Ann. Geophys. Discuss.,
https://doi.org/10.5194/angeo-2018-59-AC1, 2018

Interactive comment on "Beam tracking strategies for fast acquisition of solar wind velocity distribution functions with high energy and angular resolutions" *by* Johan De Keyser et al.

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Received and published: 7 August 2018

Reply to Reviewer Comment #1

The authors thank the reviewer for his/her thorough revision of the manuscript and the helpful comments. Below, we respond to each of the points that was raised.

General Comments

Reviewer comment:

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- Table 1 and Section 2:
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-- I would check to make sure that the shock jumps are correct,
as I recall from the CfA Shock Database that several shocks had
$\Delta$V > 200 km/s.
https://www.cfa.harvard.edu/shocks/wi_data/
-- You should reference some recent work that provides the first
long-term statistical study on solar wind parameters near 1 AU
by Wilson et al. [2018] (Note the supplemental material
does separate parameters by fast and slow wind).
-- I doubt either of these will modify the values in your table
very much, but they will provide at least a reference/source
for the provided values.
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Response:
The reviewer is absolutely right in pointing out that some shocks at 1 AU involve $\Delta V > 200$ km/s. In formulating the instrument requirements, we do not require that the beam tracking algorithm should be able to capture all shocks completely, but most of them. The "< 200 km/s" should therefore be read as "most of the time". Checking the publication mentioned by the reviewer indeed confirms the values that we list in the table.

Modifications in text:
We have added a footnote in the table to point out that the values for the shock ΔV are "most of the time" and refer there to the CfA shock list. We have added the reference suggested by the reviewer regarding typical solar wind parameters in section 2.

Reviewer comment:

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- Section 2.1: [The following are my musings, but are most
likely not critical]
-- I see you addressed most of my concerns below in Section 3
already, but I leave it here for reference.
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-- One thing of which to be careful are secondary/reflected
ions near strong collisionless shocks. I assume you have
thought of this and know how to handle it, but I should
mention that even when the reflected to incident ion density
is relatively low, it can affect the bulk flow velocity
estimate determined from typical velocity moment software
significantly.
If the spacecraft on which the instrument of interest in
this paper is to orbit Earth and not, say, L1, then bow
shock reflected ions will be an issue and the fraction of
reflected-to-incident is much higher (>25% in some cases)
than typical interplanetary shocks.
This can affect the bulk flow velocity causing it to devaiate
away from the core solar wind proton beam by upwards of 30%,
i.e., >100 km/s [e.g., Wilson et al., 2014a]. In the case of
a sun-pointed spinner on an outbound pass, the number of
reflected ions entering the detector will likely be small,
so probably not an issue. However, the reflected ions at
earthward propagating interplanetary shocks will always be
an issue. The primary difference is that most interplanetary
shocks do not reflect a significant enough fraction of the
upstream ions to generate much of a foreshock, so perhaps
this is not cause for concern?
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Response:
When restricting an instrument's field of view to a cone around the solar wind direction, it is obvious that one cannot measure the reflected ions. The idea – as originally foreseen on THOR – is to have both a fast beam tracking solar wind spectrometer and an omnidirectional spectrometer (slower, offering some mass separation capability)

operating concurrently. For THOR also the goal was to go well out into the solar wind, so as to be sure that measurements are not affected by the foreshock. Reflection from solar wind shocks indeed remains an issue.

Modifications in text:
In the conclusions, we have inserted a paragraph discussing the utility of combining a beam tracking instrument with an omnidirectional spectrometer.

Reviewer comment:

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-- I know of at least one interplanetary shock that caused
problems for the PESA Low detector from Wind/3DP that was
seen on 2001-11-24 near 05:51 UT. The thermal energies got
so large that the instrument lost the solar wind beam and
did not enter tracking mode because it thought it was still
following the beam. Granted, the mode was not as well designed
as newer spacecraft that use NV (i.e., roughly the count rate)
but it is worth considering.
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Response:
This confirms the importance of a robust beam loss recovery strategy!

Reviewer comment:

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-Section 3.4:
-- Be careful with the estimates of the spatial scales for
discontinuities. The thickness of the shock ramp is not on
ion scales, but on electron scales [e.g., Hobara et al., 2010;
Mazelle et al., 2010]. What is not shown in the Spektr-R data
is what was assumed for years to be the actual shock ramp but
was undersampled [e.g., see Wilson et al., 2012, 2017].
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In general, I think your estimates are fine, but the statement
that ion properties cannot change faster than ion scales is
factually incorrect. Further, it is not the case that the
fluctuations discussed in the above references have no effect
on the ions, as shown by Goncharov et al. [2014].
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Response:
Agreed. The ion gyroradius is a characteristic of the spatial scale of variation of the ion VDFs, but the scale can be smaller if the magnetic field changes more rapidly and/or if there are strong localized electric fields – and there the electron scales can come into play.

