SHocks: structure, AcceleRation, dissiPation

Work Package 5
Database of shock crossings and software repository

Deliverable D5.1
Technical report on the methodology to calculate the proxies for Mach number and on the software for data analysis tools available within the database

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1 Summary

This document serves as a technical report to describe the fundamental data analysis tools used to compile the terrestrial shock database as well as more advanced tools in the IRFU-MATLAB package. Also included in this report is a proxy for computing the shock Alfvén Mach number using only magnetic field data.

2 Introduction: shock database

The tools described in this report are to supplement a database of shocks, which allows easy identification of shock crossings matching a wide variety of parameter regimes. For each database entry, the shock parameter, description, and units that will be included in the terrestrial shock database are listed in Table 1 below.

Parameter	**Description**	**Units**
Shock ID	Identifier of the shock crossing entry	UTC
Shock interval	Date and time interval of the shock crossing	UTC
s/c ID	The spacecraft that observed the shock (e.g. MMS-1, Cluster-1)	n/a
s/c position	The location of the spacecraft (corresponding to s/c ID) when it observed the shock	R_E
s/c separation	Separation of the spacecraft configuration [min, max, mean]	km
Data mode	Data mode available (e.g. Burst, Fast)	n/a
V_{us}	Plasma velocity upstream of the shock	km s^{-1}
B_{us}	Magnetic field vector upstream of the shock	nT
n_{us}	Ion density upstream of the shock	cm^{-3}
$\hat{n}$	Shock normal vector [x, y, z] GSE	n/a
θ_{bn}	The angle between the shock normal and upstream magnetic field	deg
B_{cr}	Magnetic compression ratio according to $\lvert B_{ds}\rvert/\lvert B_{us}\rvert$	n/a
n_{cr}	Density compression ratio according to n_{ds}/n_{us}	n/a
B_{OS}	Magnetic field overshoot computed across the shock $B_{OS} = (max\lvert\mathbf{B}\rvert - \langle\lvert\mathbf{B_{ds}}\rvert\rangle)/\langle\lvert\mathbf{B_{ds}}\rvert\rangle$	n/a
M_A	Shock Alfvén Mach number	n/a
M_{ms}	Shock magnetosonic Mach number	n/a
V_{sh}*	Shock front speed	km s^{-1}
L_f*	Spatial length of the shock foot	km
L_r*	Spatial scale of the shock ramp	km
L_{os}*	Spatial scale of the overshoot	km
Quality flags	Flags to indicate the quality of each entry	n/a

Table 1: Shock parameters which are included in the terrestrial shock database. All vector quantities are in the Geocentric Solar ecliptic (GSE) co-ordinate system. The * indicates parameters that will be provided for terrestrial shocks during appropriate spacecraft separations.

Note that on occasions, not all parameters can be computed, such as if the spacecraft separation is inappropriate (e.g. shock speed). In these cases, the parameter(s) will be flagged. In the following section, we discuss the routines employed to compute these parameters and also introduce additional tools that can be used to perform a more advanced analysis of individual shocks.

3 Software for data analysis

3.1 Shock analysis tools: IRFU-MATLAB

The IRFU-MATLAB package is an open-access MATLAB toolbox that is continually updated and freely available online: https://github.com/irfu/irfu-matlab. It contains a comprehensive set of routines for analysing space plasma data, which includes scripts for performing fundamental calculations as well for more advanced data analysis. These routines have been developed for both single-and multi-spacecraft mission such and Solar Orbiter and MMS, respectively. IRFU-MATLAB is employed to both compute the quantities listed in the terrestrial database and perform a more detailed scientific analysis. In this section, we first highlight the relevant advanced data analysis functions before providing more specific details on the IRFU-MATLAB functions that were used to calculate database entries. Note, IRFU-MATLAB is well-documented inside each function, and the purpose of this report is not to reproduce this information (since it is regularly updated with the relevant scripts), but will direct users to the appropriate function. Entering `help routine_name` in the MATLAB command window will provide detailed descriptions of all functions. Note, replace `routine_name` with the relevant IRFU-MATLAB routine name (e.g `help irf_shock_normal`).

