Direct Measurement of the Solar-wind Taylor Microscale Using MMS Turbulence Campaign Data

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Abstract

Using the novel Magnetospheric Multiscale (MMS) mission data accumulated during the 2019 MMS Solar Wind Turbulence Campaign, we calculate the Taylor microscale ($\lambda_T$) of the turbulent magnetic field in the solar wind. The Taylor microscale represents the onset of dissipative processes in classical turbulence theory. However, an accurate estimation of the Taylor scale from spacecraft data is usually difficult due to low time cadence, the effect of time decorrelation, and other factors. Previous reports were based either entirely on the Taylor frozen-in approximation, which conflates time dependence, or were obtained using multiple data sets, which introduces sample-to-sample variation of plasma parameters, or had interspacecraft distances that were larger than the present study. The unique configuration of linear formation with logarithmic spacing of the four MMS spacecraft, during the campaign, enables a direct evaluation of the $\lambda_T$ from a single data set, independent of the Taylor frozen-in approximation. A value of $\lambda_T \approx 7000$ km is obtained, which is about three times larger than the previous estimates.

Unified Astronomy Thesaurus concepts: Interplanetary turbulence (830); Solar wind (1534); Space plasmas (1544); Magnetohydrodynamics (1964); Plasma astrophysics (1261)

1. Introduction: Turbulence Scales

Turbulence is a multiscale phenomenon. The turbulent solar wind possesses structures and processes with a broad range of length scales (Verscharen et al. 2019). The different characteristic length scales affect the dynamics in various ways. For example, the correlation scale represents the sizes of the most energetic eddies (Smith et al. 2001). The mean-free path between collisions determine the collisionality of the plasma. Proton kinetic physics dominates near the proton inertial length and gyroradius (Leamon et al. 1998); similarly, electron physics becomes important at the electron inertial length and gyroradius (Alexandrova et al. 2012). These different characteristic scales can provide useful information regarding the propagation of energetic particles, such as cosmic rays in the solar wind (Jokipii 1973).

Of these various scales, there are several related directly to fundamental turbulence properties, and understanding these in various space and astrophysical venues contributes to understanding physical effects ranging from reconnection to particle heating and scattering. For an initial orientation, we can use analogies with hydrodynamics to outline relationships that exist among these scales in classical turbulence. Accordingly, we use as a reference point the case in which the dissipation is controlled by a simple scalar kinematic viscosity $\nu$. We may begin with the scale at which the bulk of turbulence energy resides, or is injected; we call this the energy-containing scale $\lambda_c$. For a turbulence amplitude $Z$, with units of speed, one finds immediately a nonlinear timescale, or the eddy turnover time $\tau_{nl} = \lambda_c/Z$. Smaller-scale structures will have faster timescales that depend on their characteristics speeds. Using Kolmogorov’s famous similarity hypothesis as a guide (Kolmogorov 1941), we may estimate the speed of structures at smaller scales $\ell$ to be $Z_t \sim \epsilon^{1/3}/\ell^{1/3} = \tau_{nl}(\ell/L)^{1/3}$, where we also use the de Kármán & Howarth (1938) estimate of the decay rate $\epsilon \sim Z^3/\lambda_c$. Probing at still smaller scales, very much smaller than $\lambda_c$, eventually dissipative processes of viscous origin become important. As a first approximation one may estimate the timescale for the dissipation of a structure (e.g., a vortex) at scale $\ell$ to be $\tau_{diss} = \ell^2/\nu$, using standard viscous dissipation as a model. A reasonable way to estimate the characteristic scale at which dissipation becomes dominant is to ask when the eddy or structure at scale $\ell$ become critically damped. This occurs when the intrinsic nonlinear time balances the local-in-scale dissipative time. For this, we solve $\tau_{diss}(\eta) = \tau_{diss}(\eta)$, finding $\eta = \lambda_c(\nu/Z\lambda_c)^{3/4} = \lambda_c\Re^{-3/4}$. The scale $\eta$ is often called the Kolmogorov dissipation scale, and we recognize standard definition of the large-scale Reynolds number $Re \equiv Z\lambda_c/\nu$. Note that if the critically damped scale is known or estimated, as it might be in a plasma identified with an ion-inertial scale, for example, then the effective Reynolds number may be defined as $Re = (\lambda_c/\eta)^{3/2}$, or $Re = (\lambda_c/d)^{3/2}$ if dissipation is presumed to become
dominant over nonlinear effects at scales comparable to the ion-inertial length $d_i$.

