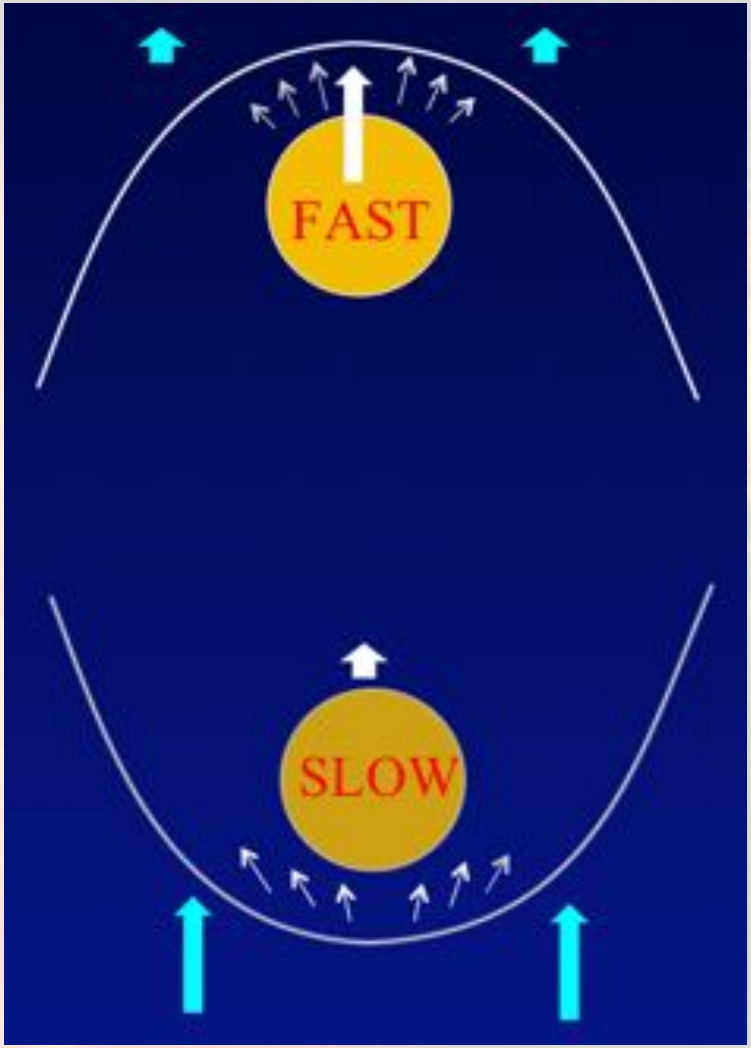
DBEM web application for heliospheric propagation of CMEs

J. Čalogović[1], M. Dumbović[2], B. Vršnak[1], D. Sudar[1], M. Temmer[2], L. M. Mays[3], A. Veronig[2], I. Piantschitsch[2]

1. Hvar Observatory, Faculty of Geodesy, University of Zagreb, Croatia
2. Institute of Physics, University of Graz, Austria
3. NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

Drag-Based Model (DBM)



Cargill et al., 1996; Vršnak and Žic, 2007; Vršnak et al. 2013

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

$$a = \sout{a_L - g} + a_d$$
$$a_d = -\gamma(v-w)|v-w|$$

Equation of motion

- 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 constant there is analytical solution

Drag-Based Model (DBM)

