The DRAG-BASED MODEL (DBM) with constant solar wind speed

Model Description

The drag-based model (DBM) tool provides predictions of the interplanetary coronal mass ejection (ICME) travel and its arrival at an arbitrary ecliptic-plane location or at already listed planets and satellites in ecliptic-plane orbits. Calculations are based on the assumption that the dominant force in the heliospheric dynamics of ICMEs is the magnetohydrodynamical (MHD) equivalent of the aerodynamic drag (for details see Vršnak et al., 2013, and references therein). The background solar wind is based on the assumption to be quasi-stationary, isotropic, and having a constant speed \( w \). From these approximations follows that the drag-parameter \( \gamma \) is constant as well. Basically, for a given set of input parameters the model provides the ICME Sun-“target” transit time, the arrival time, and the impact speed [Vršnak & Žic, 2007].

The web-tool is divided into the "real-time" and "custom" form. The "real-time" option predicts the ICME propagation in the ecliptic plane employing so-called the cone geometry [see Appendix in Zic et al., 2015] and calculates the arrival time and impact speed at Earth based on present date and proposed drag-parameter \( \gamma \) and solar wind speed \( w \). The proposed values of the drag-parameter are dependent on the type of the event (slow: \( \gamma = 0.5 \times 10^{-7} \text{ km}^{-1} \); normal: \( \gamma = 0.2 \times 10^{-7} \text{ km}^{-1} \); fast: \( \gamma = 0.1 \times 10^{-7} \text{ km}^{-1} \)), while the proposed values of the constant solar wind speed are taken from the ESA service tool (http://swe.uni-graz.at/ESWF), which estimates \( w \) at 1 AU over 4 days. The given values of the solar wind speed are: mean, median, minimal and maximal determined over 4 days of estimation based on the observed areas of coronal holes in a narrow heliographic longitudinal slit between E10° and W10° and over all heliographic latitudes. Therefore, the ICME arrival forecast is only valid for Earth, since coronal holes inside the a narrow slit are responsible for the solar wind directed toward Earth [cf. Rotter et al., 2015].

Additional information for DBM calculation includes initial values of the CME starting radial distance \( R_0 \) and speed \( v_0 \), its angular half-width \( \lambda \), and central meridian distance of its source region, \( \varphi_{\text{CME}} \), which is assumed to correspond to the direction of motion of the CME (see Table 1).

Figure 1: Relevant CME input parameters for the DBM using a SoHO/LASCO coronagraph image. Distance and speed of the CME leading edge are marked as \( R_0 \) and \( v_0 \), the estimated CME half-width angle as \( \lambda \). Missing propagation direction \( \varphi_{\text{CME}} \) is estimated from the longitude of the source region (SR) from the associated flare.
On the other hand, the "custom" form of DBM calculates the same forecasting output for selected target or (custom coordinates) in ecliptic plane with arbitrary entered values for CME take-off date and time (UT); drag-parameter $\gamma$, constant solar wind wind speed, $w$; starting CME radial distance $R_0$; starting CME radial speed at $R_0$, $v_0$; CME angular half-width, $\lambda$; longitude of source region (CME propagation direction), $\varphi_{CME}$; and selected target (Mercury, Venus, Earth, Mars, STEREO-A or STEREO-B satellite) or manually entered target coordinates: $R_{\text{target}}$, $\varphi_{\text{target}}$ (see Table 2).

**Model Input**

Generally, the input parameters of the DBM (with constant $w$ and $\gamma$) are CME take-off date and time, $t_0$, i.e. the time when the CME tip is at distance $R_0$; the constant value of the drag-parameter, $\gamma$; the constant value of solar wind speed, $w$; starting radial distance and speed at time $t_0$ of CME ($R_0$ and $v_0$); the CME angular half-width, $\lambda$; the longitude of source region (CME propagation direction), $\varphi_{CME}$; and selected (or manually entered) target position. Example how to determine DBM input from coronagraphic image is presented in Fig. 1.