Yet another scale, generally intermediate to $\lambda_\parallel$ and $\eta$, may be defined by equating the large-scale eddy turnover time to the scale-dependent dissipative time. Thus, $\tau_{nl} = \tau_{diss}(\ell)$ is solved by a particular value $\ell = \lambda_T$. This length scale is the Taylor microscale, the subject of the present paper. The first of its several equivalent definitions highlights a particular physical property, namely that it is critically damped at large-scale nonlinear time. Before turning to its evaluation in the Magnetospheric Multiscale (MMS) Turbulence Campaign, we introduce and discuss several additional properties of the Taylor scale $\lambda_T$.

### 2. Taylor Microscale

Like the majority of concepts in plasma turbulence, the Taylor scale is also borrowed from hydrodynamic turbulence research. The Taylor scale can be viewed as the measure of the curvature of the autocorrelation function $(R(r) = \langle F(x) \cdot F(x + r) \rangle)$ at the origin; for isotropy,

$$\lambda_T^2 = \frac{R(0)}{R''(0)},$$  \hspace{1cm} (1)

where $F$ is the fluctuating field of interest, e.g., the velocity field ($v$) in hydrodynamic turbulence, or magnetic field ($b$) in magnetohydrodynamic (MHD) and plasma turbulence. Here, we consider only the magnetic-field fluctuations. For small lags $r$, using $R(r) = R(-r)$, a requirement of statistical homogeneity, the autocorrelation function near the origin can be Taylor-expanded, assuming isotropy, as

$$R(r) = 1 - \frac{r^2}{2 \lambda_T^2} + \cdots.$$ \hspace{1cm} (2)

Another physically revealing way to view the Taylor microscale is obtained by noting that for viscous-like $\nu$ dissipation in an incompressible medium, the Taylor scale is also related to dissipation, in that

$$\frac{d \langle |b|^2 \rangle}{dt} = \nu \langle |\nabla \times b|^2 \rangle = \nu \langle |b|^2 \rangle \frac{\lambda_T^2}{\lambda_T^2}.$$ \hspace{1cm} (3)

In this sense, the Taylor scale is the “equivalent dissipation scale,” such that, at any instant of time, the dissipation rate is the same if all the energy were at the Taylor scale. This is the physical basis upon which Taylor (1935) first formulated the idea of this particular length scale. Some older turbulence texts (Hinze 1975) refer to the Taylor scale as “the dissipation scale,” although later Kolmogorov (Kolmogorov 1941) introduced the similarity variable ($\eta$), now known as the Kolmogorov length scale, to denote the scale at which eddies become critically damped. Notionally, the Taylor microscale represents the largest eddies in the dissipation range, or equivalently, the smallest eddies in the inertial range. The interpretation, of course, may not be so straightforward in plasma turbulence. However, one may draw some conclusions by comparing with hydrodynamics.

Keeping this parallel in mind, recall that space plasma observations show that the transition of Kolmogorov $-5/3$ spectra to a steeper slope occurs at somewhat larger scales than an ion-inertial scale or proton gyroradius (Leamon et al. 2000). In classical hydrodynamic turbulence, the Taylor scale is greater than the Kolmogorov length scale ($\eta$). Therefore, if one treats the ion-inertial length or the proton gyroradius as equivalent to the classical turbulence Kolmogorov scale, where dissipative (or kinetic) processes become dominant, the Taylor scale provides a natural descriptor of the slight steepening of spectra, and the onset of dissipation, prior to dissipation becoming dominant at still smaller scales. This also fits well with the idea, from reconnection studies, that intense kinetic activity in current sheets is initiated at some multiple of the ion scales (Shay et al. 1998).

