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

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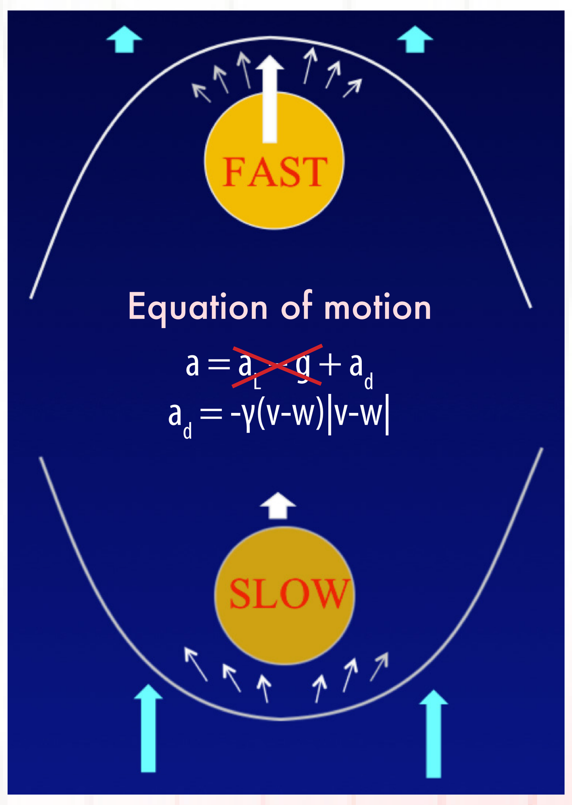
Introduction

The Drag-based Model (DBM) is a simple empirical model for heliospheric propagation of Coronal Mass Ejections (CMEs). It is based on the equation of motion that depends on the CME launch speed, background solar wind speed and CME mass and solar wind density (γ parameter). The model predicts the CME arrival time and speed at Earth or any other targets in the solar system.

However, the main problem of empirical and numerical models (e.g. ENLIL) is the lack of reliable observations that are needed for the model input. This can induce a large error in the CME arrival time (−1.7 ± 18.3 h; Vršnak et al., 2014) when observations and DBM forecasts are compared. The main advantage of DBM is its very fast computational time (<< 1s). This allows an ensemble modeling approach to provide a probabilistic forecasting of CME arrival time and speed within several minutes compared to numerical models that would need several hours (e.g. ENLIL).

The Drag-Based Ensemble Model (DBEM) takes into account the variability of model input parameters by making an ensemble of *n* different input parameters to calculate a distribution and significance of DBM results. Using such approach DBEM can determine most likely CME arrival times and speeds, quantify the prediction uncertainties and calculate the forecast confidence intervals.

Drag-Based Model (DBM)

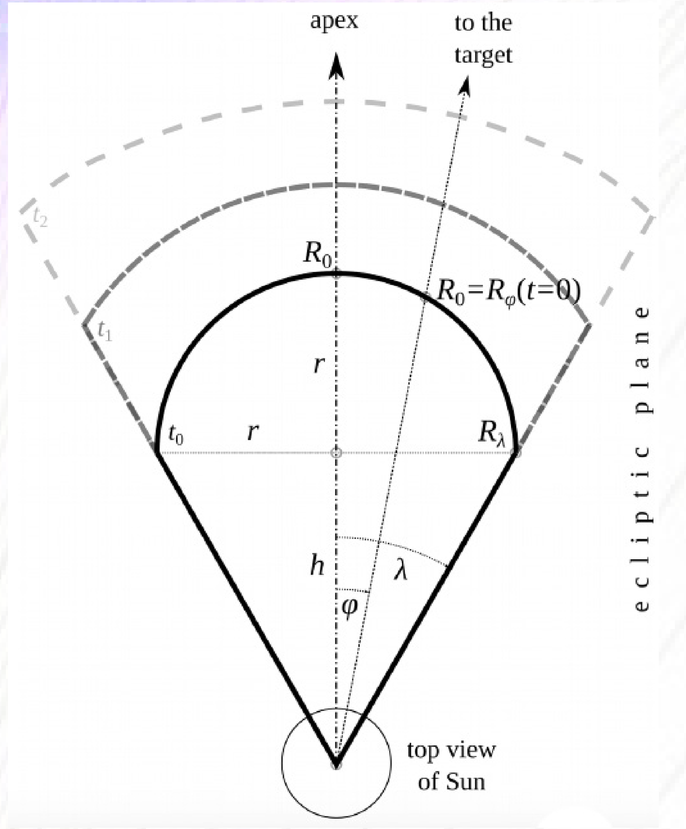


Beyond about 20 solar radii the MHD "aerodynamic" drag (a_d) caused by the interaction of CME with solar wind, becomes the dominant force.

