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Statistics of Uncertainty in OMNI Solar Wind Measurements

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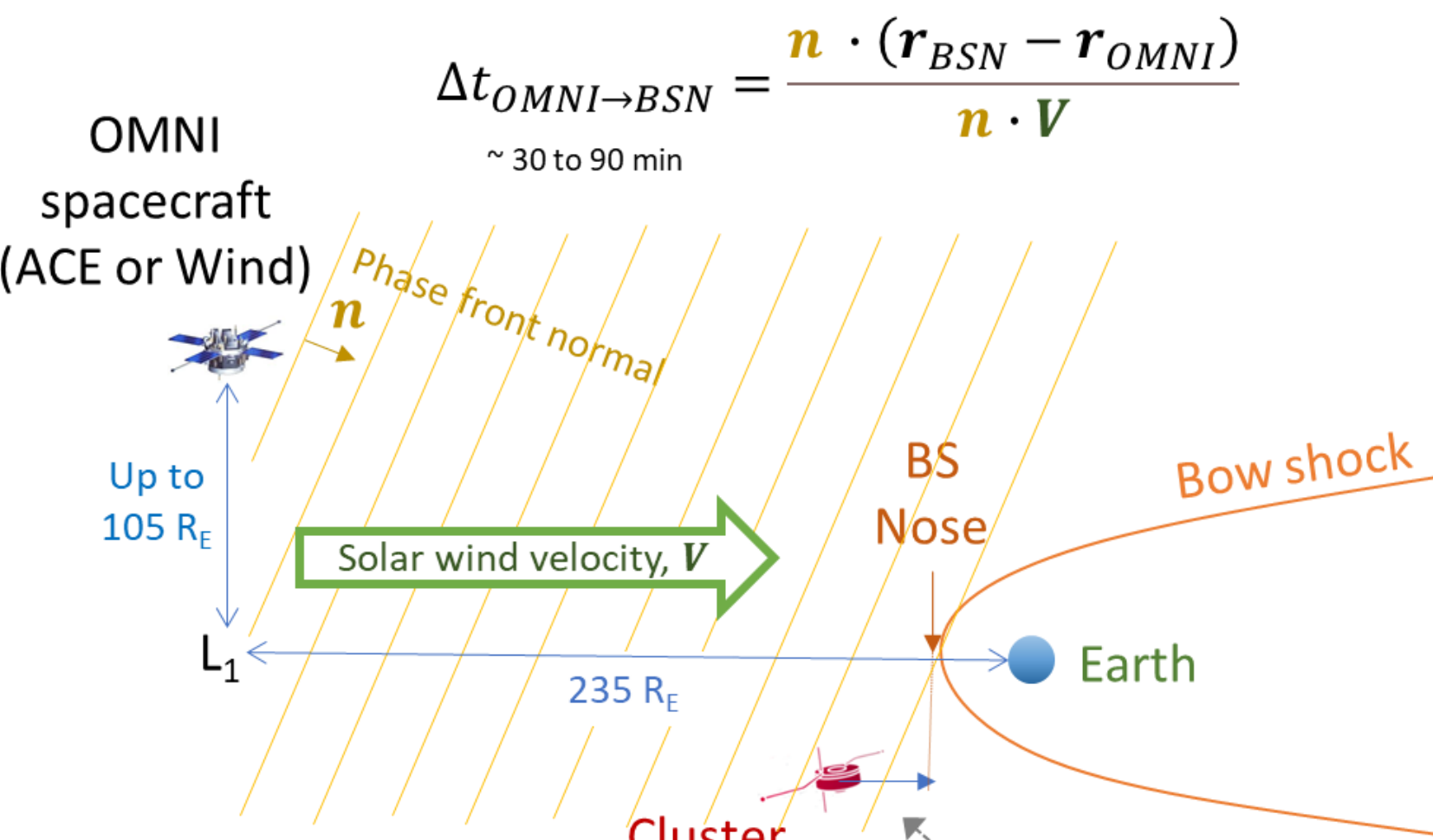
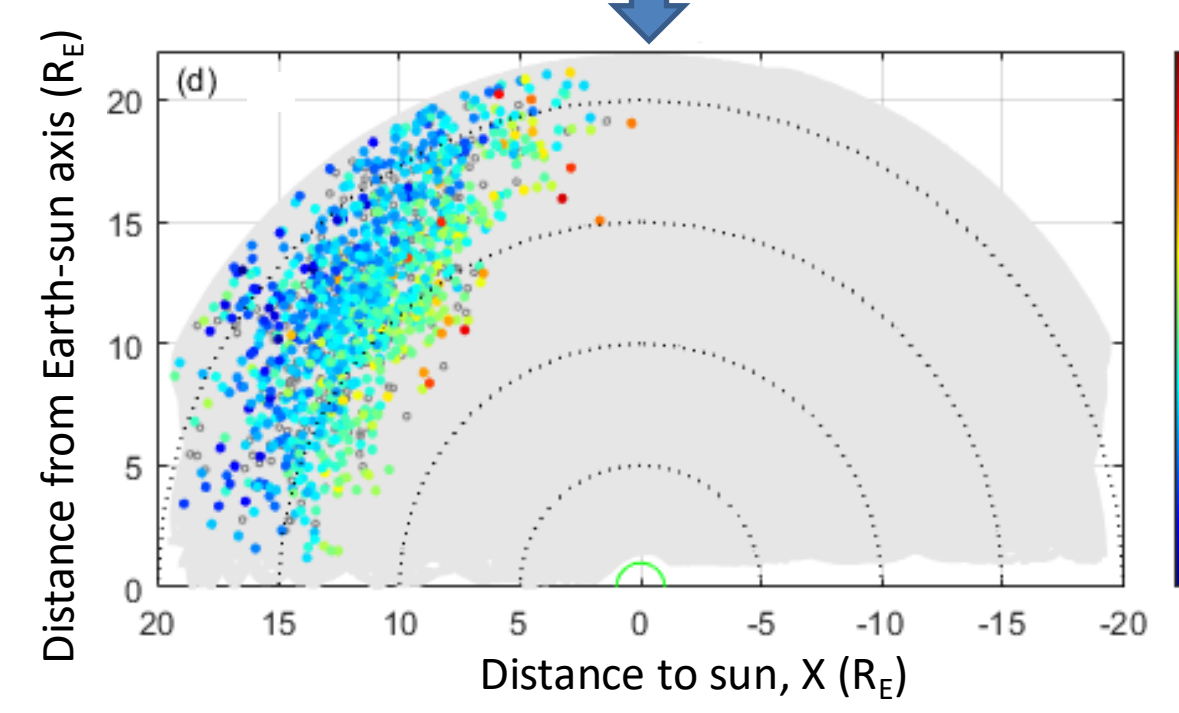
1. Introduction