### 3. Limitations

The computation of Taylor microscale is challenging in spacecraft data due to low temporal cadence, and other factors, as discussed in the following. The primary hindrance to accurate estimation of Taylor microscale, using spacecraft data, comes from the approximation due to Taylor’s frozen-in hypothesis (Taylor 1938). In situ spacecraft data are usually collected in the form of time signals at the spacecraft location. However, in the solar wind, the Alfvén speed is usually much smaller than the flow speed, so one may assume, to a good approximation, that the plasma is frozen-in to the flow (Jokipii 1973). Therefore, as the plasma convects past the spacecraft, the collected time-series data can be essentially interpreted as a one-dimensional “cut” through the three-dimensional plasma. This is the interplanetary spacecraft version of the Taylor’s frozen-in wind-tunnel approximation. Despite the widespread utility of this approach, it is apparent that, when available, the correct way to probe spatial structures is through simultaneous multipoint observations (Matthaeus et al. 2019). Moreover, the Taylor approximation is only well-justified for inertial-scale and somewhat larger fluctuations, as high-frequency kinetic activity at subproton scales might introduce substantial inaccuracy (Roberts et al. 2020).

However, the evaluation of $\lambda_T$ requires measurement of the curvature of the correlation function near the origin, precisely demanding such information regarding small spatial range fluctuations. But simultaneous multipoint data, especially at small separation, have generally not been available. Even when multipoint measurements have been obtained, those intervals are typically not very long (e.g., Roberts et al. 2015; Chasapis et al. 2017). For statistical studies of turbulence in the solar wind, continuous intervals of duration of at least a few hours, corresponding to at least a few spacecraft-frame correlation times, are desirable (Isaacs et al. 2015). Consequently, previous studies were forced to perform analyses compiled from a number of different intervals. At that point, additional uncertainty is introduced by variation of plasma conditions from interval-to-interval. The first MMS mini campaign, named the MMS Solar-Wind Turbulence Campaign, explicitly overcomes these limitations, as discussed in the next section. However, we note that the data studied are also limited in that there is one sampling direction, i.e., all spacecraft are in a line. Although four-point measurements provide many advantages, this and other related limitations are intrinsic to four-point measurements.

### 4. MMS Solar-wind Turbulence Campaign

The MMS mission was launched in 2015 with the primary goal of studying magnetic reconnection—a process responsible for releasing magnetic energy into flows and internal energy. The four MMS spacecraft are equipped with state-of-the-art
During 2019 February, the MMS apogee was raised to $\sim 27 R_E$ on Earth’s dayside of the magnetosphere and outside the ion foreshock region. This orbit allowed the spacecraft to sample the pristine solar wind, outside the Earth’s magnetosheath and far from the bow shock, for extended periods of time (see Figure 1).

During the first mini campaign, the four MMS spacecraft were arranged in a “string of pearls” or “beads-on-a-string” formation instead of the usual tetrahedral formation. With the spacecraft baseline almost perpendicular to the solar-wind flow, the spacecraft were separated by logarithmic distances ranging from 25 to 200 km, and the baseline separations remain unchanged within 10%. This configuration allows direct investigation of the scale-dependent nature of the solar-wind structures near proton scales. Laboratory experiments have utilized such formations (Cartagena-Sanchez et al. 2019), but these kinds of data are novel in observations. This work is the first of several studies undertaken to take advantage of this unique configuration (see also A. Chasapis et al. 2020, in preparation). Although not relevant for this study, the spacecraft spin-axes were tilted about 15° to obtain improved electric field measurements in the solar wind. A schematic configuration of the four MMS spacecraft in the solar wind, during the Turbulence Campaign, is provided in the top panel of Figure 1. The orbital context plot showing the MMS location relative to the nominal magnetopause (Shue et al. 1998) and bow shock (Farris & Russell 1994) is illustrated in the bottom panel of Figure 1.

5. MMS Data

During the three-week long mini campaign, a number of useful solar wind and foreshock intervals were selected. The longest of the selected pristine solar-wind intervals, a continuous interval of five hours of burst-mode data, on 2019 February 24, from 16:39:00 to 21:41:00 UTC, is analyzed in this paper. No signature of reflected ions from the bow shock is found. For this interval, we did not detect any high-frequency waves characteristic of the foreshock. We note, however, that the other 5 hr interval (2019 February 17, from 11:24:00 to 16:24:00 UTC) chosen as a part of the turbulence campaign, has foreshock signatures, and consequently that interval was not considered for this analysis.

To evaluate the magnetic-field Taylor microscale from spacecraft correlation data, we employ data from the Fluxgate Magnetometer (FGM) on board each of the four MMS spacecraft (Russell et al. 2016). The top panel of Figure 2 shows the three Cartesian components of the magnetic field in the GSE coordinate system (Franz & Harper 2002), recorded in this period by the FGM on board MMS1. It is apparent that this interval is rich in structures, including numerous current sheets, flux tubes, and broadband random fluctuations, which taken together represent a fairly typical sample of solar-wind turbulence (Bruno & Carbone 2005).