CME dynamics is governed by interaction with (ambient) solar wind (*w*):

- fast CME ($v > w$): deceleration
- slow CME ($v < w$): acceleration

Drag parameter (γ) depends on characteristics of both CME and solar wind: the drag is larger for broader, low-mass CMEs in a high-density (slow) solar wind.
If *w* and γ are held constant there is analytical solution.



DBM uses CME cone geometry with the CME leading-edge flattening: each CME leading-edge segment propagates independently (Žic et al., 2015).

Advantages

- simple and robust
- very fast (calculation time << 1 sec) compared to numerical MHD models (e.g. ENLIL)
- suitable for on-line space waether forecast tools (e.g. ESA-ESC for Solar & Heliospheric Weather: **http://swe.uni-graz.at**, COMESEP alert system: **http://www.comesep.eu/alert**)

Disadvantages

- doesn't give the best results in complex heliospheric environment (eg. CME-CME interactions, when *w* and γ aren't constant)

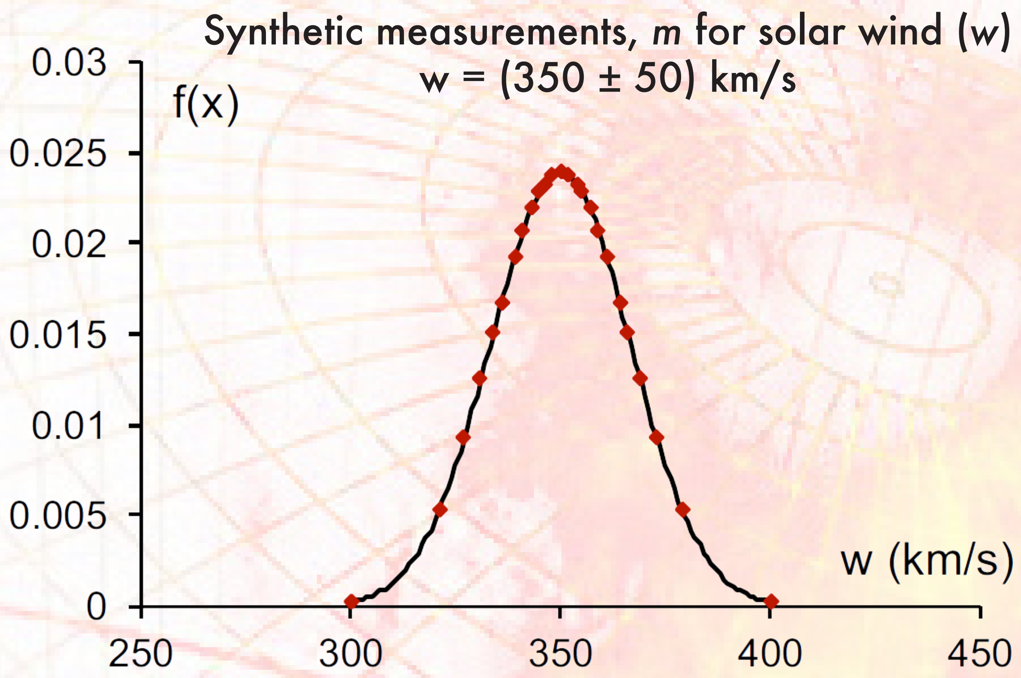
Ensemble modeling

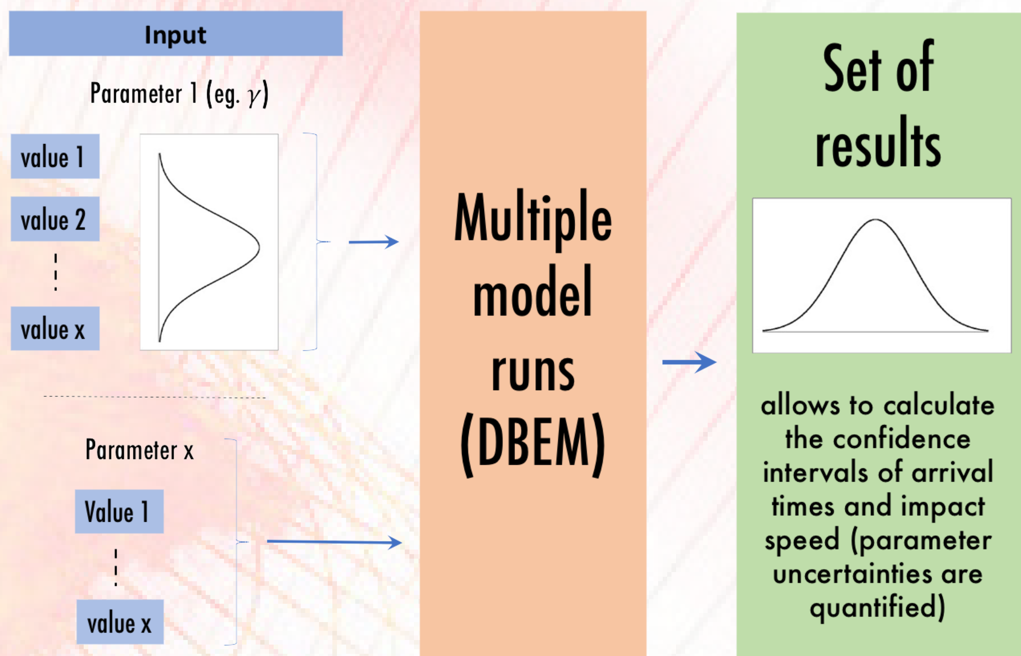
Each DBEM input parameter can be defined as a list of parameters (e.g. multiple observations of the same event) or based on the known uncertainty for each parameter can be created *m* synthetic measurements in a range determined by standard deviation. This can be done under the assumption that parameters follow a normal distribution (Dumbović et al., 2017).

$$x = \bar{x} \pm \Delta x, \Delta x = 3\sigma$$

Density of synthetic measurements *m* is denser near the mean value than at the end of distribution (3σ).

Calculated confidence intervals converge fast with increasing number of DBM runs and the optimal number of the synthetic measurements *m* is 15 or less.