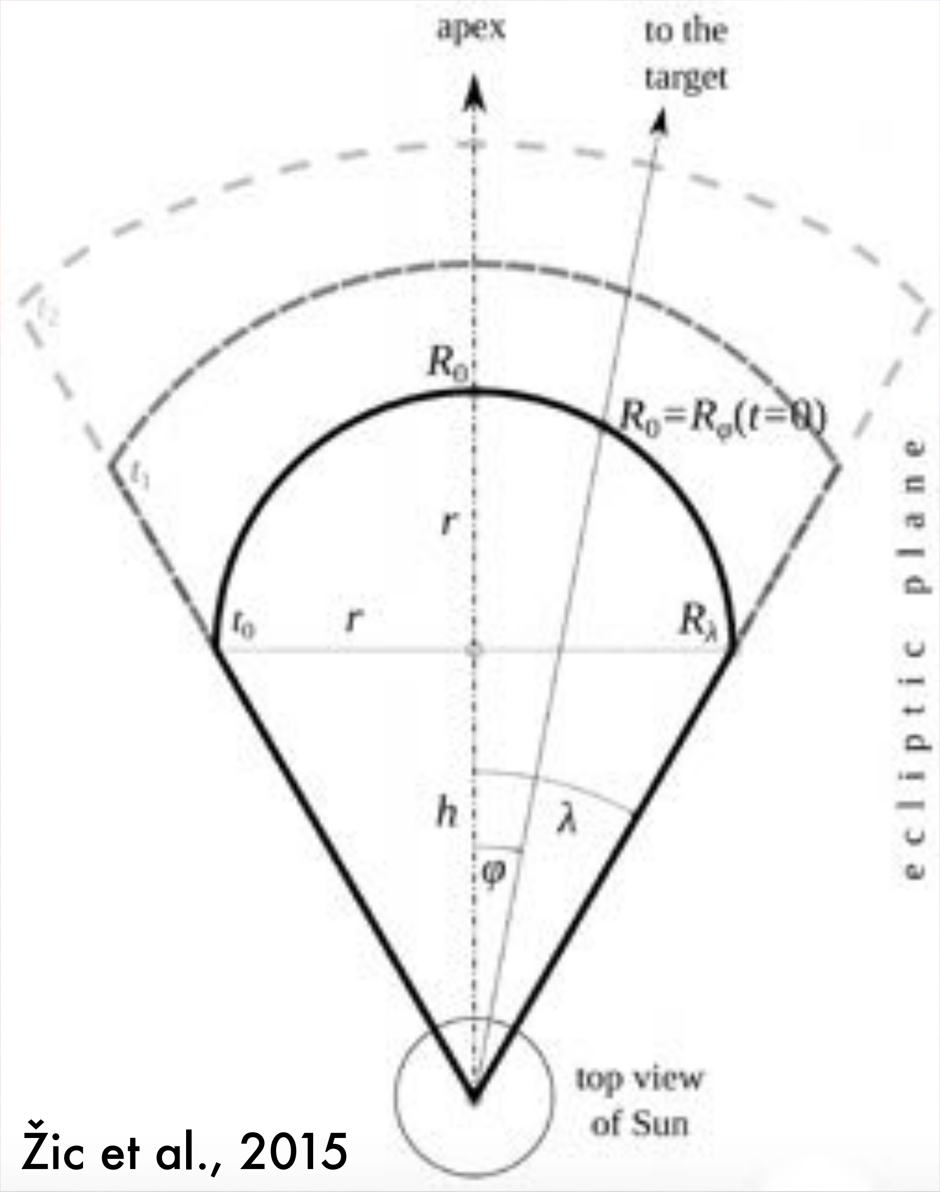
- Simple analytical model for heliospheric propagation of CMEs to predict the arrival time and speed of CME at any given target in the solar system

- **Advantages**
  - simple and robust
  - very fast (one run << 1 sec) compared to numerical MHD models (e.g. ENLIL)

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

DBM CME geometry

- Uses CME cone geometry with CME leading-edge flattening
- each CME leading-edge segment propagates independently → the initial cone geometry flattens

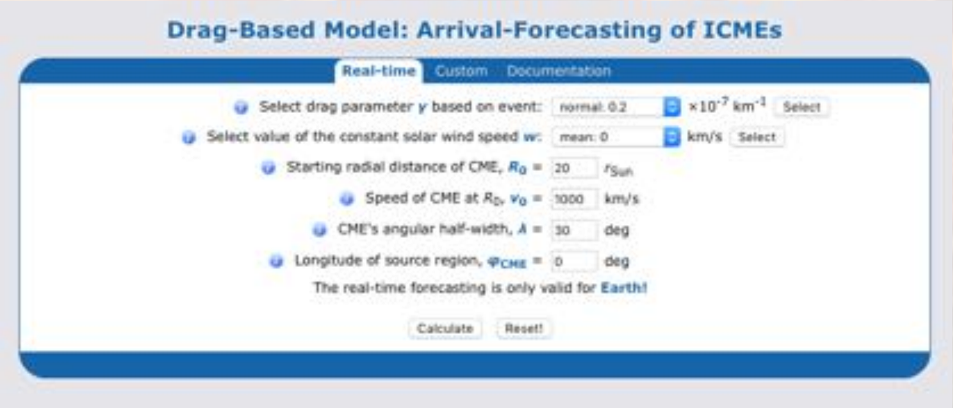


Žic et al., 2015

DBM and online space weather tools

- Latest DBM version is integrated into **ESA Space Situational Awareness** (SSA) portal (CME leading-edge flattening):

http://swe.ssa.esa.int/heliospheric-weather

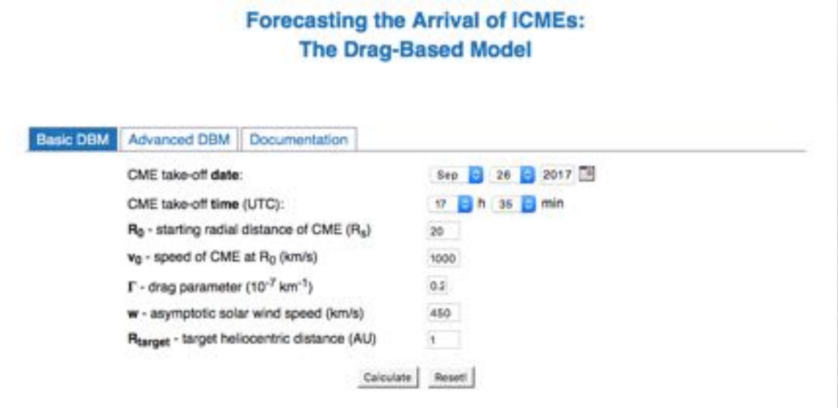


- **ESA Expert Service Center for Solar & Heliospheric Weather:**

http://swe.uni-graz.at

- **Hvar Observatory** - Forecasting the Arrival of ICMEs:

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



- **CME Arrival Time Scoreboard** – NASA Space Weather Research Center:

http://swrc.gsfc.nasa.gov/main/cmemodels

- The **COMESEP alert** system (DBM input from CACTus):

http://www.comesep.eu/alert

Reliable observations are needed for better accuracy of heliospheric propagation models

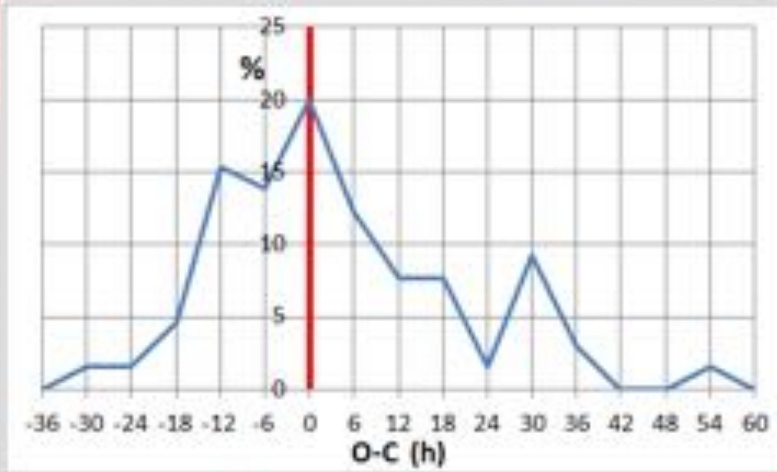
- In about **55%** of events DBM has error (observed – calculated) less than **12h** and more than **85%** of events has error less than **1 day**

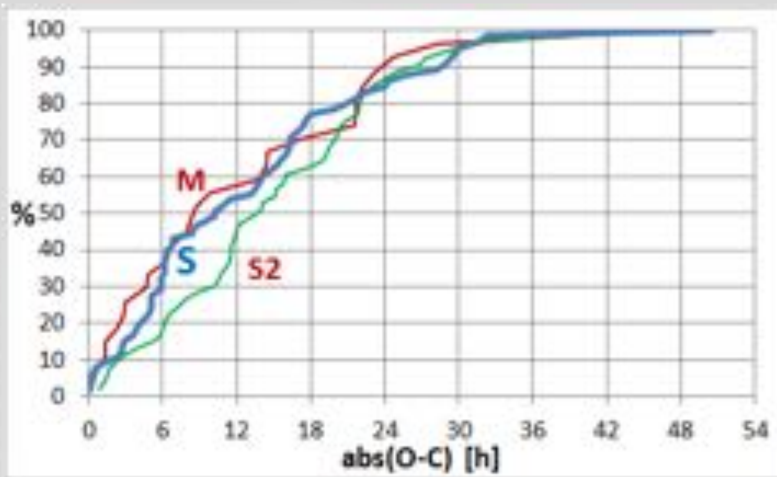
Comparison od DBM and WSA-ENLIL-CONE model (Vršnak et al., 2014)

- 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 <u>lack of reliable observations</u> (input) eg. CME launch speed

DBM errors (**O**bserved – **C**alculated)





Ensemble modelling

Input

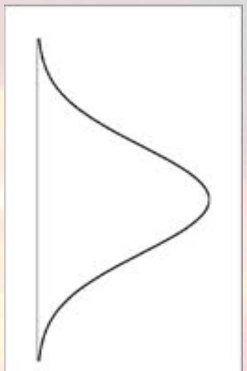
Parameter 1 (eg. γ)

value 1

value 2

⋮

value x



Parameter x

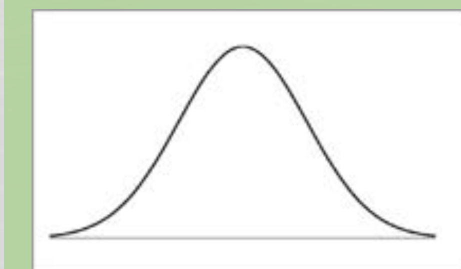
Value 1

⋮

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)

- Each DBEM input parameter can be defined as list of parameters (eg. multiple observations of the same event)