The Fast Plasma Investigation (FPI; Pollock et al. 2016) instrument measures proton and electron distribution functions and moments every 150 ms and 30 ms, respectively. Due to the limitations of the FPI instruments in the solar wind (Bandyopadhyay et al. 2018a), some systematic uncertainties remain in the moments, moreso in the higher-order moments. Therefore, we cross-check the proton moments in the selected interval with Wind (Lepping et al. 1995; Ogilvie et al. 1995) data, time-
shifted to the bow-shock nose. The MMS and Wind estimates of proton density, velocity ($V_{90}$GSE component), and temperature are shown in the bottom three panels in Figure 2. The density and velocity are in adequately close agreement, but significant discrepancies exist in the proton temperature values. The FPI estimates of temperature are significantly greater than the Wind values. Given the known limitations of FPI in the solar wind, we use the Wind measurements of temperature to evaluate proton beta and other relevant parameters. The average values of the plasma parameters are reported in Table 1.

Figure 3 shows the spacecraft-frame frequency spectrum of the magnetic field during this period. A clear Kolmogorov scaling ($\sim f^{-5/3}$) can be seen at scales smaller than the correlation length, $\lambda_c$ (inferred from the Taylor hypothesis). A break in spectral slope from $\sim f^{-5/3}$ to $\sim f^{-8/3}$ is observed near (inferred) kinetic scales ($d_i$ or $\rho_i$). Often, these scales are associated with the dissipation scale ($\lambda_{diss}$) in collisionless plasmas, equivalent to the Kolmogorov scale ($\eta$) in classical turbulence. Kinetic dissipative processes such as wave damping are effective on these small plasma kinetic scales. For example, Leamon et al. (2000) and Wang et al. (2018) argued that the ion-inertial scale controls the spectral break and onset of strong dissipation, while Bruno & Trenchi (2014) suggested the break frequency is associated with the resonance condition for a parallel propagating Alfvén wave. Another possibility is that the largest of the proton kinetic scales terminates the inertial range and controls the spectral break (Chen et al. 2014). The flattening near $f \gtrsim 1$ Hz is very likely noise-dominated, since, for example, this behavior is not seen in Cluster search coil observations (e.g., Alexandrova et al. 2009, 2012; Roberts et al. 2017).

### 6. Taylor Microscale: Results

To estimate the Taylor scale from this interval, we recall the approximation near the origin:

$$R(r) \approx 1 - \frac{r^2}{2 \lambda_T^2},$$

where the higher-order terms are neglected. Therefore, one may obtain the Taylor microscale by fitting the autocorrelation function $R(r)$ to a parabolic curve at the origin. Clearly, the quadratic approximation holds better as one asymptotically approaches smaller values of $r$. Previous multi-spacecraft estimates (Matthaeus et al. 2005) were evaluated with the Cluster spacecraft, with separations in the range 150 km $\leq r \leq 270$ km. Here, we extend that analysis by approaching the origin closer by about an order of magnitude, with 25 km $\leq r \leq 200$ km. The Appendix provides an estimate of the accuracy of the correlation measurements. As shown in Figure 4, we extract an estimate of $\lambda_T$ by fitting the six available two-point correlation functions to a parabolic curve. The resulting value of the Taylor scale is $\lambda_T = 6933$ km. For comparison, we also show the single-spacecraft, frozen-in-hypothesis based evaluation of the correlation function. Evidently, the single-spacecraft estimate decays much more rapidly to the origin, presumably due to time decorrelation of the

| Parameters for MMS Interval on 2019 February 24, from 16:00 to 21:00 UTC (5 hr) |
|--------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Solar-wind speed              | $V_{SW} = 322$ km s$^{-1}$      |                                 |                                 |
| Correlation length            | $\lambda_c = 3.2 \times 10^5$ km |                                 |                                 |
| Ion inertial length           | $d_i = 91$ km                  |                                 |                                 |
| Ion gyroradius                | $\rho_i = 64^\circ$ (150) km   |                                 |                                 |
| Electron inertial length      | $d_e = 2.3$ km                 |                                 |                                 |
| Debye length                  | $\lambda_D = 10$ m             |                                 |                                 |
| Proton beta                   | $\beta_p = 0.5$ (2.5)          |                                 |                                 |
| Magnetic field                | $B_0 = |\langle B \rangle| = 3.4$ nT |                                 |                                 |
| Magnetic-field fluctuation    | $B_m/B_0 = 0.72$               |                                 |                                 |
| Proton density                | $(n_i) = 6.2$ cm$^{-3}$        |                                 |                                 |
| Proton temperature            | $(T_i) = 2.5^\circ$ (12.4) eV  |                                 |                                 |

Note. Quantities with an asterisk (*) have been estimated using Wind data, and their MMS estimates are given in parenthesis.

