Drag-Based Ensemble Model (DBEM): probabilistic model for heliospheric propagation of ICMEs

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Heliospheric propagation models are important for space weather forecasting

- CME/ICMEs major drivers of solar wind disturbances and geomagnetic storms
- Prediction of CME/ICMEs propagation in the heliosphere – important task for space weather forecasting

- Various models are used for space weather forecasting:
  - purely empirical/statistical methods
  - kinematical-empirical methods
  - analytical (M)HD-based models (**DBM**)
  - numerical MHD-based models (**ENLIL**)
Drag-Based Model (DBM)

- Beyond about 20 solar radii the MHD "aerodynamic" drag ($a_d$) caused by the interaction of CME with solar wind, becomes the dominant force
  \[ a = a_L - g + a_d \]
  \[ a_d = -\gamma(v-w)|v-w| \]

- ICME dynamics is governed by interaction with (ambient) solar wind ($w$)
  - fast CME ($v > w$) $\rightarrow$ deceleration
  - slow CME ($v < w$) $\rightarrow$ acceleration

- Drag parameter ($\gamma$) depends on characteristics of both ICME and solar wind – the drag is larger for broader, low-mass ICMEs in a high-density (slow) solar wind

- If $w$ and $\gamma$ constant there is analytical solution

Cargill et al., 1996; Vršnak and Žic, 2007; Vršnak et al. 2013
Drag-Based Model (DBM)

- Simple analytical model for heliospheric propagation of CMEs to predict the arrival time and speed of CME at any given target in the solar system

**Advantages**
- Simple and robust
- Very fast (one run << 1 sec) compared to numerical MHD models (eg. ENLIL)

**Disadvantages**
- Doesn’t give the best results in complex heliospheric environment (eg. CME-CME interactions, \( w \) and \( \gamma \) aren’t constant)

Online space weather tools

- Latest DBM version is integrated into ESA Space Situational Awareness (SSA) portal: http://swe.ssa.esa.int/heliospheric-weather

http://oh.geof.unizg.hr/DBM/dbm.php
DBM CME geometry

- Uses CME cone geometry with CME leading-edge flattening.

- Solar wind speed \( w \) is radially dependent \( w(R) \) and \( \gamma \) is also function of radial distance \( \gamma(R) \).

- Each CME leading-edge segment propagates independently → the initial cone geometry flattens.

\[ \dot{\text{žic et al.}}, 2015 \]
DBM and observations

Examples of ICME kinematics

**Fast ICME**
- Date: 12 December 2008
- $\gamma = 2.0 \times 10^{-7} \text{ km}^{-1}$
- $w = 350 \text{ km/s}$

**Slow ICME**
- Date: 15 November 2007
- $\gamma = 1.6 \times 10^{-7} \text{ km}^{-1}$
- $w = 600 \text{ km/s}$

![Graphs showing ICME kinematics with measurements and DBM predictions.](image-url)
Reliable observations are needed for better accuracy of heliospheric propagation models

- In about **55%** of events DBM has error (observed – calculated) less than **12h** and more than **85%** of events has error less than **1 day**

**Comparison od DBM and WSA-ENLIL-CONE model (Vršnak et al., 2014)**

- Relative difference is most often less than **10%**
- ENLIL preforms better during the solar maximum due to complex solar wind structure (differences 10-11h) and DBM can provide better results during the solar minimum (differences 6-9h)

However, the main problem of all models is the lack of reliable observations (input) eg. CME launch speed
Ensemble modelling

Input

Parameter 1 (e.g. γ)
- Value 1
- Value 2
- Value x

Parameter x
- Value 1
- Value x

Multiple model runs (DBEM)

Set of results

allows to calculate the confidence intervals of arrival times and impact speed (parameter uncertainties are quantified)
Drag-based Ensemble Model (DBEM)

- Recently, the DBM code was rewritten to **python** (modular design)
- Optimizations and improvements in the code → new version of DBM runs up to 200 times faster
- Parallelization of code that supports multi thread (CPU) calculations (up to 1000x faster)

Example for input parameters for CME on 6 Feb 2013

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- Each DBEM input parameter can be defined as list of parameters (eg. multiple observations of the same event)
Create $m$ synthetic measurements based on the known error (CI) for each parameter

- For each input parameter can be generated $m$ synthetic measurements in a range determined by standard deviation.
- **Assumption:** parameters follow a normal distribution.

\[ x = \bar{x} \pm \Delta x, \Delta x = 3\sigma \]

- Density of syn. measurements is denser near mean value than at the end of distribution (3σ)
- It was found that optimal number of syn. measurements is $m=15$
Example of DBEM results
ICME on 30 August 2013

Very fast
(calculated on single thread 1.6 Ghz Intel i5, 150 it/sec)

Distributions for CME transit time (TT) and impact speed (v) including mean value, median and confidence intervals
Example of DBEM results
ICME on 30 August 2013

- Results of DBEM can be used to investigate which input parameters are responsible for certain results (e.g., criteria: hits/misses target)
DBEM and ENLIL comparison

- ENLIL and DBEM perform similarly
- number of false alarms should be reduced
- fast CMEs predicted to arrive too early

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<th>ENLIL</th>
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<td>No of hits</td>
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<td>No of misses</td>
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<td>No of false alarms</td>
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<td>No of correct rejections</td>
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Conclusions

- **Very fast** (up to 1000 runs per sec), reliable and simple model
- Suited for a fast real-time space-weather forecasting
- Comparisons with numerical MHD models (ENLIL) show good accuracy of DBM at very low computational cost
- DBM performs better during the solar minimum than in the solar maximum, due to the complex heliospheric environment (eg. CME-CME interaction)
- DBEM can provide important information such as confidence intervals of CME arrival time and impact speed related to the input errors (observations)

Outlooks for DBEM

- will be integrated soon in ESA Space Situational Awareness (SSA) portal ([http://swe.ssa.esa.int/heliospheric-weather](http://swe.ssa.esa.int/heliospheric-weather))
Thank you for your attention

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