Example for input parameters for CME on 6 Feb 2013

Member ID	date & time	Latitude	Longitude	Half-Width	Speed
1	2013-02-06 03:15	30	-25	38	1226
2	2013-02-06 03:07	30	-35	38	1300
3	2013-02-06 02:42	33	-28	28	1389
4	2013-02-06 02:37	30	-20	27	1436
5	2013-02-06 02:40	30	-26	43	1460
6	2013-02-06 02:39	30	-24	36	1474
7	2013-02-06 02:37	33	-19	28	1536
8	2013-02-06 03:01	39	-33	43	1387
9	2013-02-06 02:40	30	-26	22	1460
10	2013-02-06 02:52	35	-30	27	1430
11	2013-02-06 02:44	34	-25	30	1470
12	2013-02-06 02:54	40	-28	30	1441
*	2013-02-06 02:41	30	-26	30	1460

DBEM with ensemble and synthetic measurements

Dumbović et al., ApJ, 2018

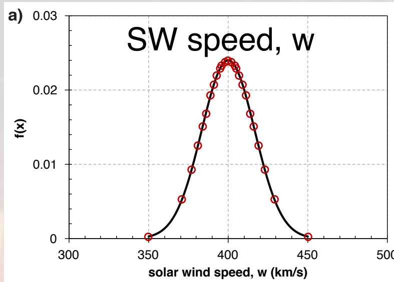
INPUT

Ensemble of CME measurements:

$T_1, v_1, \phi_1, \lambda_1$
$T_2, v_2, \phi_2, \lambda_2$
…
$T_n, v_n, \phi_n, \lambda_n$

n inputs

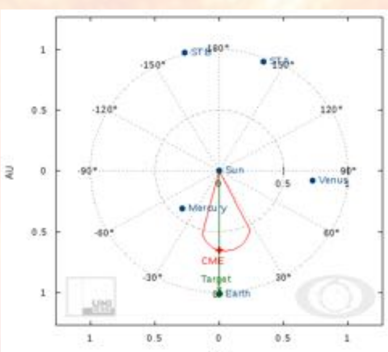
m x m inputs



Synthetic values for:
w_1, γ_2 / w_2, γ_2
…
w_m, γ_m

RUNS

nm^2 combinations (ensemble members)
nm^2 DBM runs

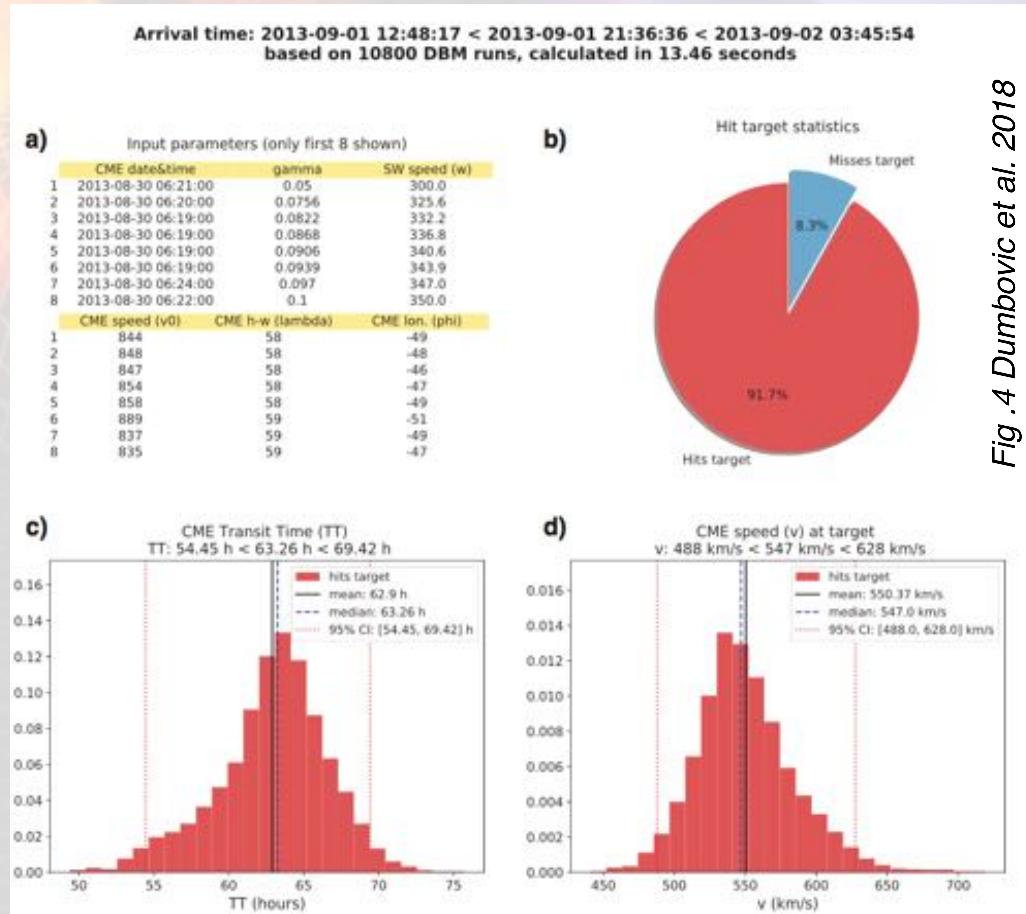


2D DBM (*Žic et al., 2015, ApJ*)