Figure 3. Spectral power density of a magnetic field measured by MMS1. Kolmogorov scaling $\sim f^{-5/3}$ is shown for reference. The vertical lines represent the correlation length ($k\lambda_c = 1$), the ion-inertial length ($kd_i = 1$), and the ion gyroradius ($k\rho_i = 1$), with wavenumber $k \approx (2\pi f)/(|V|c)$.

Figure 4. Magnetic-field correlation function based on the frozen-in approximation (green, solid line) and obtained from a two-spacecraft evaluation (red, cross symbols). An exponential fit (blue, dashed line) to the single-spacecraft measurement is used to obtain the correlation length. A quadratic fit (black, thin line) to the multi-spacecraft points estimates the Taylor scale. The inset plots part of the correlation function enlarged near the origin to clearly show the multi-spacecraft points and the parabolic fit.
solar-wind fluctuations in those scales (Matthaeus et al. 2010). At large lags, however, the frozen-in based correlation function exhibits approximately exponential decay and provides a satisfactory estimate of the correlation length, about 320,000 km, consistent with previous reports (Isaacs et al. 2015). Note that the exponential passes close to the multispacecraft points (see the inset) near the origin; however, the exponential cannot be employed to determined \( \lambda_T \) since the curvature at the origin is undefined.

**Solar-wind viscosity**—an accurate estimation of the Taylor scale also permits an evaluation of an effective viscosity (or, turbulent viscosity/resistivity) of the solar wind, according to the expression

\[
\nu = \frac{\epsilon}{2E} \lambda_T^2, \tag{5}
\]

where \( \epsilon \) is the cascade rate \( \approx 1000 \text{ J kg}^{-1} \text{ s}^{-1} \) and \( E \) is the fluctuation energy per unit mass. The cascade rate can be obtained, for example, from the third-order law or other estimates; see, e.g., Verma et al. (1995), Sorriso-Valvo et al. (2007), MacBride et al. (2008), and Bandyopadhyay et al. (2018b). Putting in the rest of the values: \( \lambda_T = 6933 \text{ km} \) and \( 2E = \langle |b|^2 \rangle = 324 \text{ km}^2 \text{ s}^{-2} \), we obtain \( \nu \approx 150 \text{ km}^2 \text{ s}^{-1} \). This value is considerably larger than that obtained using Braginskii’s (1965) formalism, which is based on simple particle–particle collision (Montgomery 1983). Our result also improves earlier indirect estimates, based on turbulence-cascade phenomenology (Coleman 1968; Verma 1996).

**7. Discussion and Conclusions**

In this paper, MMS data accumulated during the turbulence campaign have been used to evaluate the Taylor microscale of magnetic-field fluctuations using a multi-spacecraft technique, and taking advantage of a unique beads-on-a-string flight formation. The previous estimate by Matthaeus et al. (2005), using Cluster data, is \( \lambda_T = 2478 \text{ km} \), which is about three times smaller than the present evaluation. The deviation is possibly due to the relatively larger spacecraft separation used in the Cluster data set, comparatively shorter intervals, and mixing of different solar-wind intervals. It is also possible that this level of variability is intrinsic to the solar wind for a variety of reasons including 1/f noise, stream structure (Matthaeus & Goldstein 1986). Another possibility is that the differences may be attributable to the differences in the formation of the Cluster and MMS spacecraft. The Cluster spacecraft pair baselines are in a tetrahedron, introducing anisotropy effects, which are not present in the MMS linear formation analyzed here. These limitations are inherent to four-point measurements, and can be overcome by large constellations of simultaneous, in situ measurements (Klein et al. 2019; Matthaeus et al. 2019; TenBarge et al. 2019).