- NASA's OMNI database^[1] predicts Solar Wind (SW) parameters near the Earth's bow shock (BS) nose based on measurements 1.5 million km upstream, near the L₁ libration point.
- We use ~5000 hours of ESA Cluster^[2] satellite near-Earth SW measurements to determine uncertainties ("errors") resulting from unknown solar wind spatial structure and errors in time delay between the L₁ and Earth.
- We calculate probability distributions of errors in: Velocity along the Sun-Earth (X) axis, $-V_x$; speed, $|V|$; interplanetary magnetic field (IMF) strength, $|B|$; field perpendicular to X, $B_{\perp}$; ion density, ρ , and IMF clock angle, $\theta_c = \text{atan2}(B_y, B_z)$.
- These parameters are inputs to "Coupling Functions"^[3] that predict magneto-ionospheric "space weather" responses to the solar wind.

2. Data processing

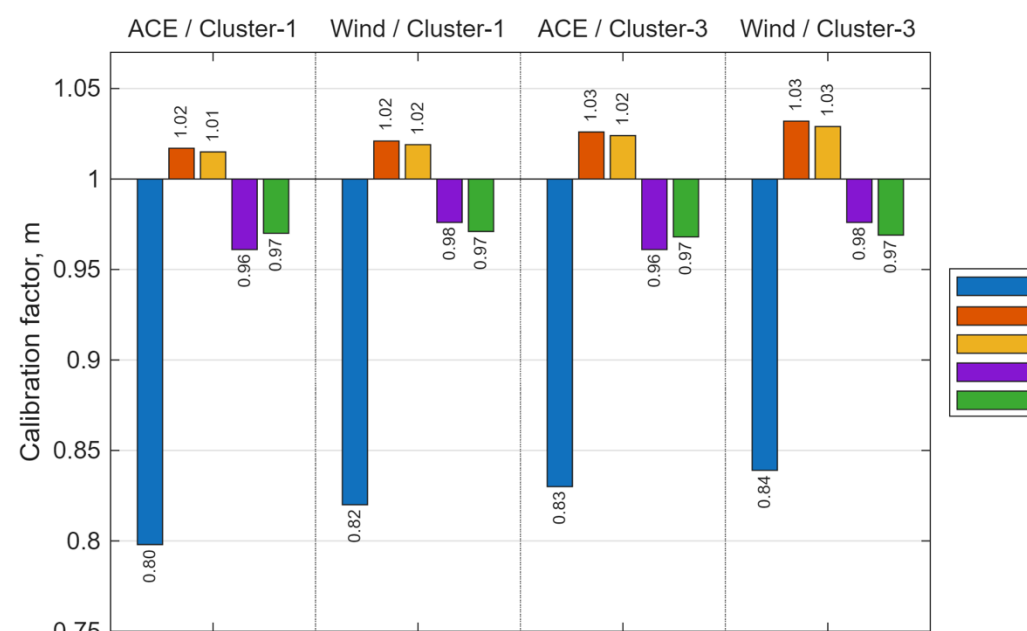
OMNI estimates the solar wind at the BS nose using ACE or Wind spacecraft measurements of SW velocity and estimates of the phase front normal. Two Cluster spacecraft measure solar wind near the Earth. We lag (or advance) Cluster measurements to the BS nose location.

Bow shock crossings of the Cluster spacecraft were identified from magnetic field measurements. The figure below shows the locations of 1246 Cluster-1 Bow Shock crossings in years 2001-2023. Note how the bow shock distance reduces with solar wind dynamic pressure, $P^{(6)}$ (colour scale). The grey region shows all spacecraft locations.