The “real-time” forecasting uses the solar wind speed prediction based on expected speed at 1 AU (averaged over 4 days starting from current date, see Table 1) and forecasting is only valid for Earth.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event type</td>
<td>Drag-parameter value $\gamma$ (in $10^{-7}\text{km}^{-1}$) is based on event speed: (a) “slow” has 0.5, (b) “normal” 0.2 and (c) “fast” 0.1 value. The slow CMEs (or “stealth”) have velocities below 500 km/s ($v &lt; 500\text{km/s}$), while the normal CMEs have velocities in range of: $500\text{km/s} &lt; v &lt; 1000\text{km/s}$, and the speeds of fast CMEs exceed $1000\text{km/s}$ ($v &gt; 1000\text{km/s}$). Optionally, the drag-parameter value can be entered manually ($0.01 \leq \gamma \leq 100$).</td>
</tr>
<tr>
<td>$w$</td>
<td>The constant solar wind speed $w$ (in km/s) is determined by solar wind speed prediction based on expected speed at 1 AU (averaged over 4 days starting from current date). Proposed values are: mean, median, minimal and maximal of the predicted solar wind speed. Optionally, the speed value can be entered manually. The valid values for solar wind speed are in between: $200\text{km/s} \leq w \leq 800\text{km/s}$.</td>
</tr>
<tr>
<td>$R_0$</td>
<td>Starting radial distance of CME (in solar radii, $r_{\text{Sun}}$, units) is the distance of CME tip in coronagraph image on today’s date (see Fig. 1). Valid values are: $1r_{\text{Sun}} \leq R_0 \leq 214r_{\text{Sun}}$.</td>
</tr>
<tr>
<td>$v_0$</td>
<td>The speed $v_0 = v(R_0)$ in km/s is the speed of CME tip located at $R_0$, see Fig. 1. Valid values are: $5\text{km/s} \leq v_0 \leq 5000\text{km/s}$.</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>CME’s angular half-width $\lambda$ (in deg) is based on coronagraphic observation, for example see Fig. 1. Valid values are: $0^\circ &lt; \lambda &lt; 90^\circ$.</td>
</tr>
<tr>
<td>$\varphi_{CME}$</td>
<td>Longitude of source region is CME propagation direction determined on observation of eruptive phenomena on the solar disc at low-heliographic latitudes (in deg). Valid values are: $-180^\circ &lt; \varphi_{CME} &lt; 180^\circ$.</td>
</tr>
<tr>
<td>Target</td>
<td>The real-time forecasting is only valid for Earth!</td>
</tr>
</tbody>
</table>

Table 1: Input parameters for the “real-time” calculation.

On the other hand, the "custom" tab allows general inputs of DBM parameters based on CME observation (see Fig. 1) and the forecasting of CME arrival at an arbitrary position in the ecliptic plane. Several targets in the ecliptic plane are proposed, nevertheless the target coordinates can be entered manually, see Table 2.
Model Output

The DBM calculates the date and time of CME arrival, transit time and impact speed on previously selected (or manually entered) target, accompanied with radially dependent \( v(R) \), \( R(t) \) plots of CME leading edge element marked by “+ CME” symbol in cone-geometry plot [Zic et al., 2015, see Appendix].

<table>
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<th>Parameter</th>
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<tbody>
<tr>
<td>Date</td>
<td>Date ( (D_0) ) when CME tip is located at radial distance ( R_0 ), see Fig. 1; ( t_0 = D_0 + UT_0 ).</td>
</tr>
<tr>
<td>Time (UT)</td>
<td>Time ( (UT_0) ) when CME tip is located at radial distance ( R_0 ), see Fig. 1; ( t_0 = D_0 + UT_0 ).</td>
</tr>
<tr>
<td>Event type</td>
<td>Drag-parameter value ( \gamma ) (in ( \times 10^{-3} ) km(^{-1})) is based on event speed: (a) “slow” has 0.5, (b) “normal” 0.2 and (c) “fast” 0.1 value. The slow CMEs (or “stealthi”) have velocities below 500 km/s ( (v &lt; 500 \text{ km/s}) ), while the normal CMEs have velocities in range of: 500 km/s &lt; ( v &lt; 1000 \text{ km/s} ), and the speeds of fast CMEs exceed 1000 km/s ( (v &gt; 1000 \text{ km/s}) ). Optionally, the drag-parameter value can be entered manually ( (0.01 \leq \gamma \leq 100) ).</td>
</tr>
<tr>
<td>( w )</td>
<td>The constant solar wind speed ( w ) (in km/s). The valid values for solar wind speed are in between: 200 km/s ≤ ( w ) ≤ 800 km/s.</td>
</tr>
<tr>
<td>( R_0 )</td>
<td>Starting radial distance of CME (in solar radii, ( r_{\text{Sun}} ) units) is the distance of CME tip in coronagraph image on today’s date (see Fig. 1). Valid values are: ( 1r_{\text{Sun}} \leq R_0 \leq 214r_{\text{Sun}} ).</td>
</tr>
<tr>
<td>( v_0 )</td>
<td>The speed ( v_0(R_0) ) in km/s is the speed of CME tip located at ( R_0 ), see Fig. 1. Valid values are: 5 km/s ≤ ( v_0 ) ≤ 5000 km/s.</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>CME’s angular half-width ( \lambda ) (in deg) is based on coronagraphic observation, for example see Fig. 1. Valid values are: ( 0^\circ &lt; \lambda &lt; 90^\circ ).</td>
</tr>
<tr>
<td>( \varphi_{\text{CME}} )</td>
<td>Longitude of source region is CME propagation direction determined on observation of eruptive phenomena on the solar disc at low-heliographic latitudes (in deg). Valid values are: ( -180^\circ &lt; \varphi_{\text{CME}} &lt; 180^\circ ).</td>
</tr>
<tr>
<td>Target</td>
<td>Several targets on the ecliptic plane can be chosen from the list (Mercury, Venus, Earth, Mars, STEREO-A or STEREO-B satellite) or entered radial distance ( R_{\text{Target}} ) (in astronomical units, AU) and Earth-target heliocentric angular separation ( \varphi_{\text{Target}} ) (in deg) manually. Valid values are: ( R_0 \leq R_{\text{Target}} \leq 50 \text{ AU} ) and ( -180^\circ &lt; \varphi_{\text{Target}} &lt; 180^\circ ).</td>
</tr>
</tbody>
</table>

