Database of Heliospheric Shock Waves

Method documentation

E. Lumme, E. K. J. Kilpua, A. Isavnin, K. Andreeova

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Contents

1 Data for the analysis

1.1 Download and processing of the data

All data were downloaded from Coordinated Data Analysis Web (CDAWeb) [1]. The downloaded parameters are shown in Table 1.

Minor processing of the data included: filtering of the worst spurious spikes from the plasma data, and centering of the time tags to the center of actual measurement interval if not already done (we did the latter only to data of ACE and STEREO spacecraft).

More information about the resolution of the parameters, the used coordinate systems and other spacecraft-related features can be found in Appendix A.

Parameter(s)	**Symbol(s)**
Interplanetary magnetic field vector and magnitude	$\mathbf{B}$, B
Solar wind velocity and bulk speed of protons/ions	$\mathbf{V}$, V
Solar wind proton/ion number density	N_p
Solar wind proton/ion temperature or the most probable thermal speed	T_p or V_{th}
Spacecraft position	$\mathbf{X}_{SC}$

Table 1: Downloaded parameters

1.2 Data gaps

The number of data points required for determining the shock upstream and downstream conditions is specified in Section 2. If significant data gaps occurred the event was excluded from the analysis.

An exception was made with the solar wind velocity component data (STEREO A and B). When only the bulk speed data were available we made an assumption of radial solar wind. STEREO B lacked the solar wind velocity component data for about half of the events after 2007. In addition, during the solar conjunction both STEREO spacecraft experienced a partial loss of the velocity components data (and also other data). For STEREO A the velocity components data is unavailable from August 2014 to January 2016 after which it is expected to be recovered. STEREO B data is not available after September 2014 due to the loss of contact with the spacecraft (for more information see `http://stereo-ssc.nascom.nasa.gov/solar_conjunction_science.shtml`).

1.3 Resampling of different datasets

Some of the parameters in the database are functions of both the magnetic field and plasma variables (N_p, T_p). These include: Alfvén speed (v_A), sound speed (c_s), magnetosonic speed (v_{ms}) and plasma beta (β). When calculating these parameters magnetic field and plasma data were resampled to the same resolution (if not already done for the downloaded data). When necessary, resampling was achieved by averaging magnetic field data to the resolution of the plasma data.

The used resolutions are detailed in Appendix A.1.

2 Identifying the shocks

2.1 Shock candidates

We employ two techniques for finding the shock candidates: (1) visual inspection and (2) an automated shock detection algorithm. Visual inspection has been used for finding most of the shock candidates in the database, but in 2016 we made a permanent transition to use the shock detection algorithm for finding the candidates for the upcoming updates. Further details can be found below and in Appendix A.1.

2.1.1 Visual inspection

In visual inspection daily plots of solar wind plasma and magnetic field parameters were surveyed to identify the shock candidates. The surveyed parameters are given in Table 1. We looked for simultaneous, sudden jumps in the plasma and magnetic field parameters. These jumps had to be significant enough and fulfil the characteristics of either fast forward (FF) or fast reverse shock (FR).

2.1.2 Automated shock detection algorithm

In case of the automated shock detection algorithm we used a novel machine-learning algorithm IPSVM (InterPlanetary Support Vector Machine) [2]. The algorithm was trained using all the shocks in the database with spacecraft detection time before October 2015 for the following spacecraft: ACE, Wind, STEREO A and B, Helios A and B, Ulysses. After training the algorithm it was then used to search the shock candidates for Voyager 1 and 2, and DSCOVR spacecraft. The shocks detected by Wind spacecraft since October 2015 were also found with the aid of IPSVM.

2.2 Determining the shock type

2.2.1 Analysis intervals

The upstream and downstream plasma states were determined over a fixed analysis interval (eight minutes, see Table 2). The number of data points within the analysis intervals varies with the data resolution and due to possible data gaps. For Helios, Ulysses and Voyager the resolution of the plasma data was occasionally low. In such cases the default length of the analysis interval was extended (up to 30 – 36 minutes depending on the spacecraft) until enough data points (at least three) were included in both upstream and downstream intervals.