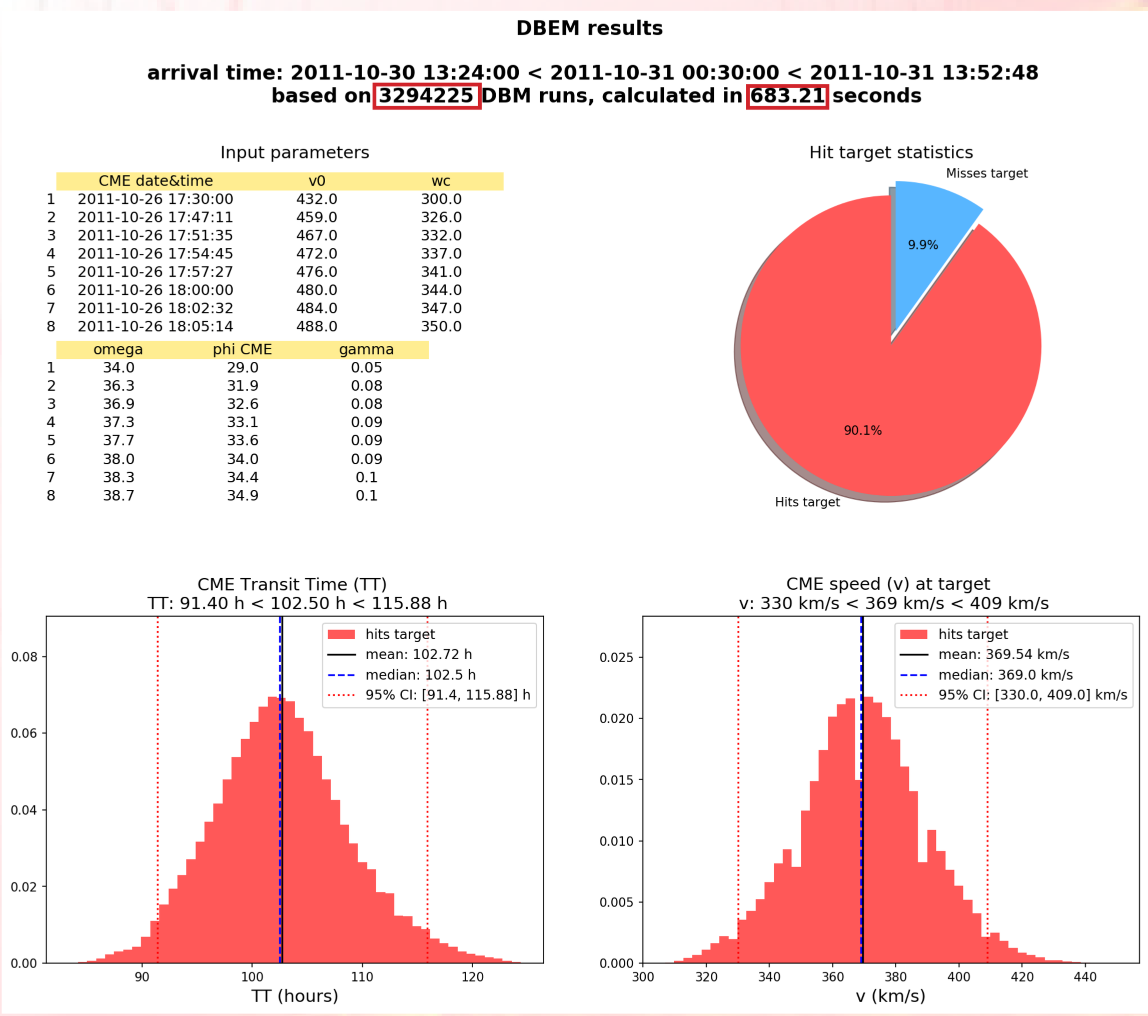
Model results and validation

DBEM input parameters (sample 2):

event	CME launch date & time	Drag parameter γ (10^{-7}) km^{-1}	Solar wind speed w (km/s)	Starting CME speed v_0 (km/s)		CME ang. half-width λ (deg)		Longitude of CME source reg. φ_{CME}, (deg)
	Δx = ±30 min, m=11	Δx = ±0.05, m=15	Δx = ±50, m=15	value	Δx, m=11	value	Δx, m=11	Δx = ±5, m=11
1	03-04-2010 15:00	0.1	350	850	85	41	4	-4
2	01-08-2010 12:00	0.1	350	1200	120	53	5	-29
3	15-02-2011 06:00	0.1	350	1000	100	36	4	-11
4	03-08-2011 17:00	0.1	350	1100	110	42	4	23
5	14-09-2011 06:00	0.1	350	500	50	40	4	19
6	24-09-2011 15:00	0.1	350	1100	110	33	3	-41