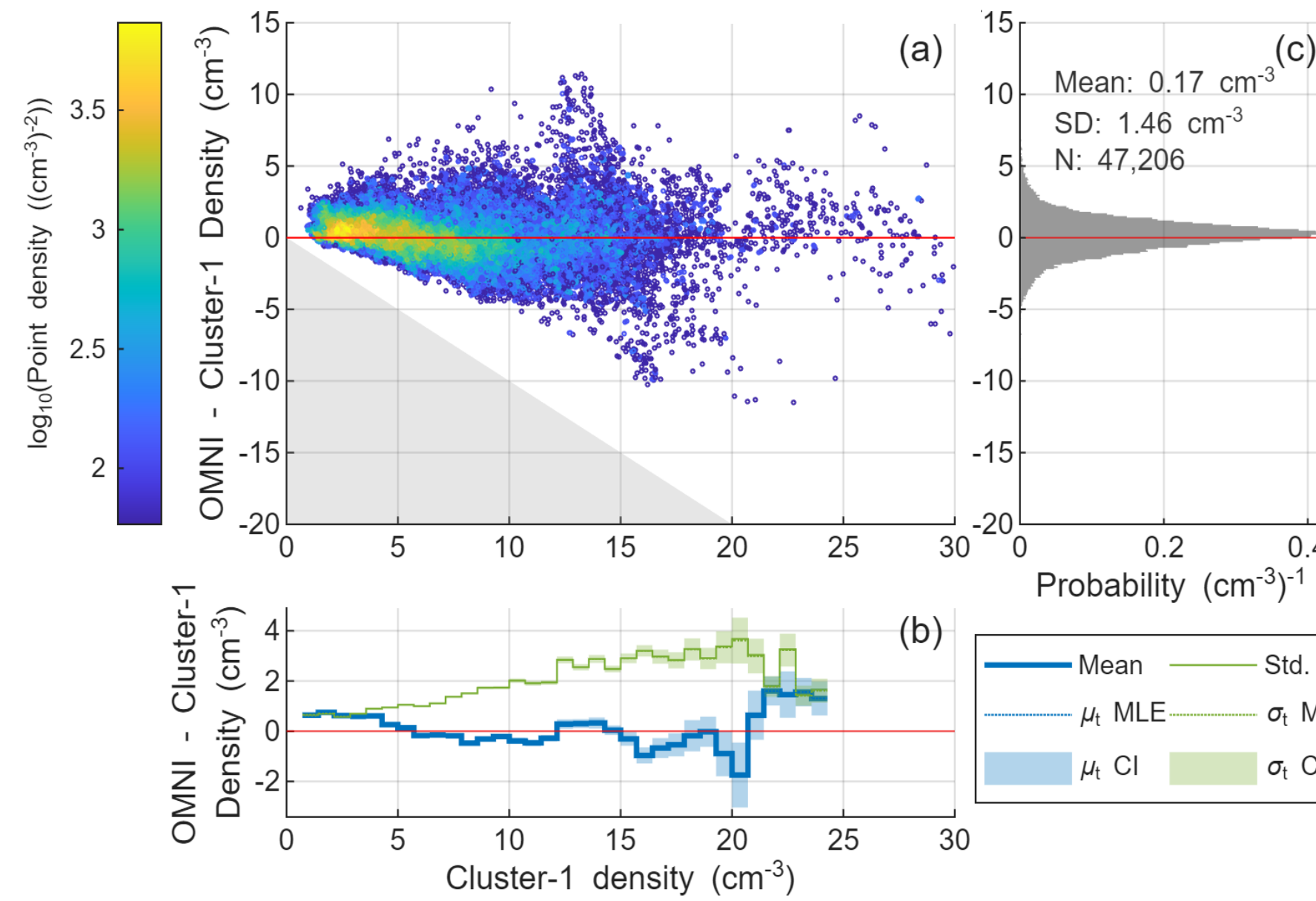


Calibration: Instrument biases between OMNI and Cluster spacecraft are calibrated by removing the overall relative biases. We multiply Cluster values by a scalar value, m , as shown.

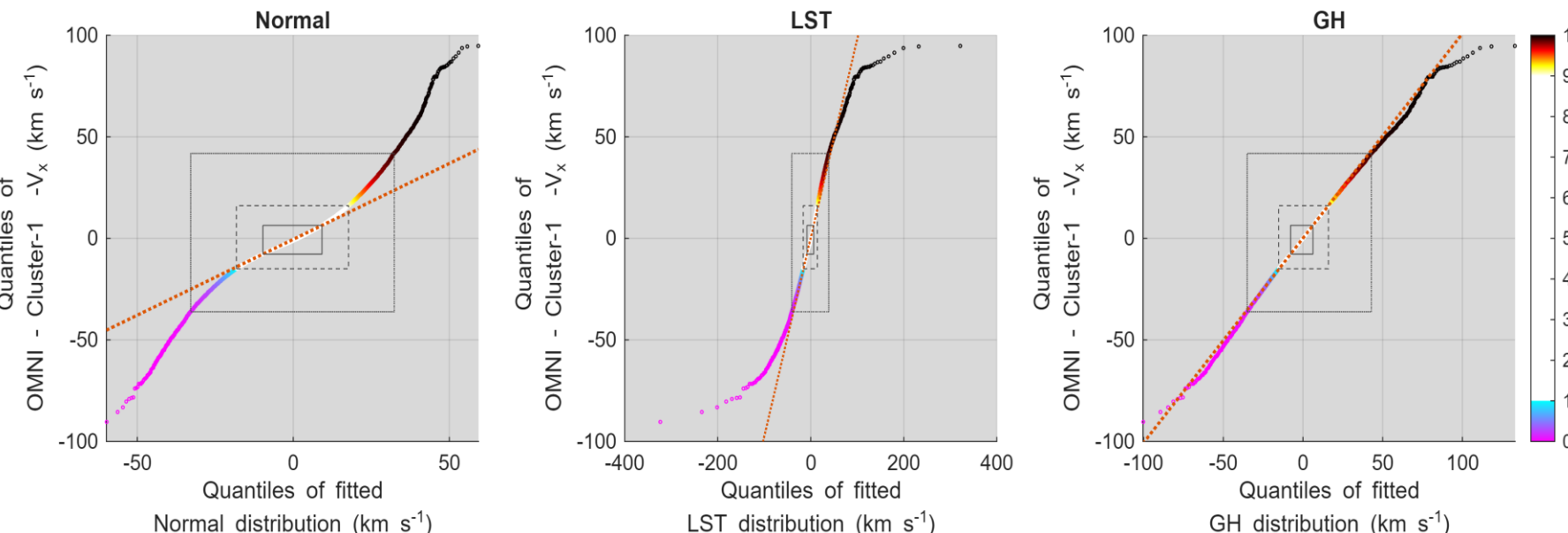
$$\Delta t_{\text{Cluster} \rightarrow \text{BSN}} = \frac{X_{\text{BSN}} - X_{\text{Cluster}}}{V_{x, \text{OMNI}}} \sim +2.5 \text{ to } -4.5 \text{ min}$$