- hit or no hit
- transit time
- arrival time
- arrival speed

Ensemble modeling applied to Drag-based Model (DBM, *Vršnak et al., 2013, SolPhys*)

DBEM OUTPUT



	CME date&time	gamma	SW speed (w)
1	2013-08-30 06:21:00	0.05	300.0
2	2013-08-30 06:20:00	0.0756	325.6
3	2013-08-30 06:19:00	0.0822	332.2
4	2013-08-30 06:19:00	0.0868	336.8
5	2013-08-30 06:19:00	0.0906	340.6
6	2013-08-30 06:19:00	0.0939	343.9
7	2013-08-30 06:24:00	0.097	347.0
8	2013-08-30 06:22:00	0.1	350.0

	CME speed (v0)	CME h-w (lambda)	CME lon. (phi)
1	844	58	-49
2	848	58	-48
3	847	58	-46
4	854	58	-47
5	858	58	-49
6	889	59	-51
7	837	59	-49
8	835	59	-47

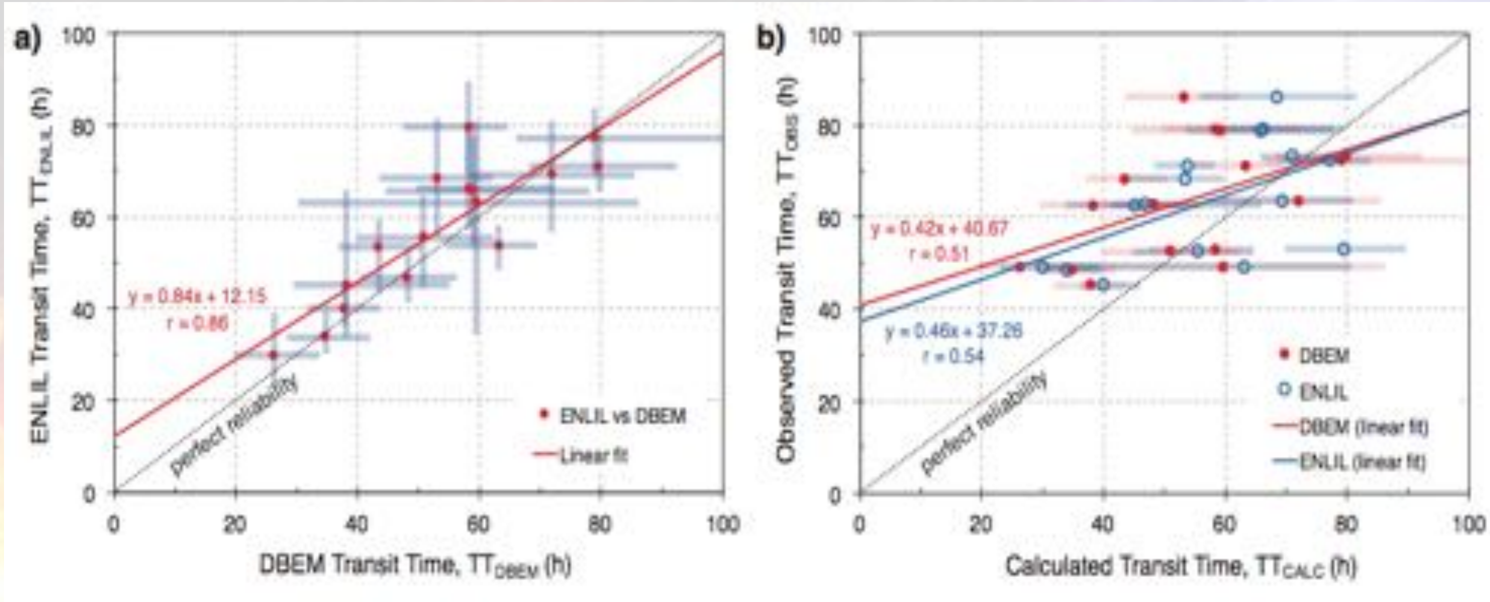
Fig .4 Dumbovic et al. 2018

Performance and comparison with ENLIL

- Based on sample: *Mays et al., 2015, SolPhys*

TRANSIT TIME

Fig. 7 from Dumbović et al., 2018



- Both ENLIL and DBEM are not far away from the line of perfect reliability

RELIABILITY DIAGRAM