Modifications in text:
We have reformulated this paragraph, and refer to Mazelle et al. (2010) and Krasnoselskikh et al. (2013) who discuss spatial scales in shocks.

Reviewer comment:

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- Section 4.1
-- I am confused. If you have a sun-pointed spinning spacecraft
and you align the central elevation angle bin with roughly the
Earth-sun line, why does the solar wind beam vary with spin in
the elevation angle? Or am I misunderstanding Figure 1 and the
discussion in this section? Is the spacecraft spin axis not
aligned with the Earth-sun line?
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Response:
The goal here is to illustrate what happens if the solar wind arrival direction does not coincide with the spacecraft spin axis. That is going to happen very often. There is the solar wind aberration angle that changes continuously within a range of a few degrees. But it is also very unlikely that the spacecraft spin axis not aligned with the Earth-sun

line. Indeed, suppose the alignment is perfect at a given instant, it will be 360°/365.25 = 1° off one day later because the spinning spacecraft axis keeps a constant direction in an inertial frame. Spacecraft operators would not want to do manoeuvres to reorient the axis on a daily basis (and the scientists wouldn't like that either).

Modifications in text:
We do think the explanation in 4.1 is clear enough.

Reviewer comment:

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-- Page 7, Lines 27-30: I do not follow the sentence starting
with "The difference between..." Is this a comment on the results
shown in Figure 1 or a general comment about the solar wind?
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Response:
That is a comment regarding the results. We simply want to point out that the measured arrival direction matches quite closely the true values with which we have set up the simulation.

Modifications in text:
We have adapted the phrase for clarity.

Reviewer comment:

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-- Page 8, Lines 4-5: Can you be a little more quantitative
with the statement "...distributions are somewhat distorted..."?
Distorted in what way? Would one interpret the VDFs as having a
higher temperature than reality, for instance? If so, by how much?
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Response:
The errors in arrival direction are quantified in Figure 2. The VDF distortion is illustrated in Figure 3. "Rotational smearing" of the VDFs will not affect the mean energy that is

measured, but it affects the mean arrival direction angles and it leads to a temperature anisotropy. Such high spacecraft spin rates are undesirable anyhow and one should stay away of that regime.

Modifications in text:
We inserted a phrase to describe the nature of the distortion more clearly (but still rely on Figure 3 to illustrate it).

Reviewer comment:

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- Section 4.3
-- Having had several long conversations with Drs. Safrankova
and Nemecek (a few years ago now) about the capabilities and
limitations of the BMSW instrument, I am curious how you
managed to get the data into GSE coordinates. It was my
understanding that there is no way to know the actual spacecraft
orientation and attitude necessary to rotate the data out of
spacecraft coordinates into a physically meaningful basis.
Has this issue been recently resolved?
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Response:
The instrument is mounted on the solar panels which can rotate. The exact solar panel rotation angle is not always known, which renders it impossible to derive the exact instrument look direction. However, for a considerable fraction of the time, including the events considered here, the solar panel rotation angle is fortunately available (though at a limited time resolution) and so the data can effectively be rotated into the GSE frame. We are particularly thankful to the referee for asking this question: digging deeper into this matter, we found out that we had actually NOT used the data in the GSE frame, but in the instrument frame, which, for the shock event, had its x-axis pointing about 11° away from the sun.

Modifications in text:
We have rerun the simulations for examples 7-8-9 using the data in the GSE frame and we have updated the figures. Note that, while we had originally observed that the solar wind seemed to go out of the CSW field-of-view, this now no longer is the case – this was simply due to the off-pointing x-axis. In retrospect, this should have triggered us to be suspicious of the reference frame of the original data. We have made the corresponding modifications in the text where we discuss these simulations. The paragraph in the conclusions that commented on the CSW field-of-view was also adapted.

Reviewer comment:

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-- The shock on 2015-06-22 arrived at L1 at ~18:08:24 UT (e.g.,
I looked at Wind data on CDAWeb). Regardless, the bulk flow
velocity along X-GSE jumps to nearly -800 km/s in the
downstream and the ion temperature exceeds 100 eV (i.e., ~1.2 MK),
so the temperatures may not be too inaccurate from BMSW. The CfA
shock database shows a density compression ratio of ~3.4 but I
think the temperature changes by a factor >4-5. [These are just
comments, not really actionable items.]
-- Page 9, Lines 50-51: Are the temperature and temperature
anisotropy significantly affected as well, or just the density
moment?
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Response:
Thanks for checking this shock with the Wind data. It can indeed be interesting to try to compare some of the BMSW data with shock measurements elsewhere in geospace. As stated in the text, the temperature measurement is affected too. BMSW does not provide temperature anisotropy.