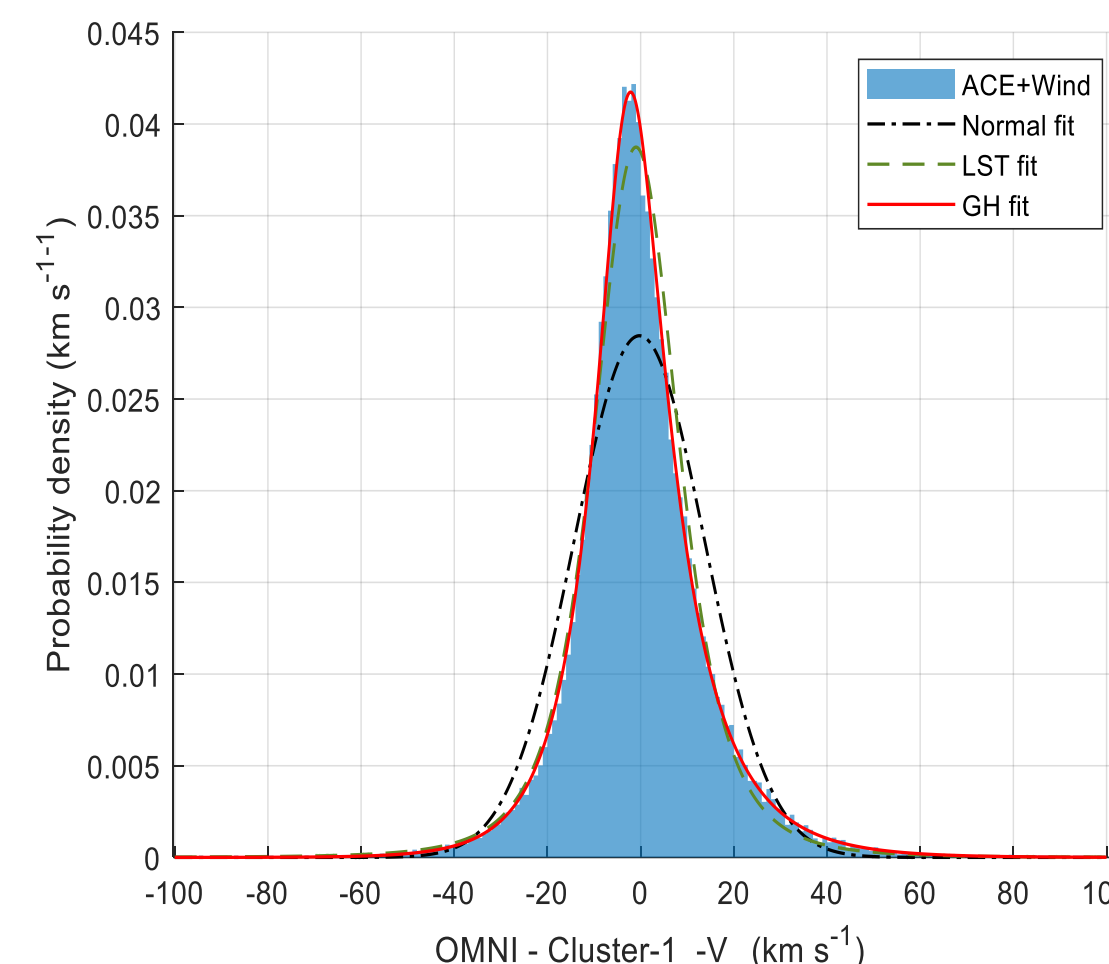
3. Error probability distributions



Fitted error probability distributions: The empirical error PDF for SW velocity, $-V_x$, is shown here in blue. The Normal distribution fit (black curve) is poor. The Location-scaled (Student's) t distribution (LST) (green) is a great improvement, but the five-parameter Generalised Hyperbolic (GH) distribution^[4] (red) is best of all.