For a parameter P the upstream and downstream values are $P_{up/down} = \left\langle P \right\rangle_{up/down}$, where subscripts "up" and "down" correspond to mean over the data points of respective analysis interval.

Upstream and downstream values of the parameters are determined in the spacecraft reference frame. In the case of FF shock the spacecraft measures first the upstream region of the shock and in the case of FR shock the downstream region is detected first. Consequently, the upstream and downstream analysis intervals ($\Delta t_{up/down}$) depend on the shock type (see Table 2).

Shock type	Analysis intervals (default) (Δt)	
	Upstream (Δt_{up})	Downstream (Δt_{down})
FF	$[t_{shock} - 9\text{ min}\ ,\ t_{shock} - 1\text{ min}]$	$[t_{shock} + 2\text{ min}\ ,\ t_{shock} + 10\text{ min}]$
FR	$[t_{shock} + 1\text{ min}\ ,\ t_{shock} + 9\text{ min}]$	$[t_{shock} - 10\text{ min}\ ,\ t_{shock} - 2\text{ min}]$

Table 2: Default analysis intervals of FF and FR shocks. For Ulysses and Helios the outer bounds were extended depending on the resolution of the plasma data.

The upstream and downstream intervals were chosen so that the mean values are taken sufficiently far from the shock ramp. The 1-minute and 2-minute time intervals are excluded from the vicinity of the shock upstream and downstream, respectively.

2.2.2 Shock criteria

In order to be included in the database the following upstream to downstream jump conditions had to be fulfilled:

$$\frac{B_{down}}{B_{up}} \geq 1.2 \tag{1}$$

$$\frac{N_p^{down}}{N_p^{up}} \geq 1.2 \tag{2}$$

$$\frac{T_p^{down}}{T_p^{up}} \geq \frac{1}{1.2} \tag{3}$$

Additionally, the solar wind speed jump had to fulfil a condition which depends on the shock type:

$$\begin{array}{cc} \textbf{FF} & \textbf{FR} \\ V_{down} - V_{up} \geq 20 \text{ km/s} & V_{up} - V_{down} \geq 20 \text{ km/s} \end{array} \tag{4}$$

The condition differs for FF and FR type shocks due to opposite order of the upstream and downstream regions when the shock passes the observing spacecraft.

Note about temperature

The condition of the temperature jump (Eq. 3) is less rigorous due to larger error of the temperature measurements. Only if the change in the temperature is clearly opposite to the behaviour of the other parameters the event is excluded from the analysis.

3 Output of the analysis

3.1 Output parameters in the database

Parameter(s)	**Database symbol(s)**	**Unit(s)**
Date and time		e.g. 11.12.2013 11:22:23
Spacecraft	SC	
Spacecraft position	SC coordinates	Appendix A.2
Coordinate system of the position	SC cs	
Shock type	Type	FF/FR
Asymptotic values	$\mathbf{B}^{up/down}$ $\mathbf{V}^{up/down}$ $N_p^{up/down}$ $T_p^{up/down}$	[nT] [km/s] [cm^{-3}] [10^4 K]
Downstream-to-upstream ratios	$\frac{B^{down}}{B^{up}}$, $\frac{N_p^{down}}{N_p^{up}}$, $\frac{T_p^{down}}{T_p^{up}}$	
Solar wind speed jump	$\lvert\Delta V\rvert$	[km/s]
Upstream sound speed	C_s^{up}	[km/s]
Upstream Alfvén speed	V_A^{up}	[km/s]
Upstream magnetosonic speed	V_{ms}^{up}	[km/s]
Upstream plasma beta	β^{up}	
Shock normal	Normal	
Coordinate system of the normal	Normal cs	
Shock theta	θ_{Bn}	[deg.]
Shock speed	V_{sh}	[km/s]
Alfvén Mach number	M_A	
Magnetosonic Mach number	M_{ms}	
Radial solar wind	Radial V_{SW}	"yes"/"no"
Length of the analysis interval	Δt_{a}	[min]
Mean resolution of the magnetic field data	Δt_{mag}	[sec]
Mean resolution of the plasma data	Δt_{pla}	[sec]

Table 3: Output parameters in the database. Error estimate is provided for parameters written in bold (see section 3.3)

3.2 Specification of the output parameters

Remarks

- For a parameter P, $P_{up/down}$ corresponds to upstream and downstream mean values defined in the Section 2.2.1.
- The definitions of sound speed (c_s), Alfvén speed (v_A), magnetosonic speed (v_{ms}) and plasma beta (β) are based on certain assumption listed in Appendix B.
- When forming time series for (c_s), (v_A), (v_{ms}) and (β) the magnetic field data is resampled to the resolution of the plasma data (see Section 1.3).