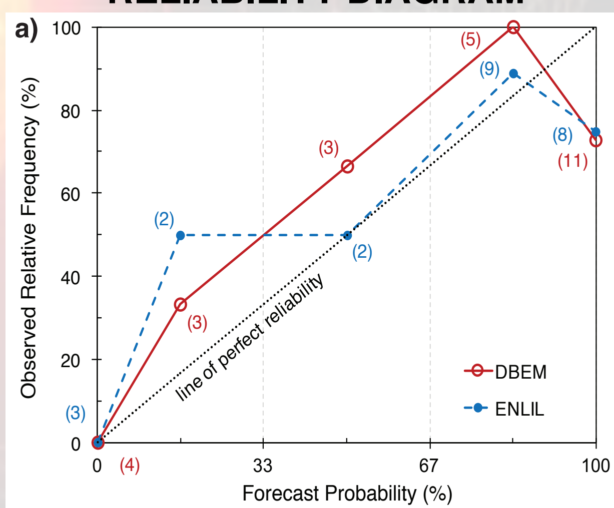


Fig. 5 from Dumbovic et al. , 2018

ARRIVAL SPEED

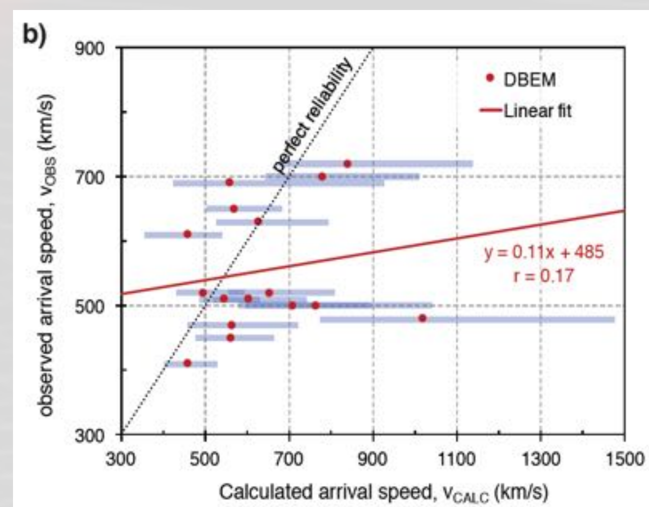


Fig. 8 from Dumbovic et al., 2018

Main points - DBEM

Dumbović et al., ApJ, 2018

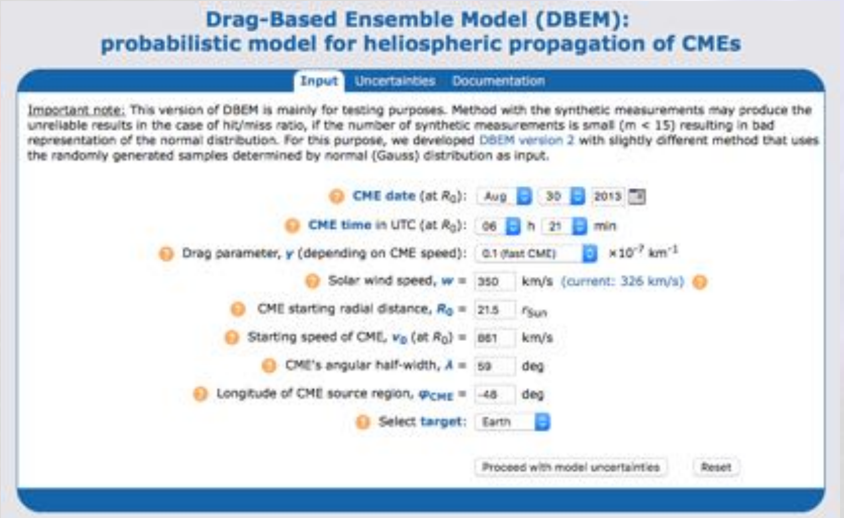
- Offers probabilistic forecasting of **CME hit chance**, **transit time** and **arrival speed** for different targets in solar system
- Reliable and simple model
- Runs **very fast** (more than 1000 DBM runs per sec on a single CPU)
- ENLIL and DBEM perform similarly
- Fast CMEs predicted to arrive too early for both DBEM and ENLIL
- Suitable for implementation as on-line (web) forecasting tool: **DBEMv1** and **DBEMv2** - ESA Expert Service Group for Solar & Heliospheric Weather (swe.uni-graz.at)

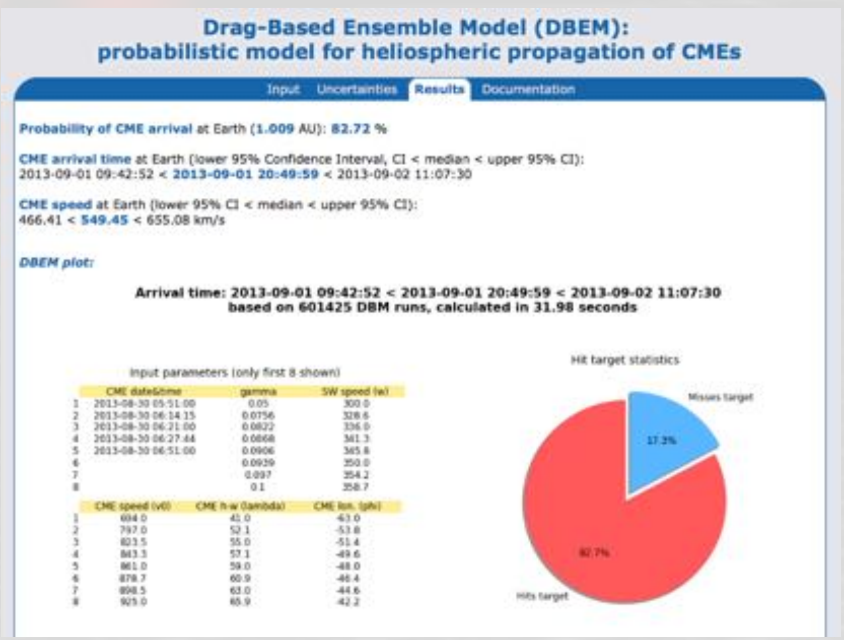
c) prediction errors for TT (h)	DBEM	ENLIL
mean error (ME)	-9.7	-6.1
mean absolute error (MAE)	14.3	12.8
root mean square error ($RMSE$)	16.7	14.4