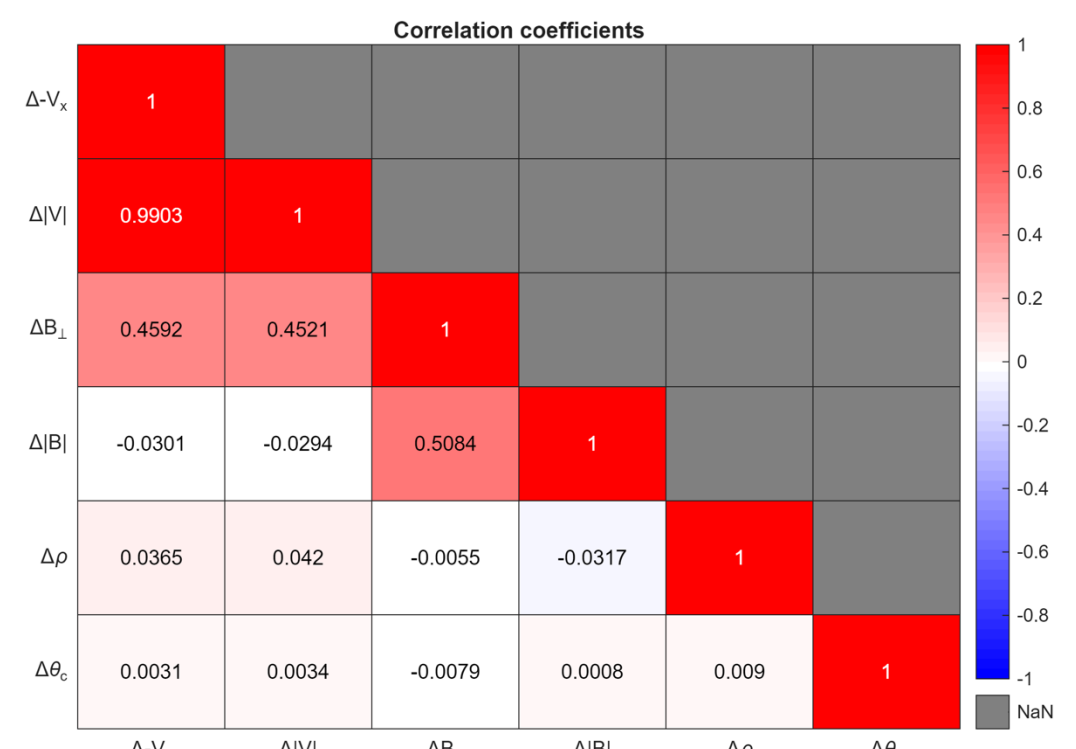
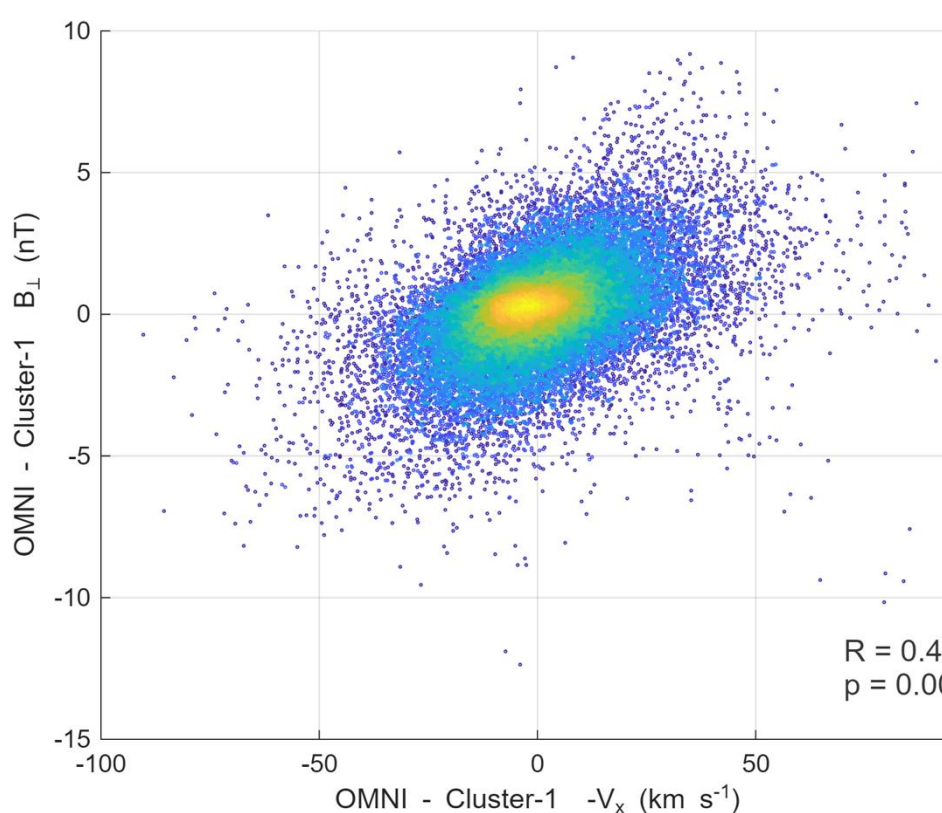
OMNI errors: This 3-panel figure shows: a) a scatter plot ("heatmap") of the SW ion density differences (OMNI minus Cluster) vs the calibrated Cluster values. Panel (b) shows that the bias (blue line) is relatively constant, but the standard deviation (green line) increases with density. The right panel (c) is the probability density function (PDF) of errors.



Quantile-quantile plots for the three fitted distributions (each panel on left) confirm that only the GH distribution^[4] is a good fit to the upper and lower few percentiles. This is also true for the other solar wind parameters.