7	26-10-2011 18:00	0.1	350	480	48	38	4	34
8	26-11-2011 11:00	0.1	350	1000	100	63	6	56
9	15-03-2013 10:00	0.1	350	1100	110	52	5	9
10	07-01-2014 21:00	0.1	350	1400	140	47	5	32
11	15-03-2015 06:45	0.1	350	817	82	75	8	30

All events were calculated with the CME starting radial distance, R_0=**21.5** R_s and for target **Earth**. For each event DBEM performed altogether **3 294 225** runs.

DBEM output for event nr. 7:

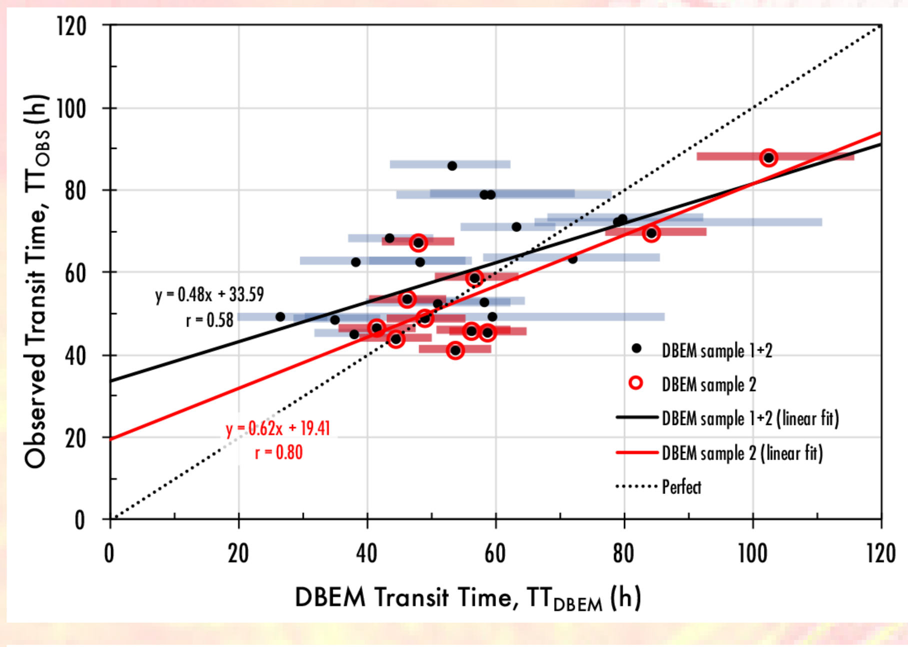


The new version of DBM was rewritten to **python** and due to code optimization and improvements it runs more than 1000 times faster than previous version (multi CPU support allows even further performace improvements).