3.1.1 Getting started: reading a cdf file and creating a TSeries object

IRFU-MATLAB uses time-series (TSeries) objects, which can easily be constructed from cdf files using the following steps:

1. `data_object = dataobj('FILENAME')`
2. `data = get_ts(data_object,'variable'))`

3.1.2 Advanced analysis tools

IRFU-MATLAB contains many tools for advanced data analysis applicable to waves, turbulence, and converting from temporal to spatial coordinates. Here we list the key tools that have a high degree of applicability to shock analysis:

- `irf_ebsp` - Calculates the wavelet spectra of magnetic and electric fields and Poynting flux (using wavelets). The polarization parameters of the magnetic field are computed using Singular Value Decomposition (SVD). See Santolík et al. [2003].
- `irf_4_v` - Uses 4-spacecraft timing to calculate velocity of discontinuity.
- `c_4_grad` - Calculates the gradients, curls, divergences, etc., of measured plasma quantities using 4-spacecraft techniques.

- `irf_minvar` - Computes the minimum variance direction (eigenvalues and eigenvectors).
- `irf_psd` - Estimates the Power Spectral Density of a signal using Welch's averaged periodogram method.
- `PDist` - Routines for the analysis and plotting of MMS distribution functions.
- `irf_wavelet` - Compute a wavelet transform of a signal.

3.1.3 Routines for calculating shock parameters

Shock normal calculation
The function `nst = irf_shock_normal(spec)` can be used to compute the shock normal using a variety of methods (see Paschmann and Daly [1998]). The output returns a structure (`nst`), which contains data on the shock normal vectors given by providing the plasma parameters as inputs (`spec`). The data can be averaged values or values from the time series in matrix format. The time-series input must have the same size (upstream and downstream can be different), so the user may need to resample the data accordingly. The shock normal can be derived based on spacecraft measurements (e.g. coplanarity) or by a model if the spacecraft position is also provided.

Shock normal using spacecraft measurements (see Abraham-Shrauner [1972]):

- `mc` - Magnetic coplanarity
- `vc` - Velocity coplanarity
- `mx1` - Mixed method 1
- `mx2` - Mixed method 2
- `mx3` - Mixed method 3

Model shock normals requiring the spacecraft position:

- `farris` - Farris et al. [1991]
- `slho` - Slavin and Holzer [1981]
- `per` - Peredo et al. [1995], ($z = 0$)
- `fa4o` - Fairfield [1971]
- `fan4o` - Fairfield [1971]
- `foun` - Formisano [1979]

In addition to the above, the function `irf_minvar(scd)` will perform Minimum Variance Analysis (MVA) and can compute the shock normal. If this is used, then the eigenvalue ratios (above 10 for the intermediate/minimum) should be taken into account as an indication of the quality of the normal direction. For the shock normal listed in table 1 we use the model shock normal by Farris et al. [1991] to avoid the well-known issues of MVA shock normal directions.

Basic shock parameters

The MATLAB function `dspec = irf_shock_parameters(spec)` returns a structure (`dspec`) with derived plasma parameters from an input structure (`spec`) composed of measured plasma parameters. Listed in table 2 are the outputs, their units, and the required inputs. See also the function `irf_plasma_calc`, which is able to calculate fundamental plasma parameters including some of the above. Users can enter `help irf_plasma_calc` for a thorough description on its uses.

Table 2: Output parameter for IRF-MATLAB function `irf_shock_parameters`.

Output parameter	**Required input**
Speeds [km/s]:	
Alfven speed (Va)	$\mathbf{B}, n$
Fast speed (Vf)	$\mathbf{B}, \mathbf{V}, n, Ti, Te$
Sound speed (Vts)	Ti, Te
Frequencies [s^{-1}] (not radians):	
proton gyrofreq (Fcp)	$\mathbf{B}$
Lengths [km]:	
ion inert.len (Li)	n
proton gyroradius (Rcp)	$\mathbf{B}, \mathbf{V}$ (not thermal motion)
Dimensionless:	
Alfven Mach # (Ma)	$\mathbf{B}, \mathbf{V}, n$
fast Mach # (Mf)	$\mathbf{B}, \mathbf{V}, n, Ti, Te$
ion beta (bi)	n, Ti
electron beta (be)	n, Te

3.2 Proxy for the Alfvén Mach number

To derive the Mach number proxy, we have used the Cluster shock list published at the Cluster Science Archive (https://www.cosmos.esa.int/web/csa). The list was compiled by Kruparova et al. [2019] and contains 529 timings of shock crossings during the years 2001-2013 for all four spacecraft. In the present analysis, we used only CS1 crossings. A MATLAB script was written which synchronously downloads the `FGM_FULL`, `CIS-HIA_ONBOARD_MOMENTS`, and `WHI_ELECTRON_DENSITY` files in CDF format from the Cluster Science Archive. The script uses the downloading and CDF-reading procedures of IRFU-MATLAB. For each shock, the data was downloaded in the time range listed crossing time ±360 s. The magnetic field magnitude ($|\mathbf{B}|$), the CIS ion density (n_u^{CIS}), and the WHI electron density (n_u^{WHI}) were plotted together, and 6 data points, ($t_i, i = 1, \dots 6$), were manually chosen: two for the upstream region, two for the downstream region, and two for minimum variance analysis around the ramp.

