible that the LKR study simply contained shocks which were not included in our data set, and so we checked specifically for those cases which appear in the LKR plot right at $M_f/M_c = 1$. We were able to identify seven of the 12 LKR points at $M_f/M_c \sim 1$, and when we did so, we found that they came from two days on which there were difficulties with the preliminary solar wind parameters used by LKR. Different problems were associated with each of these days, which were December 2, 1977, and January 6, 1978. The December 2 shocks were included in our data set, but the solar wind density which we used in our calculations, which was a more refined estimate than that used by LKR, was considerably larger ($n \sim 20$ as compared with $n \sim 10$). As a result, our calculated value of $M_f/M_c$ was $\sim 2$ rather than 1, and the points associated with those shocks were moved to the right on our plot as compared to LKR. On January 6, 1978, the solar wind ion temperature was quite low, and accurate temperature determination was not feasible (M. F. Thomsen, private communication, 1987). Shocks from this day were not included in our study for this reason.

2. Also, note that overshoots were seen at every shock in our data set. This contrasts with the results of LKR, who included in their analysis 24 "laminar" shocks which reportedly had no overshoots. Most of these shocks were included in our data set, and in looking at them closely we found that they all did, in fact, exhibit overshoots, albeit small ones. This is illustrated in Figure 5, where the averaged field for a dispersive shock with $M_f/M_c \sim 0.8$ is presented. In this case the maximum field was 45.1 nT and the average downstream field was 41.9 nT, the overshoot was thus $\sim 8\%$, small but nonnegligible. The omnipresence of overshoots is consistent with laboratory data [Strokin, 1985] and spacecraft observa-
effects of turbulence on overshoot measurement ever since the original work was done. Continuing discussion with C. F. Kennel concerning the issues raised here has been helpful and is much appreciated. The data on which the study was based were provided by C. T. Russell (magnetometer) and M. F. Thomsen (solar wind parameters). This work was supported by the ISEE Guest Investigator Program through grant NAG5-570, by the ISEE Project Office through contract NASS-28701, and through grant NGL-16-001-002.

The Editor thanks P. Cargill and another referee for their assistance in evaluating this paper.

The subcritical-supercritical distinction is still important, because different ion heating mechanisms operate in the two cases: the ion temperature increase in supercritical shocks can essentially be explained in terms of the reflection process [Sckopke et al., 1983], whereas ion heating at subcriticals is bulk perpendicular heating [Thomsen et al., 1985] and probably requires the operation of wave particle interactions. Our point here is that the simple presence or absence of reflected ions is not an adequate discriminator between two classes.

CONCLUSIONS

1. Overshoot amplitude appears to result from a combination of ion dynamics and turbulence.
2. Once turbulent effects have been filtered out, it can be seen that overshoot magnitude increases with both Mach number and beta, up to $Ma \sim 8-10$ and electron beta $\sim 3$, and then levels off.
3. There is little evidence for the existence of a first critical Mach number in this study.

Our general conclusion is that shock overshoots contain a turbulent component in addition to that produced by the ion dynamics, and that one must take data resolution into account in defining shock overshoots. Finally, we would like to note that comparison between this study and that of Livesey et al. [1982] provides a good example of Greenstadt’s theorem, which states that the physics inferred from any given plot is inextricably related to the scale on which the data is plotted.

Acknowledgments. This study originated in response to pressure from J. T. Gosling, who has been urging us to consider the

REFERENCES


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(Received June 5, 1987; revised August 11, 1987; accepted August 14, 1987.)