We note here that the two-spacecraft data points cover a very small range, in contrast with the frozen-in based correlation function (compare the inset in Figure 4 to the main plot). However, we do not expect any weakness in the analysis due to this point. The estimation of correlation length by an exponential approximation is only valid at long lag, while the quadratic approximation to the expansion of the correlation function is expected to hold only near the origin. Therefore, the small coverage of scale is not expected to hinder the Taylor-scale estimation.

We find that the break frequency, in the magnetic-field spectrum, is situated between the Taylor scale \( (\lambda_T) \) and dissipative scales \( (d_i, \rho_i) \). Wang et al. (2018) showed that for \( \beta \approx 1 \) plasma, the spectral break frequency is better associated with \( d_i \) than \( \rho_i \) and it is insensitive to \( \beta \) values. In general, \( \lambda_T/\lambda_{\text{dis}} > 1 \) in hydrodynamic turbulence, and the separation increases with Reynolds number. Although the dissipation mechanism in the collisionless solar wind is not due to a viscous closure, we note here that if one associates the ion-inertial length \( d_i \) or ion gyroradius \( \rho_i \) with the dissipation scale, then we find that \( \lambda_T/\lambda_{\text{dis}} \approx 70 \). The relationship of the Taylor scale to ion kinetic scales in the solar wind however, appears to be much more variable than it is in hydrodynamics, and in particular the relationship has been found to depend on the turbulence-cascade rate (Matthaeus et al. 2008).

The present paper is the latest step in a broad progression of interplanetary measurements of fundamental plasma turbulence properties. The 1980 NASA Plasma Turbulence Explorer Panel emphasized the need for simultaneous multipoint measurements, in particular, plasma and magnetic-field measurements, to make progress in this area (Montgomery et al. 1980). More recently, the space plasma community has witnessed growing interest in understanding the multiscale nature of turbulence processes in space, using multipoint measurements in observations (Klein et al. 2019; Matthaeus et al. 2019), as well as laboratory experiments (Schaffner et al. 2014; Schaffner & Brown 2015), especially with regard to the physics of dissipation and heating mechanisms. The MMS turbulence campaign provides the first opportunity to capture multiscale processes near the proton scales with a single data interval. Therefore, the results presented in this paper will be useful for future and proposed multi-spacecraft missions (Vaivads et al. 2016; Bookbinder et al. 2018; Plice et al. 2019; Verscharen & Wicks 2019; Wicks & Verscharen 2019).

The 2019 Solar Wind turbulence campaign is the first of the many MMS mini-campaigns that are planned to be held in the second extended mission phase. The results presented in this paper will serve as a demonstration of the MMS instrumental capabilities, working outside their original region of interest. Exploring the potential advantages of different MMS formations will allow better understanding of MMS range of capabilities, which will open the door to other scientific campaigns.

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Appendix
Measure of Confidence in the Two-spacecraft Analyses

As can be seen in Figure 4, the signals between spacecraft are strongly correlated; however, the differences are very small between them. The very small variation in the two-spacecraft correlations, between 1 and 0.9995, calls for further analyses of its accuracy. Here, we provide an error estimate to check the quality of the measurements.

Recall the definition of correlation function for magnetic-field fluctuations \( \mathbf{b} \),

\[
R(r) = \langle \mathbf{b}(x) \cdot \mathbf{b}(x + r) \rangle. 
\]

(A1)

Keeping in mind that the uncertainties in FGM magnetic-field measurements are less than \( \delta b = 0.1 \) nT (Russell et al. 2016), and that the average magnetic field is about \( b \sim 2 \) nT, the fractional error in the individual sample points of the correlation function, \( \langle \mathbf{b}(x) \cdot \mathbf{b}(x + r) \rangle \), is less than \( 2 \delta b / b \sim 0.1 \). Furthermore, averaging over all the data points reduces the statistical error by \( \sim 1 / \sqrt{n} \), where \( n \) is the number of data points (the error in the mean estimate would be even smaller by another factor of \( 1 / \sqrt{n} \)). So we estimate the error in the two-spacecraft \( R(r) \) as \( \delta R / R \sim 10^{-7} \). Therefore, even by a very conservative estimate, the two-spacecraft values are reliable up to six decimal points. Finally, the rms of two-spacecraft magnetic-field increments, for the smallest separations, is about \( 0.1 \) nT, the error in the mean estimate would be even smaller by another factor of \( 1 / \sqrt{n} \).

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