To compare with some reference parameters we have used OMNI data [King and Papitashvili, 2005]. OMNI ion density (n_u^{OMNI}) was retrieved using the function `irf_get_data_omni` from IRFU-MATLAB. The objective of the analysis was to arrive at approximate empirical relation(s) which are not sensitive to errors from 1) plasma parameter measurements, 2) the choice of the upstream and downstream regions, and 3) shock normal calculations. No effort was invested in finding the most suitable upstream and downstream regions or checking the shock normal by plotting $(\mathbf{B}\cdot\hat{\mathbf{n}})$ and visual assessment of the requirement $(\mathbf{B}\cdot\hat{\mathbf{n}} \approx \mathit{const})$ across the shock. However, for the upstream and downstream regions over which the magnetic field is averaged a visual choice procedure was applied using all three instruments. The magnetic coplanarity (MC) normal was employed since it provides a global normal as opposed to local normals, which can be heavily influenced by waves and other embedded structures.

For each shock, the following variables are obtained directly from the data (if available):

- The mean upstream, (B_u), and downstream, (B_d), magnetic field magnitudes, derived from FGM measurements in the full resolution mode.
- The mean upstream, (n_u), and downstream, (n_d), densities derived from measurements by a number of instruments.
- The mean upstream,$(\mathbf{V}_1)$, and downstream, $(\mathbf{V}_2)$, flow velocities, derived from CIS measurements.
- The maximum magnetic field magnitude, (B_m), in the whole transition region.

Once we have these parameters, we define $N = n_d/n_u$, $R_B = B_d/B_u$, $R_m = B_m/B_u$. The Alfvén speed as

$$v_A = \frac{B_u}{\sqrt{4\pi n_u m_p}} \tag{1}$$

Once the shock normal, $(\hat{\mathbf{n}})$, is identified (see below), we derive the upstream flow speed in the normal incidence frame, (V_u), using

$$V_u = \frac{|V_{1n} - V_{2n}|}{1 - 1/N} \tag{2}$$

and find the Alfven Mach number as $M = V_u/v_A$. The details of the analysis and the results are provided in the attached paper (submitted to JGR). The main conclusion is that there is clear relation of R_m to M. No other correlations have been found. It is suggested to use theoretically proposed relation [Gedalin, 2021]

$$R_m = \sqrt{2M^2(1 - \sqrt{1-s}) + 1} \tag{3}$$

where s is the normalized cross-shock potential, $(s = 2e\varphi_{NIF}/m_p V_u^2)$, as a proxy for the Mach number. Figure 1 shows B_m/B_u plotted against the Mach number. For the analyzed set of shocks, the best fit is achieved when $(s = 0.6)$:

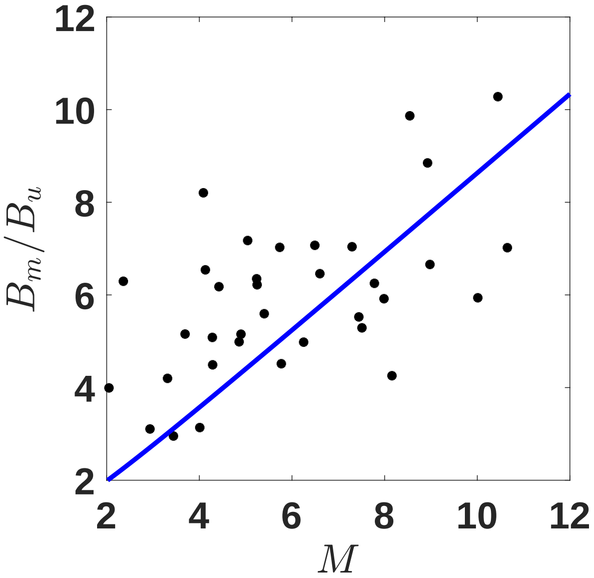

Figure 1: Theoretical fit to the Mach number.

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