On-line DBEMv1 tool with synthetic measurements

- Needs as input only one CME measurement with estimated uncertainties
- Uses **synthetic measurements for all 6 input parameters** (T, v, ϕ, λ, w, ɣ)
- Needs certain number of synthetic measurements (m > 9) to perform reliably - large number of DBM calculations (slow)
- **DBEMv2** is faster and more reliable than DBEMv1

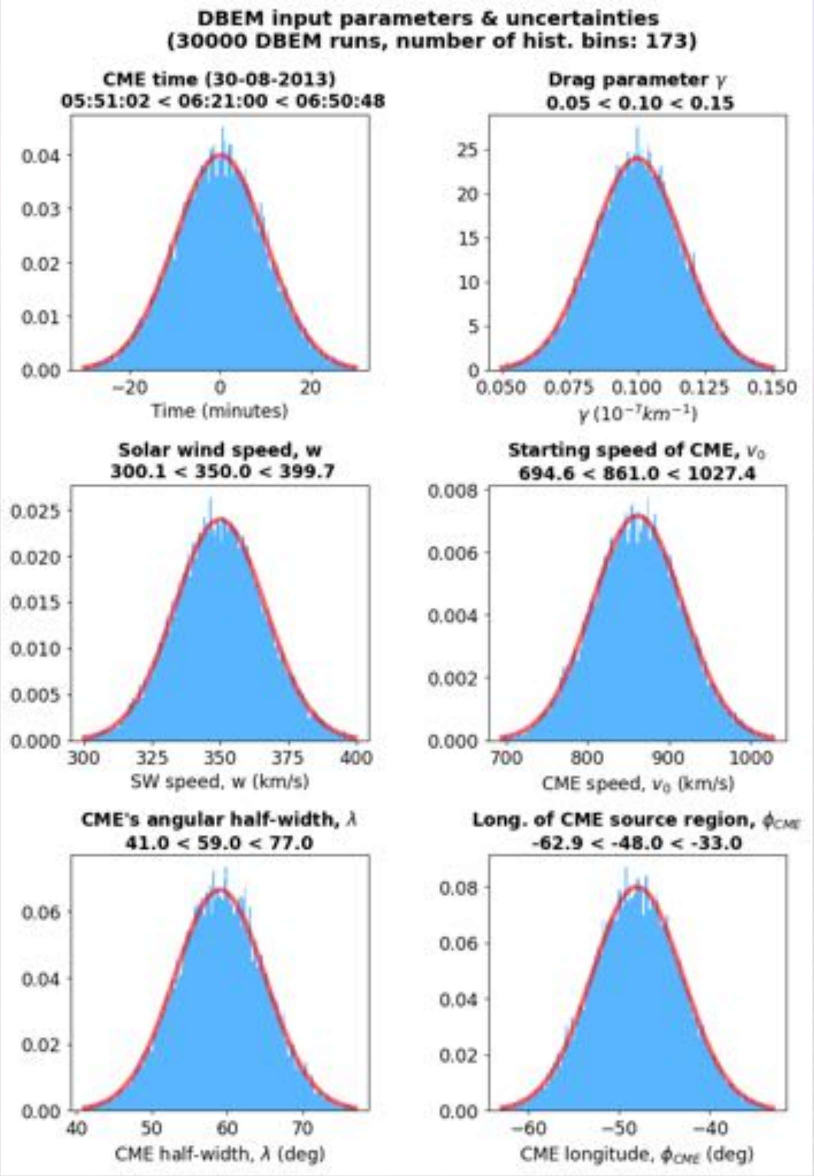
1. oh.geof.unizg.hr/DBEM
2. phyk039240.uni-graz.at:8080/DBEM