- Use of a fixed electron temperature (T_e) may introduce errors to related parameters (C_s^{up}, V_{ms}^{up}, β^{up}, M_{ms}). See Appendix B.
- Inaccuracies in the determination of the shock normal ($\hat{\mathbf{n}}$) may introduce errors to related parameters (M_A, M_{ms}, V_{sh}, θ_{Bn}). See 3.2.11.

3.2.1 Spacecraft position

The data point closest to the time of the shock is chosen as the position of the spacecraft.

3.2.2 Coordinate system of the position

Appendix A.2

3.2.3 Shock type

Section 2

3.2.4 Asymptotic values

Asymptotic values are the mean values calculated over the upstream and downstream regions for: magnetic field magnitude (B) and vector components ($\mathbf{B}$), solar wind bulk speed (V) and velocity components ($\mathbf{V}$), proton/ion number density (N_p) and temperature of solar wind protons/ions (T_p).

3.2.5 Downstream-to-upstream ratios

The ratios of the magnitudes of asymptotic values: $\frac{B^{down}}{B^{up}}$, $\frac{N_p^{down}}{N_p^{up}}$ and $\frac{T_p^{down}}{T_p^{up}}$

3.2.6 Solar wind (bulk) speed jump

$$|\Delta V| = |V_{down} - V_{up}| \tag{5}$$

3.2.7 Upstream sound speed

$$C_s^{up} = \langle c_s \rangle_{up} = \left\langle \sqrt{\gamma k_B \frac{T_p + T_e}{m_p}} \right\rangle_{up} \tag{6}$$

3.2.8 Upstream Alfvén speed

$$V_A^{up} = \langle v_A \rangle_{up} = \left\langle \frac{B}{\sqrt{\mu_0 N_p m_p}} \right\rangle_{up} \tag{7}$$

3.2.9 Upstream magnetosonic speed

$$V_{ms}^{up} \;=\; \left\langle v_{ms} \right\rangle_{up} = \left\langle \sqrt{v_A^2 + c_s^2} \right\rangle_{up} \tag{8}$$

where (v_A) is the Alfvén speed and (c_s) is the sound speed defined as above.

3.2.10 Upstream plasma beta

$$\beta^{up} \;=\; \left\langle \beta \right\rangle_{up} = \left\langle \frac{2\mu_0 k_B N_p (T_p + T_e)}{B^2} \right\rangle_{up} \tag{9}$$

3.2.11 Shock normal

The normal vector of the shock ($\hat{\mathbf{n}}$) is calculated using the mixed mode method (”MD3” method in [3]):

$$\hat{\mathbf{n}} = \pm \frac{(\mathbf{B}_{down} - \mathbf{B}_{up}) \times ((\mathbf{B}_{down} - \mathbf{B}_{up}) \times (\mathbf{V}_{down} - \mathbf{V}_{up}))}{|(\mathbf{B}_{down} - \mathbf{B}_{up}) \times ((\mathbf{B}_{down} - \mathbf{B}_{up}) \times (\mathbf{V}_{down} - \mathbf{V}_{up}))|} \tag{10}$$

In the case of a data gap in the velocity components the normal is calculated using the magnetic field coplanarity [4]:

$$\hat{\mathbf{n}}_{\mathbf{MC}} = \pm \frac{(\mathbf{B}_{down} - \mathbf{B}_{up}) \times (\mathbf{B}_{down} \times \mathbf{B}_{up})}{|(\mathbf{B}_{down} - \mathbf{B}_{up}) \times (\mathbf{B}_{down} \times \mathbf{B}_{up})|} \tag{11}$$