Table 2: Input parameters for the “custom” calculation.

References and relevant publications

- Vršnak, 2001
- Vršnak and Žić, 2007
- Vršnak et al., 2010
- Vršnak et al., 2013
- Zic et al., 2015

Developer Contact: Tomislav Zic (tzic@geof.hr)
A) Detailed mathematical description

One of the central issues of solar weather forecasting is the prediction of interplanetary coronal mass ejection (ICME) arrival to the Earth or any other point in the heliosphere. The main tool foreseen to provide predictions of the ICME arrival to the “target” is the so-called drag-based model (DBM, see Vršnak and Žic, 2007, Vršnak et al., 2013). The model is based on the assumption that beyond certain heliocentric distance the ICME propagation is governed solely by its interaction with the ambient solar wind, i.e., that acceleration/deceleration of the ICME can be expressed in terms of the magnetohydrodynamical (MHD) analogue of the aerodynamic drag (for details see Cargill et al., 1996). The “drag” force depends on the relative speed of the ejection and the solar wind; in a collisionless environment the acceleration can be expressed as $a = -\gamma (v - w) |v - w|$, where $\gamma$ is the “drag-parameter”, $a$ and $v$ refer to the instantaneous acceleration and speed of the ejection, whereas $w$ represents the ambient solar wind speed [Vršnak, 2001, Cargill, 2004, Owens and Cargill, 2004, Vršnak and Žic, 2007, Borgazzi et al., 2009, Lara and Borgazzi, 2009, Vršnak et al., 2010, Vršnak et al., 2013]. In DBM the CME is represented by the cone shape, where each element of the CME leading edge is defined by its position relative to the CME apex. The parameters $\gamma$ and $w$ represent the most sensitive elements of the DBM and play the main role in the drag-based simulation of the heliospheric CME propagation.

A.1 Kinematics of ICME

In DBM, the ICME propagation is determined by the equation of motion which reads

$$a = -\gamma (v - w) |v - w| \quad (1)$$

where $a$ and $v$ are the instantaneous ICME acceleration and speed, $w$ is the instantaneous ambient solar-wind speed, and $\gamma$ is the so-called drag-parameter, or drag efficiency. Note that all quantities in Eq. (1) are time/space dependent. Eq (1) reflects the most basic characteristics of the ICME heliospheric propagation: ICMEs that are faster than the ambient solar wind are decelerated, whereas those slower than the solar wind are accelerated by the ambient flow (cf., Gopalswamy et al., 2000).