Reviewer comment:

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- Hot and/or Tenuous VDFs
-- One of the biggest issues that I did not see addressed in
the manuscript occurs during intervals when the density is low
[i.e., below ~1 cm^(-3)] or the temperature is high (i.e.,
Ti > ~100-200 eV, depending on the instrument). If we assume
a bi-Maxwellian or even an isotropic Maxwellian, the peak phase
space density goes as N*T^(-3/2). The one-count level
during the same interval does not drop/change relative to an
adjacent, earlier interval. Thus, the signal-to-noise ratio
can drop preciptously during these periods. I realize this
is an issue faced by all particle instruments, but it is
worth discussing to ensure you do not lose the critical parts
of the distribution downstream of strong shocks with high
temperatures but relatively low density (e.g., for really
low upstream density).
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Response:
The referee is absolutely right in stressing the importance of making sure that there are no problems with the signal-to-noise ratio. We want to point out 3 elements in this respect:

- As mentioned in the introduction, any plasma spectrometer faces a trade-off between (a) angular and energy resolution, (b) time resolution, (c) signal-to-noise ratio. Obviously this trade-off is linked to hardware limitations (e.g. the instrument's geometrical factor is limited by the volume and mass budget, there are constraints due to the telemetry budget, etc...). It is precisely here that beam tracking is useful: by making measurements only where it matters, the best trade-off remains possible. For instance, for given time, angular and energy resolutions, beam tracking allows to maximize the data collection time per measurement bin

so that even for low count rates a significant number of counts can be collected, thereby improving the signal-to-noise ratio. So implementing beam tracking in general helps to avoid low counts.

- The important question here is whether the beam tracking strategy would not get confused in low density / high temperature environments. With the simple beam loss detection strategy used here, low densities would trigger the “beam loss” condition. But that would not be dramatic: the instrument simply returns to a measurement strategy that samples the full phase space accessible by the instrument. Although one would lose time resolution, providing VDFs over the full phase space is one of the best things one can do in such a situation (especially for the high temperature case). A posteriori, one can bin the measurements in energy, azimuth, elevation and/or time to improve the signal-to-noise ratio even further so that these measurements are scientifically useful.

- Beam tracking driven by a Faraday cup instrument would suffer less from problems in such situations, since a Faraday cup inherently provides a better signal-to-noise as it integrates the particle flux over its entire field of view.

Modifications in text:
We have inserted a paragraph in section 3.3 (Beam loss detection and recovery) discussing this matter.

Minor Concerns

Reviewer comment:

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-- Page 1, Lines 35-50: You could also mention waves and
instabilities [e.g., Malaspina et al., 2013], as
electromagnetic fluctuations are not solely limited to
turbulence. It is also important to measure the full 3D
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VDFs for analysis of instabilities.
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Modifications in text:
Sure. We have added a sentence + a few references.

Reviewer comment: – Page 2, Lines 2-18: The Wind spacecraft's 3DP instrument suite is also relevant here [e.g., Lin et al., 1995].

Modifications in text:
We have added a sentence about 3DP (mentioning also its higher angular resolution near the ecliptic plane) as well as the reference.

Reviewer comment:

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-- Page 2, Line 47: I know voxel is a term analogous to a
velocity-space pixel, but could you provide a definition
for the reader that may not know this.
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Modifications in text:
Provided a definition upon first occurrence

Reviewer comment:

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-- Page 7, Lines 10-12: I am not sure I understand the
sentence starting with "It starts measuring..." You state
the instrument starts sampling at 600 ms and the duration
required to obtain one full VDF is another 600 ms. Is that
correct?
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Response:
Yes, absolutely correct.

Typos, Grammar, etc.

Reviewer comment:

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[The following are suggestions, not requirements
(e.g., I do not recall rules for British vs.
American grammar for when to use commas after things
like "e.g." or "i.e.")]
Page 4, Line 25: "12, i.e. an order" --> "12, i.e., an order"
Page 5, Line 56: "i.e. one uses" --> "i.e., one uses"
Page 5, Lines 77-79: "In order to eliminate values that are
completely off, a voting" -->
"In order to eliminate outliers, a voting"
Page 5, Line 87: Try rephrasing the following "Note that
such a more robust procedure
requires" as it is awkwardly phrased and not clear what is meant.
Page 6, Line 38: "robust (i.e. when" --> "robust (i.e., when"
Page 6, Line 40: "...cient (i.e. when" --> "...cient (i.e., when"
Page 6, Line 98: "direction (i.e. with" --> "direction (i.e., with"
Page 8, Lines 62-63: "The measurement points" --> "The measurements"
Page 9, Line 19: "neither dramatic in magnitude nor very" -->
"neither dramatic in magnitude or very"
Page 11, Line 5: "instrument (i.e. of" --> "instrument (i.e., of"
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Modifications in text:
Thanks, all have been dealt with.

Reviewer comment:

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Page 14, Line 5: "manoeuvres" --> "maneuvers"
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Response:
We stick with British English.

References

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