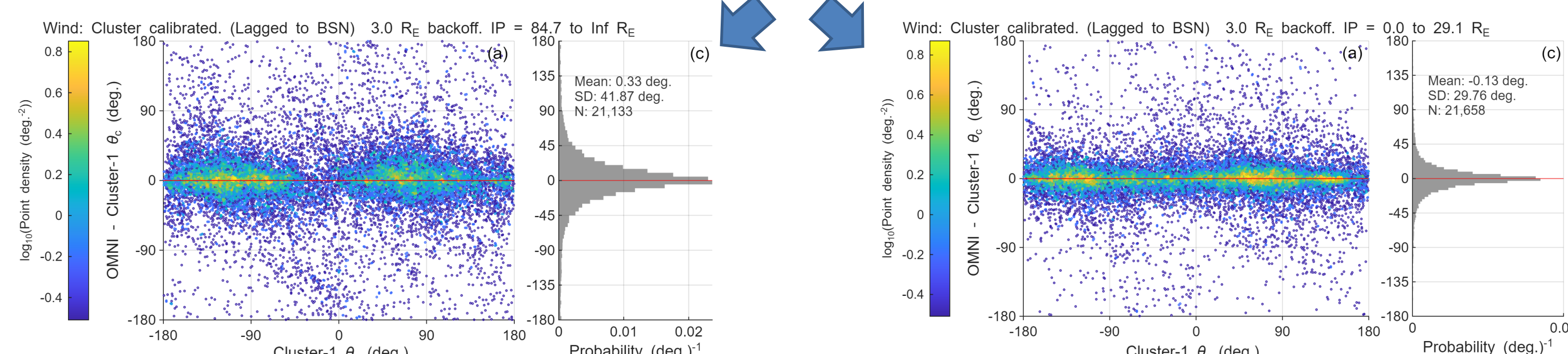
4. Error covariance

A strong positive correlation is observed between the error distributions of $B_{\perp}$ and $-V_x$. This is evident in the scatter plot (right) where colors indicate point density. Other correlation coefficients are given in the table (far right).



5. Effect of OMNI spacecraft transverse distance

Distance of the OMNI spacecraft from L₁ significantly increases the standard deviation (SD) of error in IMF clock angle, θ_c . This is illustrated below where the left figure is for Wind spacecraft locations $> 85 R_E$ from L₁ (the upper quartile), whilst the right figure is for locations $< 29 R_E$ from L₁ (the lower quartile). The error standard deviation reduces from 42° to 30° . (Distances here are "Impact Parameter" values, which include a small correction for Earth orbital motion.)

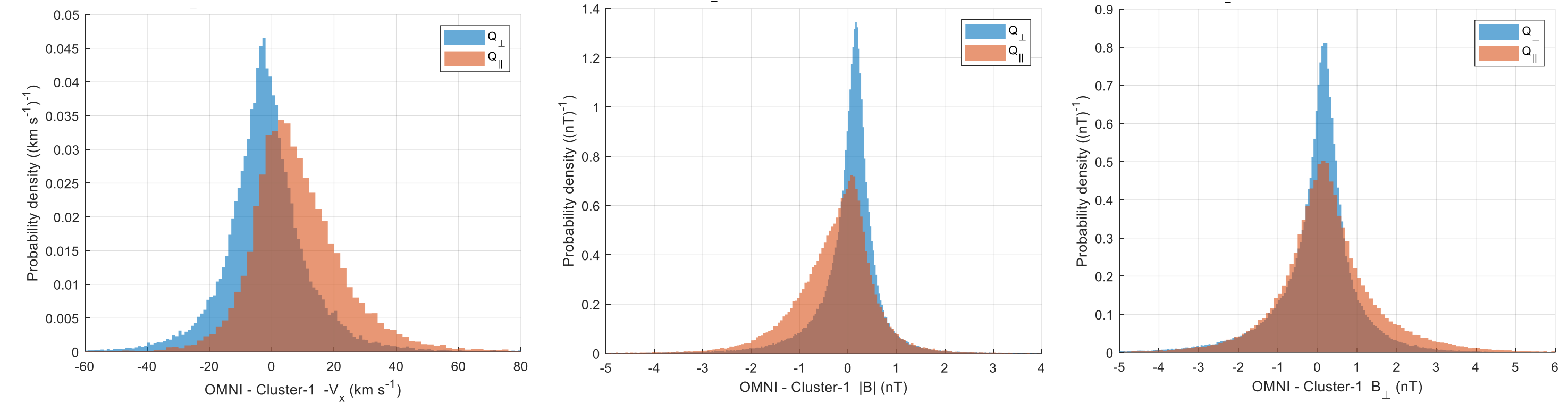


6. Ion Foreshock effects

The Ion Foreshock region extends up to a few R_E upstream of the bow shock where the IMF, B , is quasi-parallel ($Q_{\parallel}$) to the bow shock normal ($< 45^\circ$ away).