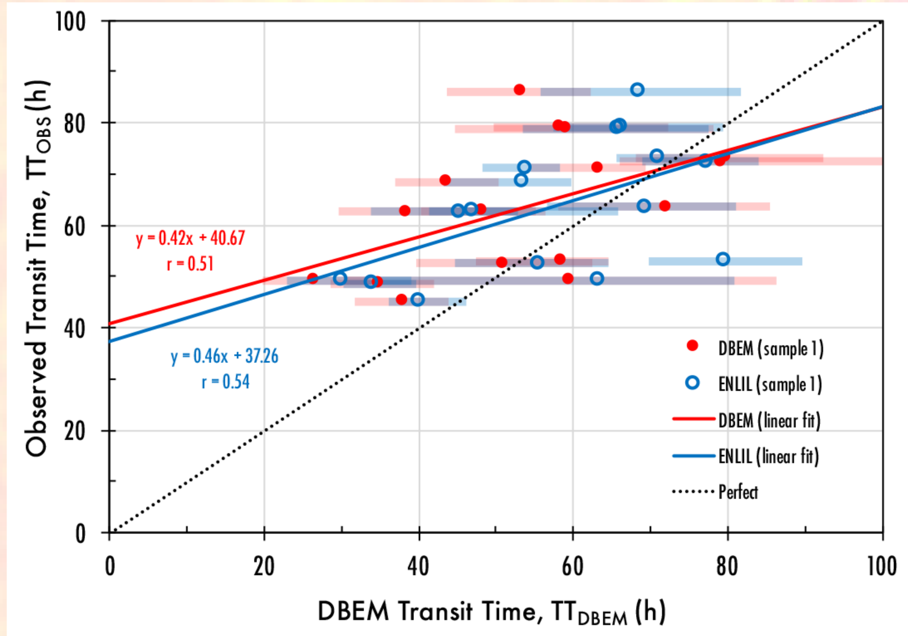
DBEM output (sample 2):

event	CME launch date & time	Probability of arrival, p (%)	DBEM Transit Time, TT_{DBEM} (hours)				Observed Transit Time, TT_{OBS} (h)
			mean	median	std	95% conf. int.	
1	03-04-2010 15:00	100.00	53.63	53.58	2.85	48.06 - 59.41	41.43
2	01-08-2010 12:00	100.00	46.23	46.18	3.01	40.17 - 52.33	53.68
3	15-02-2011 06:00	100.00	47.88	47.83	2.82	42.28 - 53.58	67.50
4	03-08-2011 17:00	100.00	49.00	48.94	3.06	42.92 - 55.20	48.85
5	14-09-2011 06:00	100.00	84.45	84.23	3.84	77.02 - 92.77	69.72
6	24-09-2011 15:00	0.83	58.65	58.59	2.98	52.85 - 64.71	45.57
7	26-10-2011 18:00	90.08	102.72	102.50	6.14	91.40 - 115.88	88.02
8	26-11-2011 11:00	96.69	56.84	56.78	3.32	50.43 - 63.60	58.83
9	15-03-2013 10:00	100.00	44.47	44.42	2.79	38.85 - 50.10	43.98
10	07-01-2014 21:00	100.00	41.52	41.47	2.95	35.59 - 47.55	46.65
11	15-03-2015 06:45	100.00	56.32	56.26	2.91	50.68 - 62.27	46.00

Comparison between observed and DBEM Transit Time, TT (sample 1: 16 ICME events, sample 2: 11 ICME events)



Comparison between DBEM and ENLIL (sample 1: 16 ICME events)



In general, DBM as well ENLIL underestimate TT for fast CMEs ($TT_{DBM}<TT_{OBS}$) and slightly overestimate TT for slow CMEs ($TT_{DBM}>TT_{OBS}$).

Conclusions & outlook

- DBEM is simple and **very fast** model (easily achieving few thousand DBM runs per sec on a common PC)
- Suitable for a fast real-time space-weather forecasting
- Comparisons with the observations and numerical MHD models (e.g. ENLIL) show very good accuracy of DBEM at low computational cost
- Performs better during the solar minimum than in the solar maximum, due to the more complex heliospheric environment (e.g. CME-CME interaction)
- Provides the important information such as confidence intervals of CME arrival time and impact speed related to the model input errors (observations)
- Will be soon integrated in ESA Space Situational Awareness (SSA) portal as new space weather forecast tool (**http://swe.ssa.esa.int/heliospheric-weather**)

References:

- Dumbović et al., ApJ (2017), in review
- Vršnak et al., ApJS, 213 (2014), 2, doi:10.1088/0067-0049/213/2/21
- Žic et al., ApJS, 218 (2015), 2, doi:10.1088/0067-0049/218/2/32

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