Bearing in mind $a = \frac{\partial^2 R}{\partial t^2}$ and $v = \frac{\partial R}{\partial t}$, Eq. (1) provides kinematics of each ICME leading edge segment, $R(t)$, $v(t)$, $v(R)$, for given initial conditions, $t = 0$, $R = R_i$, $v = v_i$, and the values $\gamma$ and $w$. The drag-parameter $\gamma$ defines the velocity change-rate, i.e., shows for how much the ICME speed changes over the unit-distance. It can be expressed as:

$$\gamma = c_d A \rho_{sw} / M \quad (2)$$

where $c_d$ is a dimensionless drag coefficient, usually being on the order of 1 (for details see Cargill, 2004), $A$ and $M$ are the ICME cross section and mass, respectively, whereas $\rho_{sw}$ is the density of the ambient solar wind. The unit for $\gamma$ in M.K.S. system is $m^{-1}$; however, for practical reasons, in the following we will use the dimensionless abbreviation $\Gamma$ defined by $\gamma = \Gamma \times 10^{-7} \text{ km}^{-1}$. 
For the solar wind density we employ the empirical model by Leblanc et al. [1998], which at sufficiently large distances (say, \( R > 20r_{\text{Sun}} \), where \( r_{\text{Sun}} \) is the solar radius) asymptotically behaves as \( \rho \propto 1/R^2 \). Assuming the isotropic solar wind, i.e., \( \rho w R^2 = \text{const.} \), this defines the solar wind speed \( w = w_{\infty} = \text{const.} \), with the asymptotic value \( w_{\infty} \). On the other hand, if the cross-sectional area of CME behaves as \( A \propto R^2 \) and we assume that its mass does not change during the propagation, and at large distance approximation drag coefficient is preserved \( (c_d = \text{const.}; \text{for details, see Cargill, 2004}) \), the Eq. (2) immediately shows that drag-parameter has asymptotic value \( \gamma_{\infty} \) and is constant \( (\gamma = \gamma_{\infty} = \text{const.}) \) as well.

Finally, note that in the following we will denote the asymptotic values \( w_{\infty} \) and \( \gamma_{\infty} \) simply as \( w \) and \( \gamma \). The parameter \( \gamma \) can be expressed alternatively also as:

\[
\gamma = c_d \frac{A \rho_{\text{SW}}}{V_{\text{ICME}} \rho_{\text{ICME}}} \approx c_d \frac{1}{L} \frac{\rho_{\text{SW}}}{\rho_{\text{ICME}}}, \quad (3)
\]

where \( V_{\text{ICME}} \), \( L \), and \( \rho_{\text{ICME}} \) are the ICME volume, thickness, and density, respectively. Eq. (3) shows that massive ICMEs that are much denser than the ambient solar wind are affected by the drag much less than light ICMEs.

**A.2 DBM with cone geometry**

In this option we employ the so-called cone geometry (see Figure 2; Zic et al., 2015, Appendix A) where the leading edge is considered to be a semi-circle, spanning over the full angular width of the ICME, \( 2\lambda \). Considering the geometrical relationships between various parameters marked in Figure 2, the heliocentric distance \( R_{\phi}(t) \) and the speed \( v_{\phi}(t) \) of an element at the angular position \( \phi \) depend on the heliocentric distance of the CME tip, \( R_0(t) \), the speed of the CME tip \( v_0(t) \), the cone half-width \( \lambda \) (which stays constant during ICME propagation), and the angle \( \phi \). The CME expansion is modeled by providing the initial speed \( v_0 \) and heliocentric distance \( R_0 \) of an arbitrary single point on the CME leading edge (e.g., in Figure 2 the CME tip leading edge segment has the distance \( R_0(0) \) and the speed \( v_0(0) \)), thus the heliocentric distances \( R_{\phi}(0) \) and speeds \( v_{\phi}(0) \) of a certain segment along the leading edge with \( \phi \in [-\lambda, \lambda] \). At later time the leading edge evolves accordingly, as described in Eq. (1).

The prognostic online tool forecasts only ICME propagation in ecliptic plane, as a result of CME initiation at low heliographic latitudes. The geometric setup of the latest online DBM version is presented in Figure 2 where the CME frontal part evolves in time, i.e. the expansion of the CME leading edge is simulated by applying the DBM equation of motion Eq. (1) on each leading-edge segment independently. The initial cross-section in the ecliptic plane of CME shape is constructed by a single \( R_0(0) \) measurement of the CME tip element (which lies on the line of CME propagation direction and in the ecliptic plane as well) and by the conical CME geometry assumption. The leading edge gradually deforms since different segments are at initial time \( t_0 \) have different initial velocities, thus the DBM equation of motion results in different radial kinematics.
Since the flanks move slower, thus in fast ICMEs the drag-deceleration of flanks is weaker, whereas flank acceleration in slow events is stronger, the variation of speed along the ICME front decreases and the front gradually flattens. Note that such an “independent-element” DBM procedure could be equivalently applied to any other presumed initial CME geometry.

References