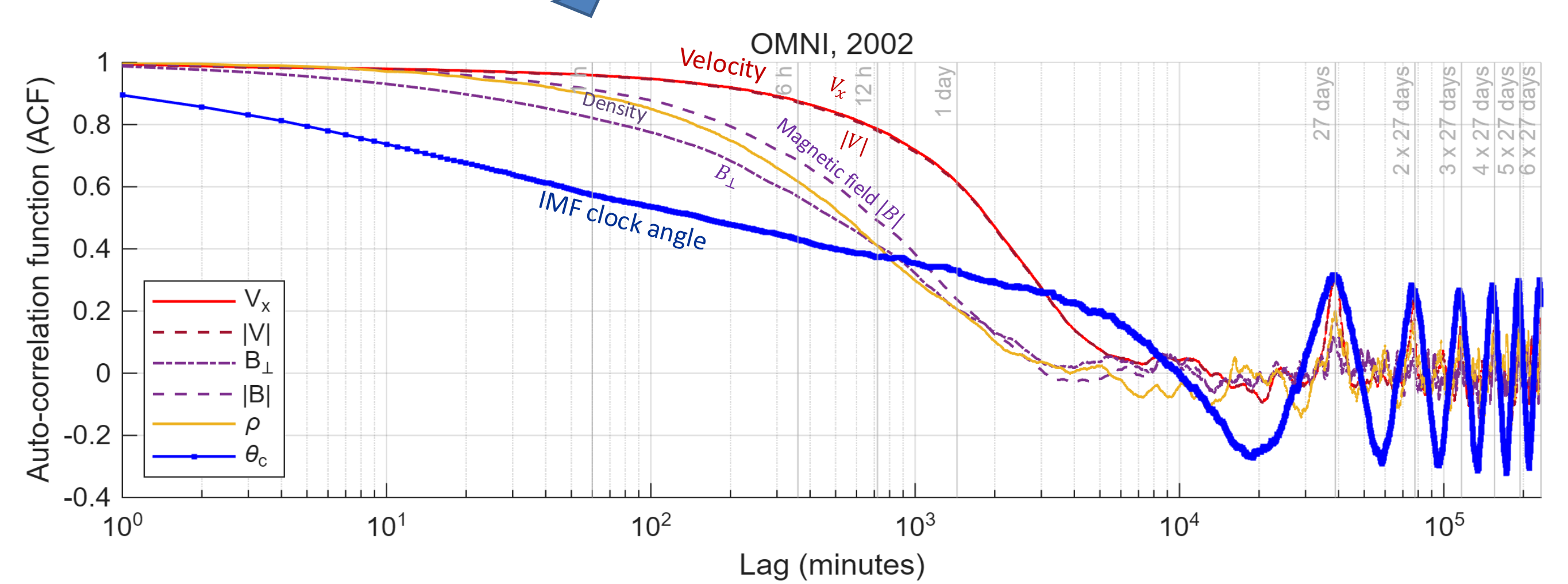
Error PDFs are shown below filtered for quasi-parallel $Q_{\parallel}$ (orange bars) and quasi-perpendicular conditions ($Q_{\perp}$) (blue bars) at Cluster-1 when it was $< 3 R_E$ upstream of the bow shock. In the $Q_{\parallel}$ ion foreshock region Cluster measures (on average)...

10 km s⁻¹ lower velocity, 0.3 nT higher field strength $|B|$, and 0.24 nT lower transverse field strength, $B_{\perp}$.