The sign of the normal vector is determined using conditions of the solar wind velocity:

$$\begin{cases} \mathbf{V}_{up} \cdot \hat{\mathbf{n}} \geq 0, & \text{FF-type shocks} \\ \mathbf{V}_{up} \cdot \hat{\mathbf{n}} \leq 0, & \text{FR-type shocks} \end{cases} \tag{12}$$

Regardless of the used method there are always several caveats in the determination of the shock normal, and therefore its values may have significant errors (see e.g. [5]). Therefore the shock normal and related parameters (M_A, M_{ms}, V_{sh} and θ_{Bn}) should be considered with care.

Particular issue in our determination of the shock normal is the utilisation of fixed upstream and downstream intervals (Table 2). In order to get the correct results the shock layer has to be entirely excluded from these intervals. In addition, the intervals need to correspond to the actual upstream and downstream data points and leave out disturbances not related to the shock itself. They are also required to be long enough to average out the turbulence and wave activity. Consequently, the extent and location of the best upstream and downstream analysis intervals vary depending on the shock. The used fixed upstream and downstream intervals were chosen to meet the aforementioned conditions for as many shocks as possible. Nevertheless, the used intervals can not be ideal for all investigated events, which may result in large errors in the shock normals and related parameters.

3.2.12 Coordinate system of the normal

See appendix A.2.

3.2.13 Shock theta

The angle between the normal vector ($\hat{\mathbf{n}}$) and the magnetic field lines upstream:

$$\theta_{Bn} = \frac{180^\circ}{\pi} \arccos\left(\frac{|\mathbf{B}_{up} \cdot \hat{\mathbf{n}}|}{\|\mathbf{B}_{up}\|\|\hat{\mathbf{n}}\|}\right) \tag{13}$$

3.2.14 Shock speed

The shock speed in the spacecraft reference frame (see A.2) is calculated using the mass flux over the shock [5]:

$$V_{sh} = \left|\frac{[\rho_m \mathbf{V}]}{[\rho_m]} \cdot \hat{\mathbf{n}}\right| = \left|\frac{N_p^{down}\mathbf{V}_{down} - N_p^{up}\mathbf{V}_{up}}{N_p^{down} - N_p^{up}} \cdot \hat{\mathbf{n}}\right| \tag{14}$$

where $\hat{\mathbf{n}}$ is the shock normal.

3.2.15 Alfvén Mach number

In order to calculate M_A a Galilean coordinate transformation to the rest frame of the shock must be made (solar wind velocity transforms $\mathbf{V}_{up} \rightarrow \mathbf{V}'_{up}$). As a result [5]:

$$M_A = \frac{|\mathbf{V}'_{up} \cdot \hat{\mathbf{n}}|}{V_A^{up}} = \frac{|\mathbf{V}_{up} \cdot \hat{\mathbf{n}} \pm V_{sh}|}{V_A^{up}} \tag{15}$$

where ($\hat{\mathbf{n}}$) is the shock normal, (V_A^{up}) is the upstream Alfvén speed and (V_{sh}) is the shock speed. The ($-$) -sign corresponds to FF type of shock and ($+$) -sign to FR type.

It is assumed that both shock types propagate away from the Sun in the spacecraft reference frame (see appendix A.2).

3.2.16 Magnetosonic Mach number

Similarly to Alfvén Mach number (above):

$$M_{ms} = \frac{|\mathbf{V}'_{up} \cdot \hat{\mathbf{n}}|}{V_{ms}^{up}} = \frac{|\mathbf{V}_{up} \cdot \hat{\mathbf{n}} \pm V_{sh}|}{V_{ms}^{up}} \tag{16}$$

where (V_{ms}^{up}) is the upstream magnetosonic speed.

3.2.17 Radial solar wind

Parameter indicates whether the solar wind was assumed to be radial in the analysis. It is significant only for STEREO A and B (see section 1.2), for which the assumption was needed when solar wind velocity components data were missing, but the bulk speed data was available. In such case we assume:

$$\mathbf{V} = V\hat{\mathbf{e}}_{\mathbf{r}} \tag{17}$$

where V is the bulk speed and $\hat{\mathbf{e}}_{\mathbf{r}}$ is unit vector pointing radially away from the Sun.