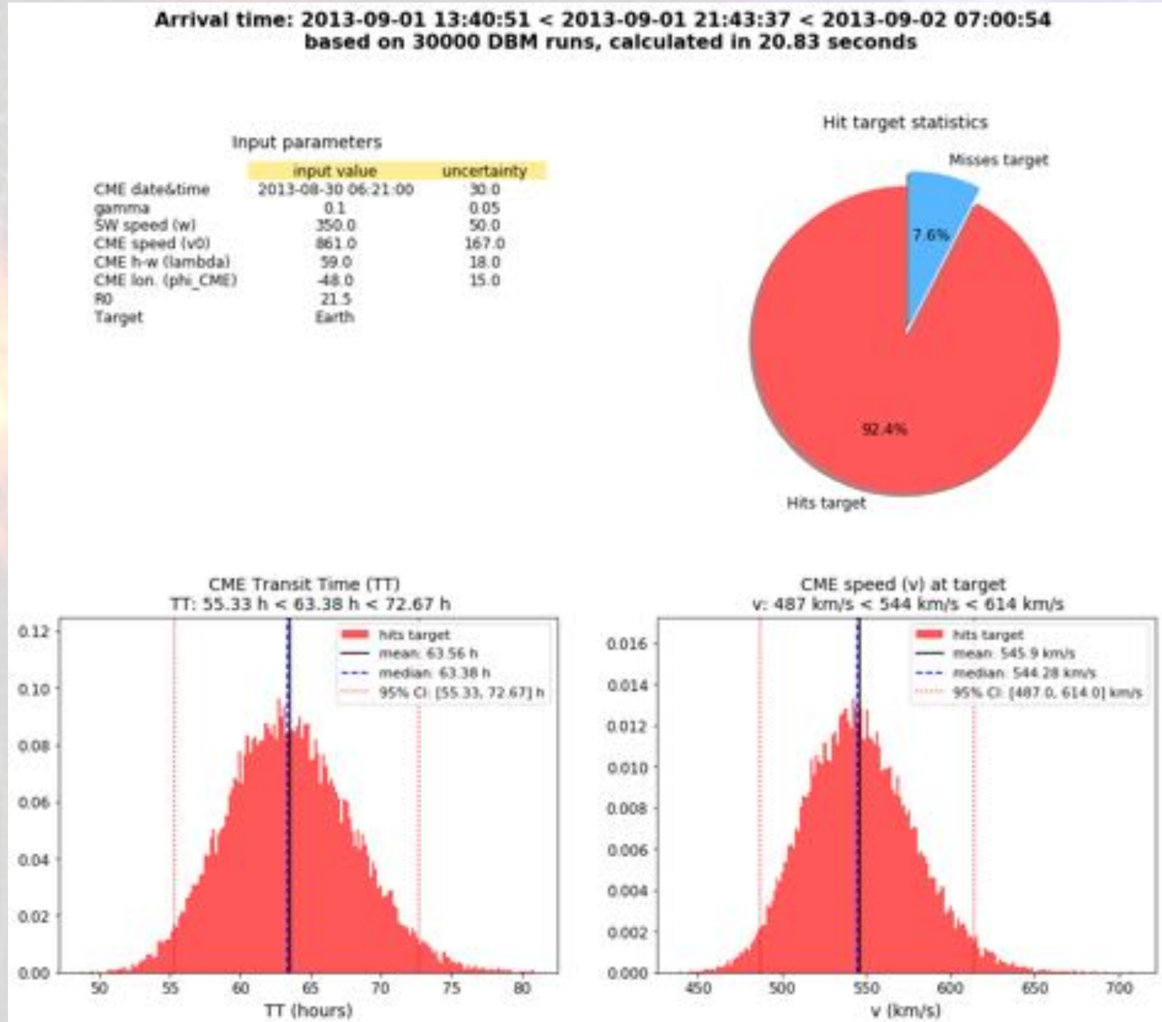
DBEMv2 (version 2) input parameters

- Same engine (software) as DBEMv1 with synthetic measurements, however different method is used for input uncertainties
- For all 6 input parameters (T, v, ϕ, λ, w, ɣ) random values are generated in a range input ± uncertainty (3 σ) following a normal (Gaussian) distribution
- <u>Advantages:</u>
  - input distributions are better represented than with DBEMv1
  - converges to stable results much faster than method with syn. measurements
  - allows lower number of DBM runs - **faster**
  - user can choose the exact number of DBEM runs
- <u>Disadvantages:</u>
  - due to random input, it produces every time slightly different results - differences converge with increasing nr. of runs (differences are negligible at >10 000 runs)



DBEMv2 results

- More accurate hit/miss ratio due to better representation of normal distribution in uncertainty range
- Provides statistics (mean, min, max, StDev, CI) for all calculated parameters
- User can download all results in a zip file
- Integrated in **ESA SSA portal** as operational forecasting tool in the frame of the **ESA Expert Service Group for Solar & Heliospheric Weather**



swe.ssa.esa.int/heliospheric-weather

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)

Thank you for your attention

We acknowledge the **ESA Space Situational Awareness** Programme's network of space weather service development activities, supported under **ESA contract number 4000113183/15/D/MRP**.