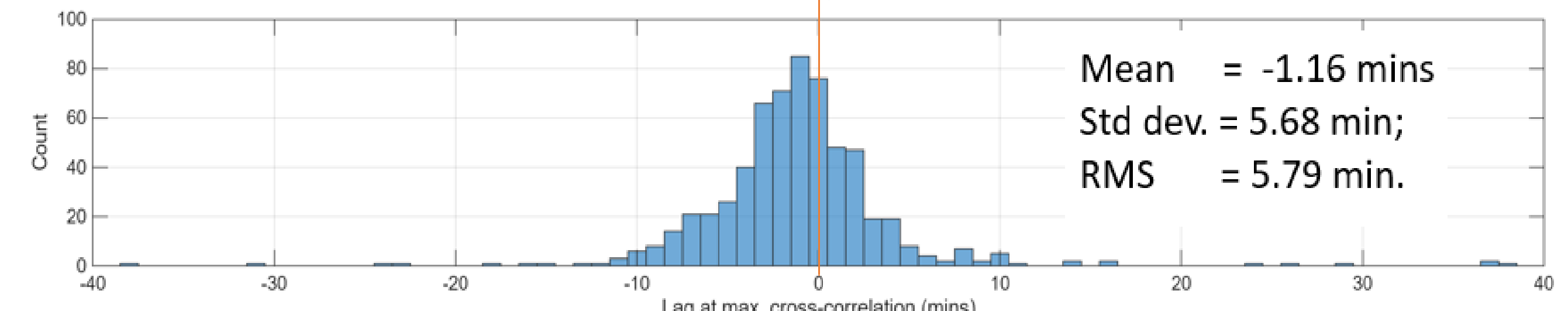


7. Uncertainty due to L₁ → Bow Shock nose propagation time error

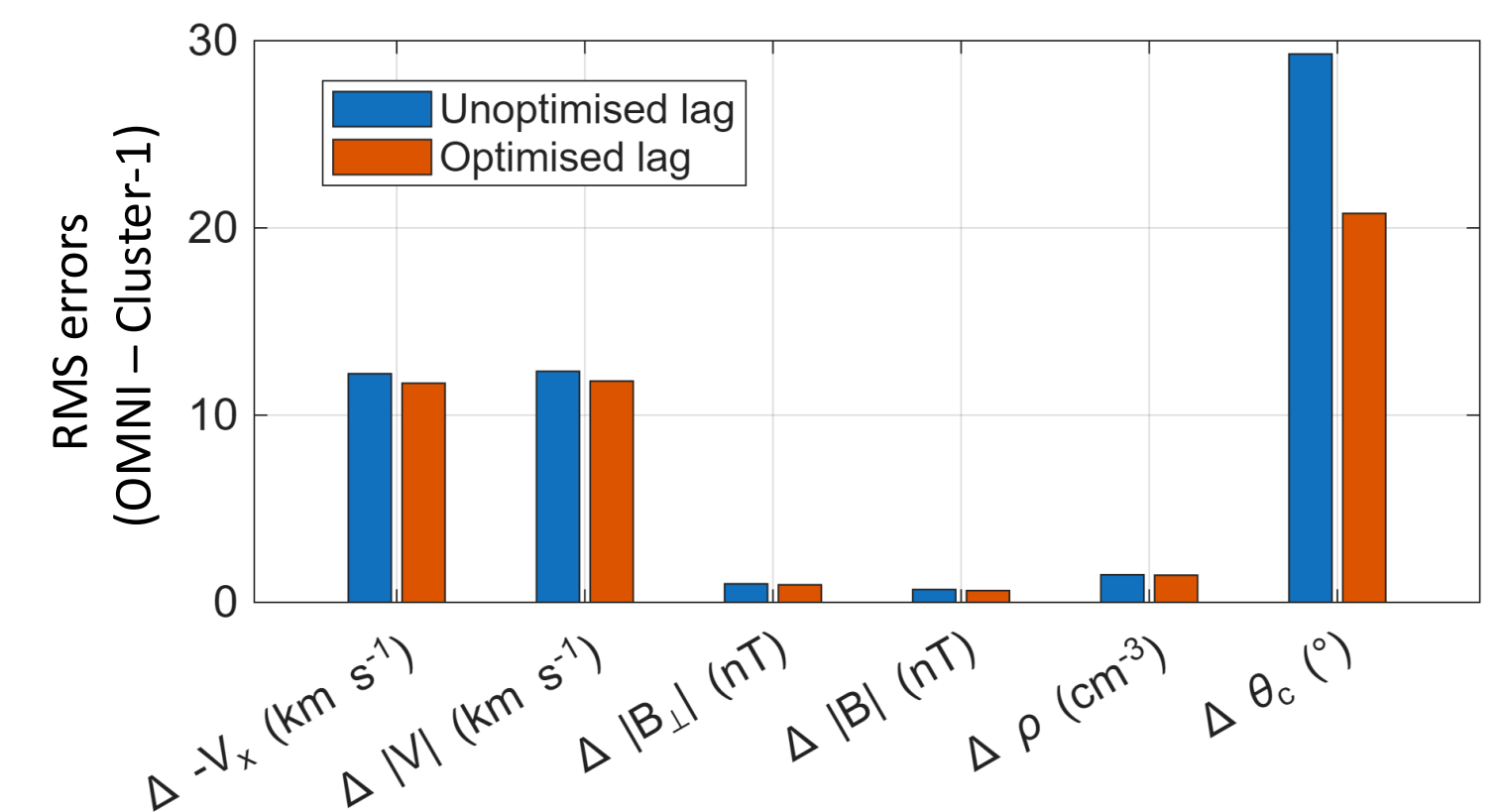
We evaluate the impact of uncertainty in the solar wind propagation time from the OMNI L₁ spacecraft to the BS nose. The optimal time lag is found by cross correlation of the IMF clock angle, θ_c , since this property of the solar wind has the shortest autocorrelation time (as shown below).



Below is a histogram of the distribution of time lags required to correct the OMNI data and give maximum cross-correlation (and minimum RMS error) with the Cluster-1 measurements of clock angle:



Applying these "optimised" time lags produces only small reductions in the root-mean-square (RMS) differences between OMNI and Cluster-1 measurements, except in the clock angle error distribution.



Summary

- OMNI estimates of solar wind conditions near the bow shock nose agree well with Cluster measurements, provided:
 - Cluster data within $3 R_E$ of the bow shock are excluded (due to ion foreshock contamination).
 - Relative biases between Cluster and OMNI (ACE or Wind) instruments are corrected pairwise by calibration.
 - The OMNI spacecraft is not far distant from the Earth-Sun line (for IMF clock angle distributions).
- Error (OMNI - Cluster-1) standard deviations are:
 - $\sigma(V_x) = \sigma(|V|) = 14 \text{ km s}^{-1}$, $\sigma(B_{\perp}) = 1.2 \text{ nT}$, $\sigma(|B|) = 0.7 \text{ nT}$, $\sigma(\rho) = 1.5 \text{ cm}^{-3}$, and $\sigma(\theta_c) = 41^\circ$.
- OMNI estimates of propagation delay (L₁ → BS nose) are correct to within ± 6 mins (RMS) (based on optimal cross-correlation of IMF clock angles, θ_c).
 - Correcting these delay errors yields only a slight reduction in RMS errors in SW parameters other than θ_c .
- The Normal distribution is a poor fit to the empirical error distributions but the Generalised Hyperbolic (GH) distribution^[4] is an excellent fit even in the tails of the distributions.
- When Cluster is in the quasi-parallel ion foreshock region we observe an average 10 km s^{-1} ion velocity reduction, and 0.3 nT increase in magnetic field strength.

References

- [1] Papitashvili, N. E., & King, J. H. (2020), OMNI 1-min Data [Data set], NASA Space Physics Data Facility, <https://doi.org/10.48322/45bb-8792>; Accessed on 14 May 2024.
- [2] Laakso, H., et al. (Eds.) (2010), Cluster Active Archive: Overview, 3-37, The Cluster Active Archive, *Astrophysics and Space Science Proceedings*, Springer. https://doi.org/10.1007/978-90-481-3499-1_1.
- [3] Lockwood, M., & McWilliams, K. A. (2021b). On optimum solar wind – Magnetosphere coupling functions for transpolar voltage and planetary geomagnetic activity. *Journal of Geophysical Research: Space Physics*, 126, e2021JA029946. <https://doi.org/10.1029/2021JA029946>
- [4] Barndorff-Nielsen, O. (1978). Hyperbolic Distributions and Distributions on Hyperbolae. *Scandinavian Journal of Statistics*, 5(3), 151–57. <http://www.jstor.org/stable/4615705>

Acknowledgements

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