3.2.18 Length of the analysis interval

The length of the analysis interval (upstream and downstream) in minutes. Analysis intervals are defined in section 2.2.1.

3.2.19 Mean resolution of the magnetic field data

Mean resolution of the magnetic field data over the analysis domain (between the outermost edges of the analysis intervals from the shock).

3.2.20 Mean resolution of the plasma data

Mean resolution of the magnetic field data over the analysis domain (between the outermost edges of the analysis intervals from the shock).

3.3 Error estimates

Error estimate is provided for parameters written in bold font in Table 3. Estimates are based on the sample standard deviations of the mean values calculated over the upstream and downstream intervals (parameters specified in 3.2.4 and 3.2.7 - 3.2.10). For these mean values the presented error is the sample standard deviation with the possible addition of the error resulting from our electron temperature estimate (see Appendix B). These errors are then propagated to get the error estimate for the rest of the output parameters.

NOTE: Due to simplicity of the error propagation, the error estimates may have unrealistically high values in cases where the data has particularly large fluctuations in the analysis intervals. In such cases one should be extra cautious when interpreting the results of our analysis.

References

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A Spacecraft specification

A.1 Data sources

Spacecraft	Parameter(s)	Instrument	Resolution
ACE	B, $\mathbf{B}$	MAG	16 s
	N_p, V, $\mathbf{V}$, T_p	SWEPAM	64 s
	$\mathbf{X_{SC}}$		16 s (or 64 s)*
Wind[1]	B, $\mathbf{B}$	MFI	3 s
	N_p, V**, $\mathbf{V}$**, T_p***	SWE	$\sim$ 90 s
	$\mathbf{X_{SC}}$		60 s (/$\sim$ 90 s/10 min)*
STEREO	B, $\mathbf{B}$	IMPACT/MAG	0.125 s
	N_p, V, $\mathbf{V}$, T_p	PLASTIC	60 s
	$\mathbf{X_{SC}}$		60 min
Ulysses	B, $\mathbf{B}$	VHM	1 s
	N_p, V, $\mathbf{V}$, T_p	SWOOPS	4-8 min
	$\mathbf{X_{SC}}$		60 min
Helios	B, $\mathbf{B}$	E3 (E2)****	6 s ($\geq$ 40.5 s)
	N_p, V, $\mathbf{V}$, T_p	E1	$\geq$ 40.5 s
	$\mathbf{X_{SC}}$		$\geq$ 40.5 s
Cluster 1 and 3	B, $\mathbf{B}$	FGM	4 s
	N_p, V, $\mathbf{V}$, T_p	CIS/HIA	4 s
	$\mathbf{X_{SC}}$		4 s
Cluster 4	B, $\mathbf{B}$	FGM	4 s
	N_p, V, $\mathbf{V}$, T_p	CIS/CODIF	4 s
	$\mathbf{X_{SC}}$		4 s
DSCOVR[2]	B, $\mathbf{B}$	PlasMag	1 s
	N_p, V, $\mathbf{V}$, T_p	PlasMag	60 s
	$\mathbf{X_{SC}}$		60 s
Voyager[2]	B, $\mathbf{B}$	MAG	1.92 s*****
	N_p, V, $\mathbf{V}$, T_p	PLS	12 – 192 s
	$\mathbf{X_{SC}}$		48 s

[1] Shock candidates for Wind data with detection time before October 2015 were searched using visual inspection of the data. Shocks detected after this were searched with the aid of our automated shock detection algorithm (see Section 2.1 for details).

[2] Shock candidates for Voyager and DSCOVR spacecraft were searched using our automated shock detection algorithm (see Section 2.1 for details).

*Position data $\mathbf{X_{SC}}$ was downloaded from the source with best resolution. In the case of ACE and Wind there were multiple sources with different resolutions, and in the case of Wind, there were also data of predicted orbit available. If one source had a data gap, other sources were used if possible.

**In the case of Wind solar wind velocity $\mathbf{V}$ and bulk speed V were determined as ion velocity and ion bulk speed.

***In the case of Wind temperature data was not available as such but T_p was determined using the most probable thermal speed of solar wind V_{th}, from which:

$T_p = \frac{m_p V_{th}^2}{2k_B}$ (this result is based on the assumptions in appendix B).
****Magnetic field data of Helios spacecraft was collected preferably from the instrument with best resolution (”E3”). When this data was unavailable, secondary instrument (”E2”) was utilised.
*****Voyager magnetic field data has frequent data gaps that reduce the resolution.

Notes about Cluster events

For Cluster we included only the shocks detected when the spacecraft was in the solar wind and the plasma experiment CIS was in solar wind mode. CIS experiment has two instruments HIA and CODIF of which HIA is best suited to solar wind measurements [6]. For most of the shocks detected between 2001-2011 Cluster 1 and 3 had sufficient HIA data for the analysis. Cluster 4 was used as a backup when both Cluster 1 and 3 had a data gap, and as primary spacecraft after 2011, when CIS in Cluster 3 had been shut down and functionality of CIS in Cluster 1 became restricted. Since CIS/HIA instrument of Cluster 4 is switched off, plasma data was taken from CIS/CODIF-instrument, which is not ideally suited to solar wind measurements. Therefore the parameters dependent on the plasma measurements should be considered only as crude approximates for events detected by Cluster 4.

A.2 The coordinate systems and reference frames

The spacecraft reference frame and its coordinate system is used for: magnetic field vector ($\mathbf{B}$), velocity vector ($\mathbf{V}$) (also the bulk speed V) and normal vector of the shock ($\hat{\mathbf{n}}$). Position of the spacecraft may have different frame and coordinates.

Spacecraft	**Coordinate system of the spacecraft reference frame**	**Coordinate system of the position vector**
ACE	GSE	GSE
Wind	GSE	GSE
STEREO A and B	RTN	HGI
Ulysses	RTN	HGI
Helios A and B	HGIRTN	HGI
Cluster	GSE	GSE
DSCOVR	GSE	GSE
Voyager	RTN	HGI

Table 4: Coordinate systems used in the database.

B Assumptions about the solar wind plasma

General

- Ideal gas: $\gamma = \frac{5}{3}$ and $p_\alpha = n_\alpha k_B T_\alpha$
- Adiabatic equation of state

- Neglecting other ions than protons
- Neglecting the mass of electrons: $m_e/m_p \ll 1$

Assumptions about the solar wind electrons

- The bulk speeds of electrons and protons are equal: $V_e = V_p$
- Constant electron temperature depending on the radial distance from the Sun:

$$T_e = T_e(R_{\mathrm{AU}}) = 146277 \cdot R_{\mathrm{AU}}^{-0.664} \text{ K} \tag{18}$$

Assumption of equal bulk velocity for electrons and protons ($V_e = V_p = V$) results in additivity of pressures [7]. In isotropic case with the ideal gas assumption:

$$p = p_p + p_e = k_B N_p (T_p + T_e) \tag{19}$$

Electron temperature measurements were not generally available and we used constant value $T_e(R_{AU})$ (Eq. 18) instead. The variations of T_e with the radial heliospheric distance from the Sun (required for Helios, Ulysses and Voyager) are typically expressed as a power law $T_e(R_{AU}) \sim R_{AU}^{\beta}$ (Maksimovic et al. [8] and references therein). The index β, however, varies considerably between the studies. Here we made our own $T_e(R_{AU})$-fit, similarly to [9]. We used electron temperature measurements made by Helios and Ulysses spacecraft at radial distances from 0.29 AU to 5.41 AU. Suitable Helios data points were taken from [10] and all available Ulysses data were collected from CDAWeb [1]. The power law was fitted to these data points so that both spacecraft had equal weight in the fit. The result (Eq. 18) gives $T_e(1 \text{ AU}) = 146277$ K, which is, within error bounds, consistent with Newbury et al. [11]. This constant value was used for ACE, Wind, STEREO and Cluster spacecraft (thus neglecting their small deviations from the radial distance of 1 AU).

NOTE: Before 8/2015 the analysis results in the database were based on rigid electron-to-proton temperature ratio so that $T_e = 2T_p$.